National Renewable Energy Laboratory
Innovation for Our Energy Future

Solar Energy – Capturing and Using Power and Heat from the Sun

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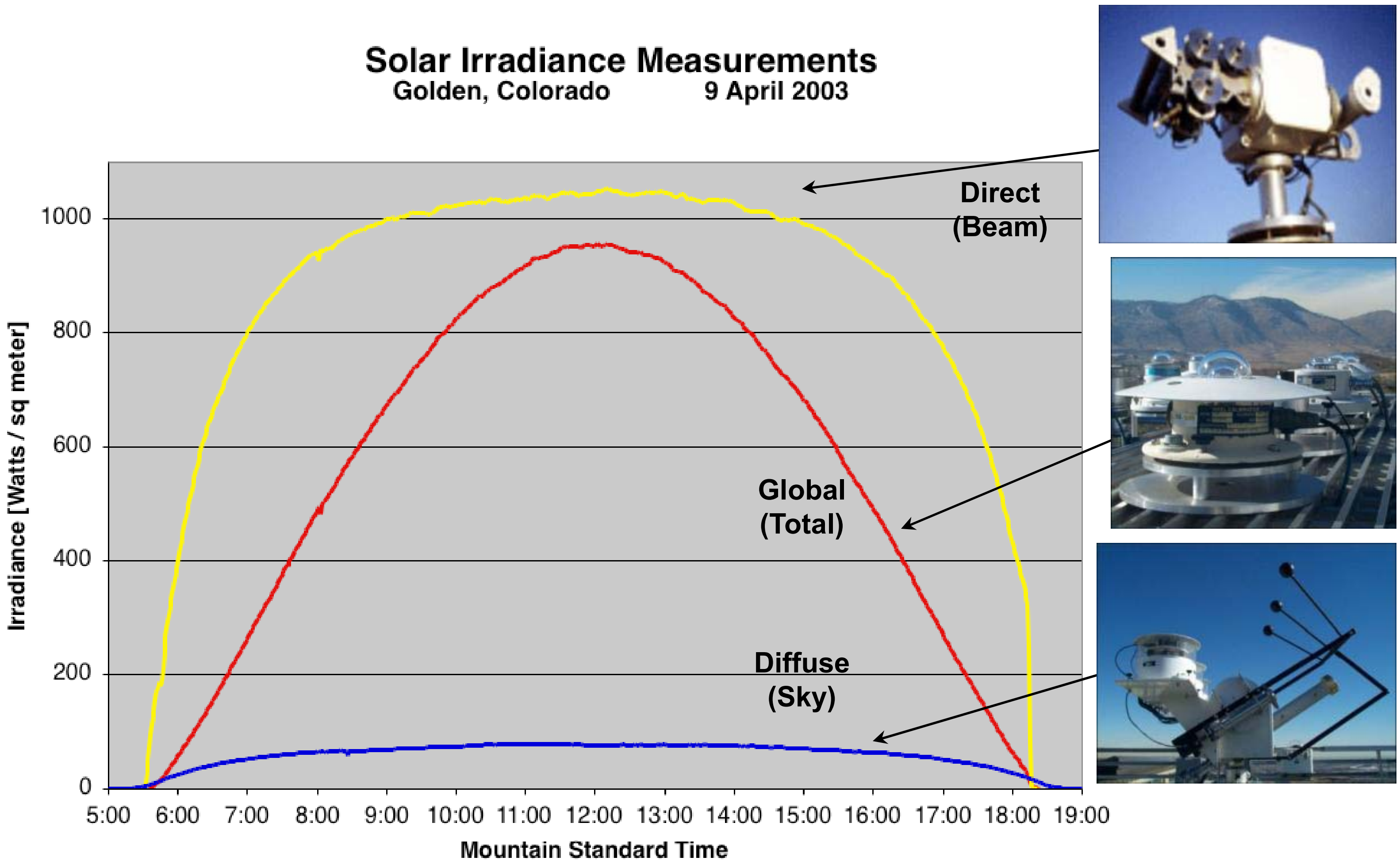
National Renewable Energy Laboratory

Golden, CO

Topics

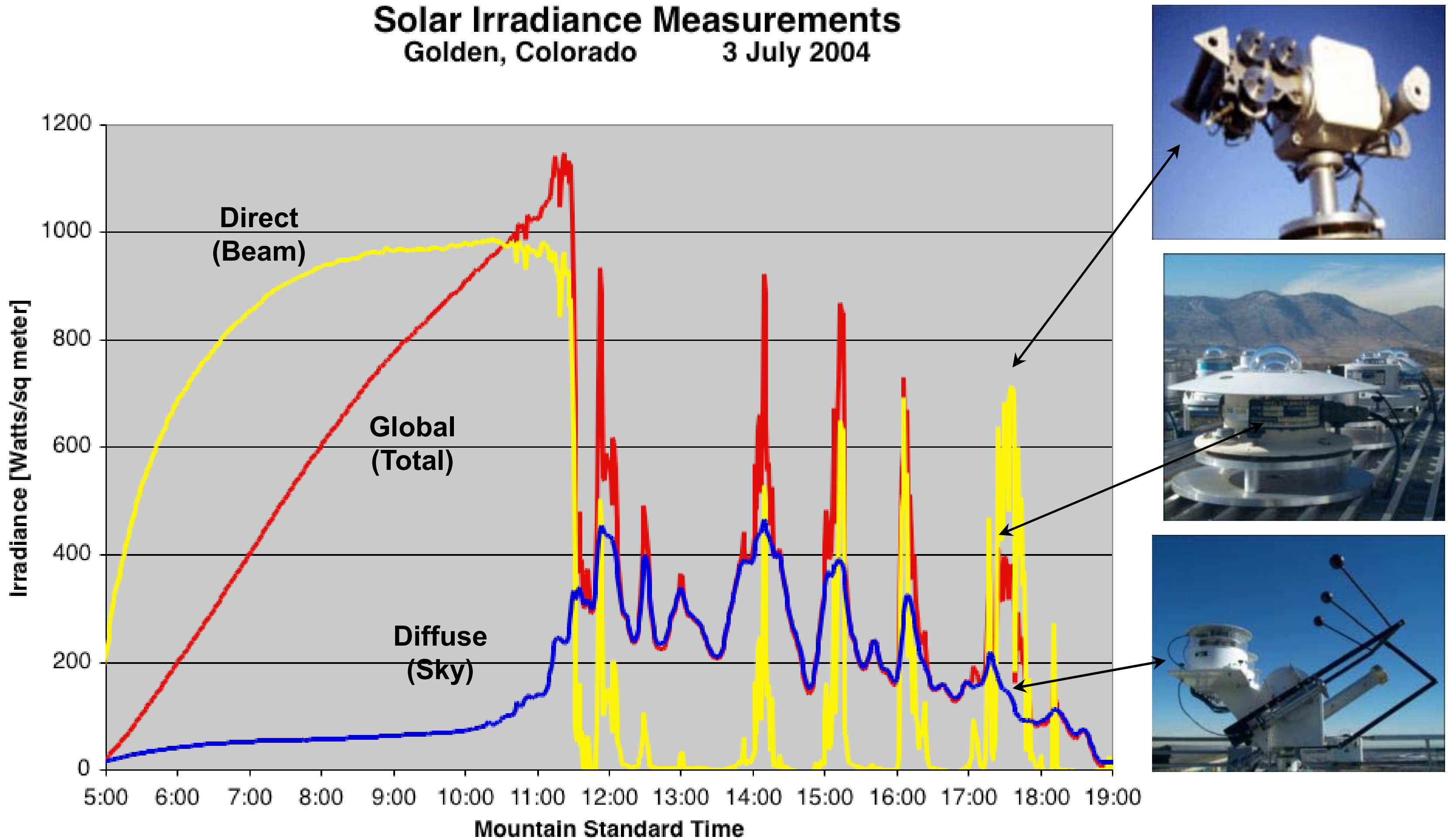
- **Solar Resource Overview**
- Solar Hot Water Systems
- Solar Photovoltaic Systems
- Concentrating Solar Power Systems

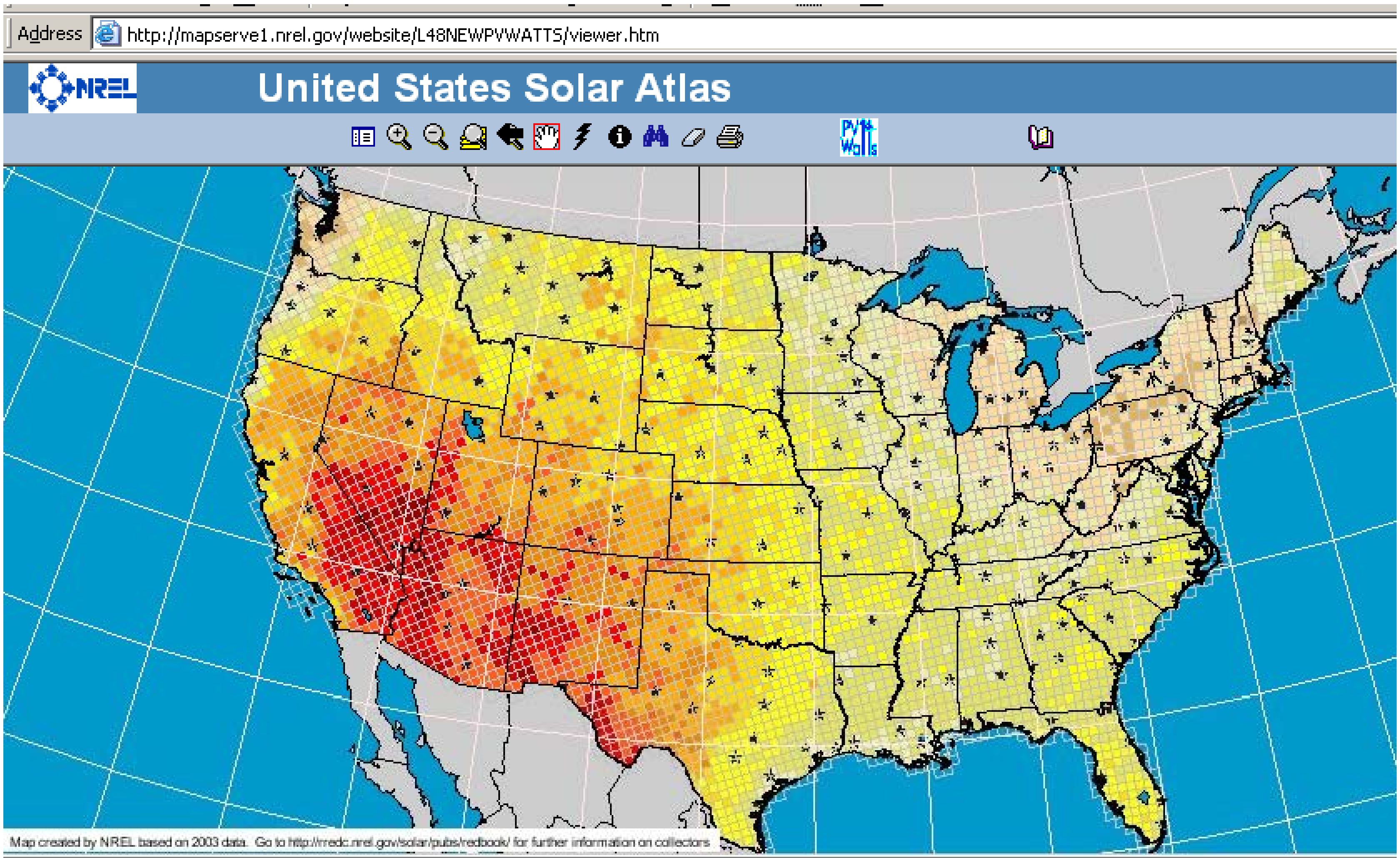
Clear Sky



Solar Irradiance Measurements
Golden, Colorado
9 April 2003
Irradiance [Watts / sq meter]
0
200
400
600
800
1000
5:00
6:00
7:00
8:00
9:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
Mountain Standard Time
Direct (Beam)
Global (Total)
Diffuse (Sky)

Partly Cloudy Sky




Address http://mapserve1.nrel.gov/website/L48NEWPVWATTS/viewer.htm
NREL
United States Solar Atlas
Map created by NREL based on 2003 data. Go to http://rredc.nrel.gov/solar/pubs/redbook/ for further information on collectors

http://www.nrel.gov/rredc/

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Renewable Resource Data Center

More Search Options SEARCH
Site Map

- Biomass Resource Information
- Geothermal Resource Information
- Solar Resource Information
- Wind Resource Information

The Renewable Resource Data Center (RReDC) provides access to an extensive collection of renewable energy resource data, maps, and tools. Biomass, geothermal, solar, and wind resource data for locations throughout the United States can be found through the RReDC.

Almost every area of the country can take advantage of renewable energy technologies, but some technologies are better suited for particular areas than others. Knowing the resources of a region, state, city, or neighborhood is therefore critical to renewable energy planning and siting.

RReDC provides detailed resource information through tools, reports, maps, and data collections. Additional resource data can be found on the NREL Dynamic Maps, GIS Data, and Analysis Tools Web site.

The Renewable Resource Data Center is maintained by NREL's Electricity, Resources, and Building Systems Integration Center.

Learn more about your solar resource by exploring these Web sites:

- SMARTS
- PVWatts
- NREL Measurement and Instrumentation Data Center
- NREL Solar Radiation Research.

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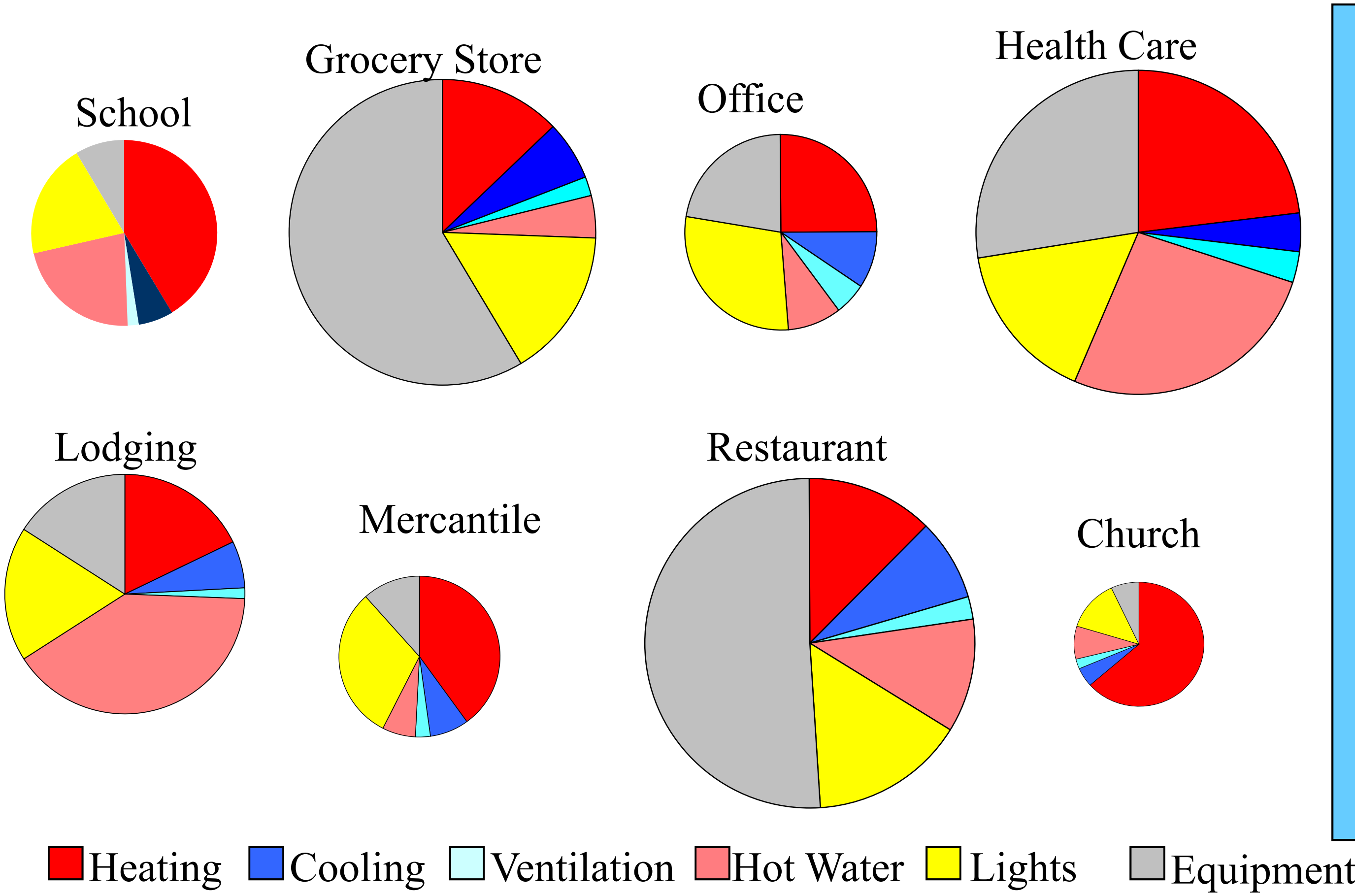
Solar Thermal Technology & Applications

Building Hot Water Energy Use
average 125 kbtu/sf/year



Energy for Water Heating kBtu/sf/year	
Office	8.7
Mercantile	5.1
Education	17.4
Health Care	63.0
Lodging	51.4
Pub Assembly	17.5
Food Service	27.5
Warehouse	2.0
Food sales	9.1
Public Safety	23.4
Other	15.3
All Buildings	13.8

Solar Water Heating Is Not New!

Before the advent of gas pipelines and electric utilities, the technology gained footholds in Florida and California before the 1920's

Over 1,000,000 systems are in use in American homes and business

The technology is in widespread use in:

- Caribbean basin
- Israel
- Japan
- China
- Greece
- Australia

Technical And Economic Viability Depends Upon

- Amount of annual sunshine
- Capital cost of the solar system
- Prices of conventional fuels
- Solar system annual O&M cost
- Annual energy requirement and energy use profile
- Temperature and amount of hot water (kWh produced)
- Rate at which conventional fuels are escalating in price
- Other (e.g. legislative mandates, tax credits)

Solar Thermal Applications

Low Temperature (> 30C)

- Swimming pool heating
- Ventilation air preheating

Medium Temperature (30C – 100C)

- Domestic water and space heating
- Commercial cafeterias, laundries, hotels
- Industrial process heating

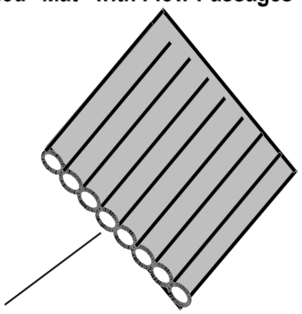
High Temperature (> 100C)

- Industrial process heating
- Electricity generation

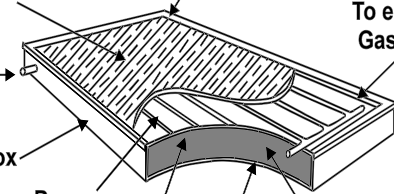
Solar thermal and photovoltaics working together

Collector Types

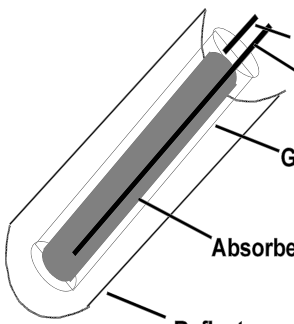
Unglazed EPDM Collector



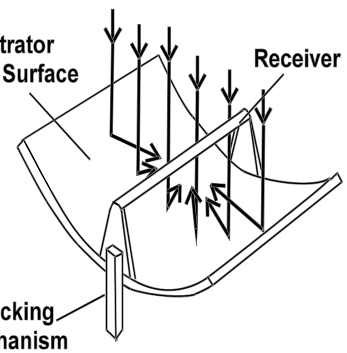
Flat Plate



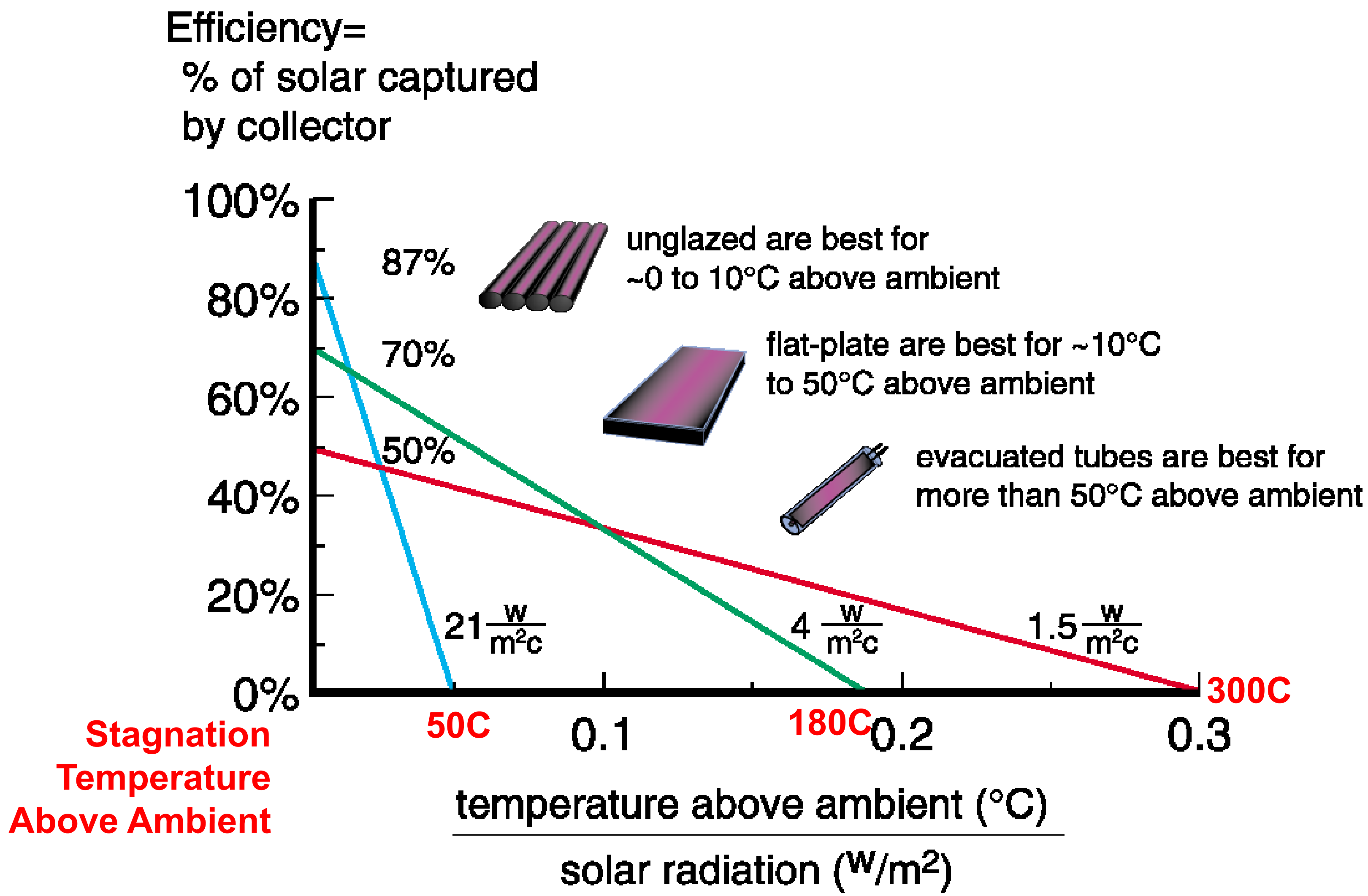
Evacuated Tubes



Parabolic Trough



Which collector is best depends on the temperature...



Solar Rating and Certification Corp.

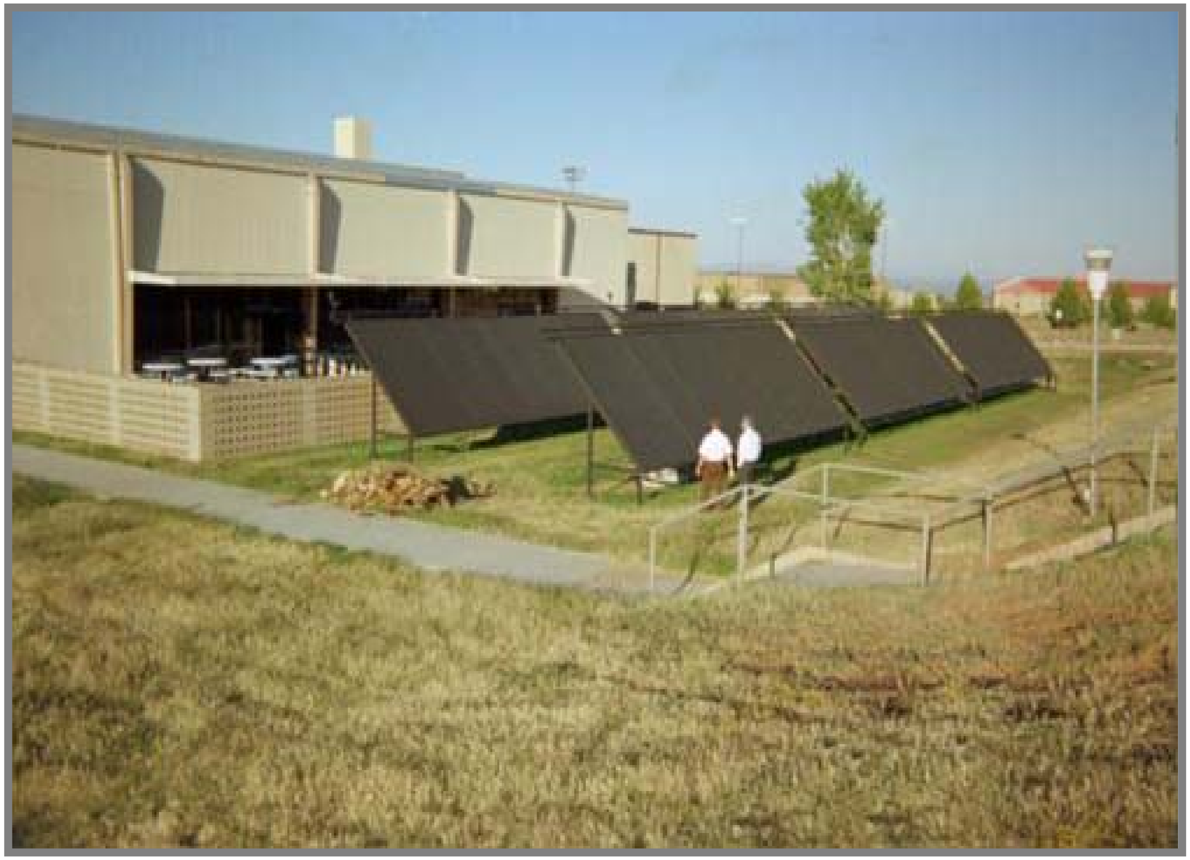
Contact information
Solar Rating and Certification Corporation
c/o FSEC, 1679 Clearlake Road
Cocoa, FL 32922-5703
Voice (321)638-1537
Fax (321)638-1010
E-mail: srcc@fsec.ucf.edu

- An independent nonprofit organization that tests performance and certifies almost every solar heater on the market today.
- Reports efficiency and annual performance for different climates and temperature uses.

Typical Low Temperature Application

Low Temperture Example:

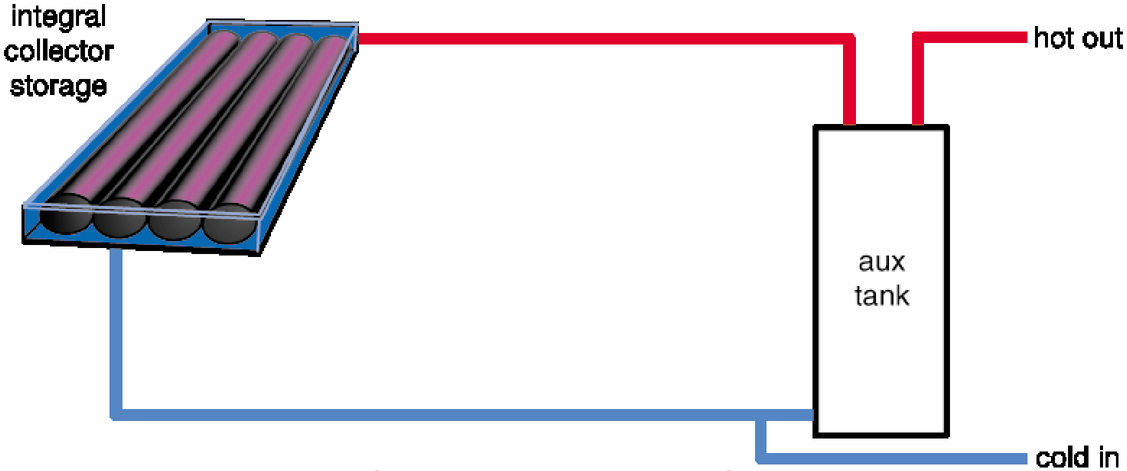
Barnes Field House, Fort Huachuca, AZ



- 2,000 square feet of unglazed collectors
- 3,500 square feet indoor pool
- Installed cost of $35,000
- Meets 49% of pool heating load
- Saves 835 million Btu/ year of natural gas
- Annual savings of $5,400
- Installed by the Army in June, 1980.

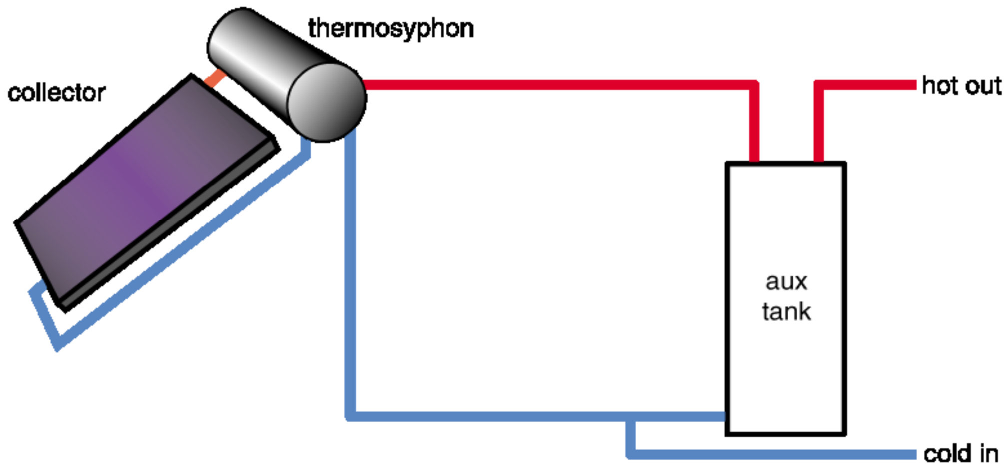
Passive, Integral Collector Storage (ICS)

Direct System



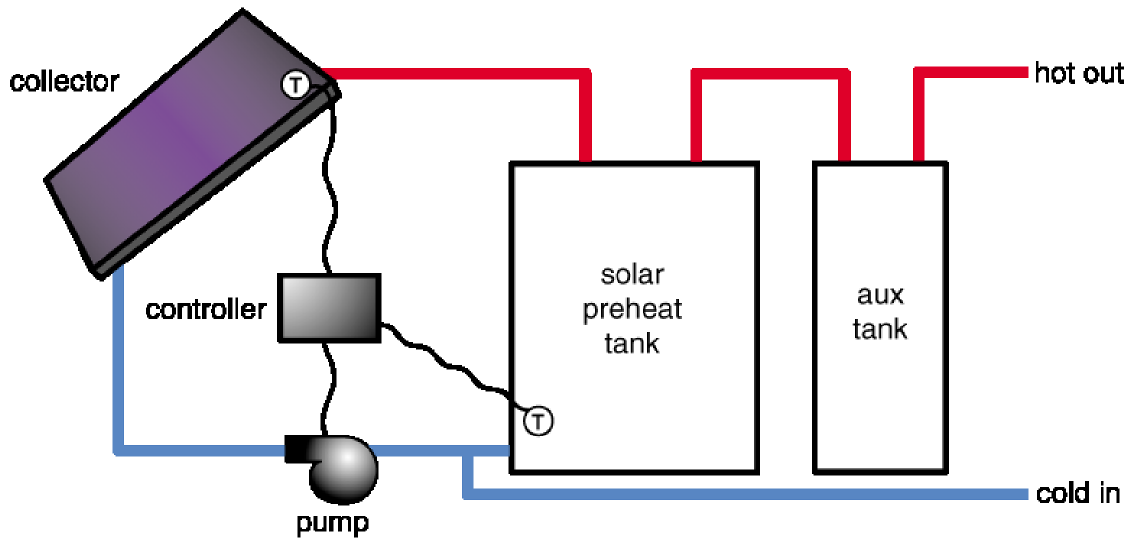
- Moderate freeze protection (pipes at risk)
- Minimal hard water tolerance
- Very low maintenance requirements

Passive, Thermosyphon, Direct System



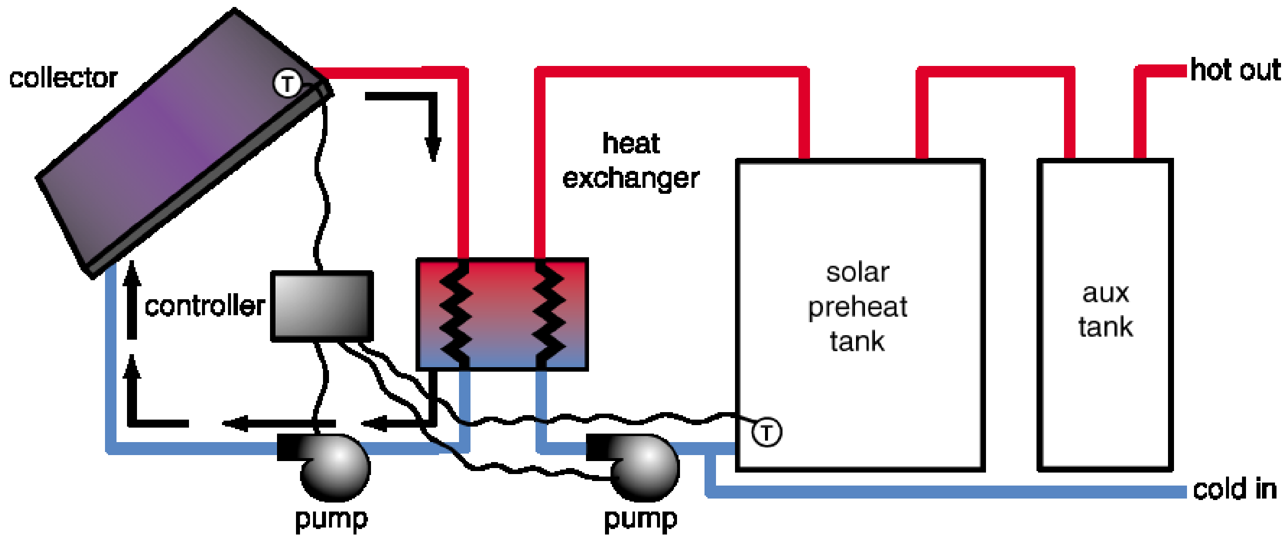
- Auxiliary element can also be in tank above collector, eliminating the auxiliary tank altogether.
- No freeze protection
- Minimal hard water tolerance
- Low maintenance requirements

Active, Open-loop, Pumped Direct System



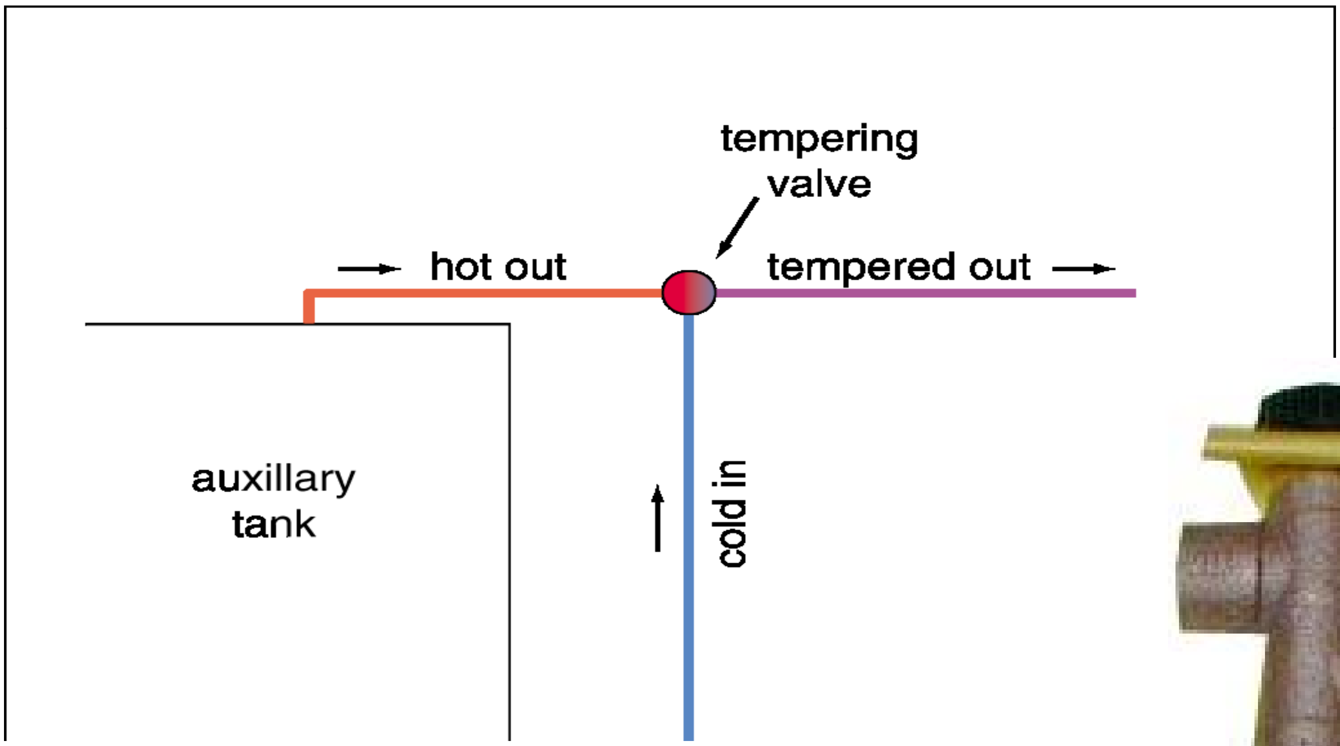
- No freeze protection
- Minimal hard water tolerance
- High maintenance requirements

Active, Closed-loop (antifreeze), Indirect System



- Excellent freeze protection
- Good hard water tolerance
- High maintenance requirements

Tempering Valve to Prevent Scalding: Extremely Important for Safety!



Mid-Temperature Example:

Chickasaw National Recreation Area, OK

Small Comfort Stations

- 195 square feet of flat plate collectors
- 500 gallon strorage volume
- Cost $7,804
- Delivers 9,394 kWh/year
- Saves $867 / year

Large Comfort Stations

- 484 square feet of flat plate collectors
- 1000 gallon strorage volume
- Cost $16,100
- Delivers 18,194 kWh/year
- Saves $1,789 / year

High Temperature Example:

Phoenix Federal Correctional Institution

- 17,040 square feet of parabolic trough collectors
- 23,000 gallon storage tank
- Installed cost of $650,000
- Delivered 87.1% of the water heating load in 1999.
- Saved $77,805 in 1999 Utility Costs.
- Financed, Installed (1998) and Operated under Energy Savings Performance Contract with Industrial Solar Technology, Inc.
- The prison pays IST for energy delivered by the solar system at a rate equal to 90% of the utility rate (10% guaranteed savings), over 20 years.

Resources and References

American Society of Heating, Air Conditioning and Refrigeration Engineers, Inc.

- ASHRAE 90003 -- Active Solar Heating Design Manual
- ASHRAE 90336 -- Guidance for Preparing Active Solar Heating Systems Operation and Maintenance Manuals
- ASHRAE 90346 -- Active Solar Heating Systems Installation Manual

Solar Rating and Certification Corporation

- SRCC-OG-300-91 -- Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems

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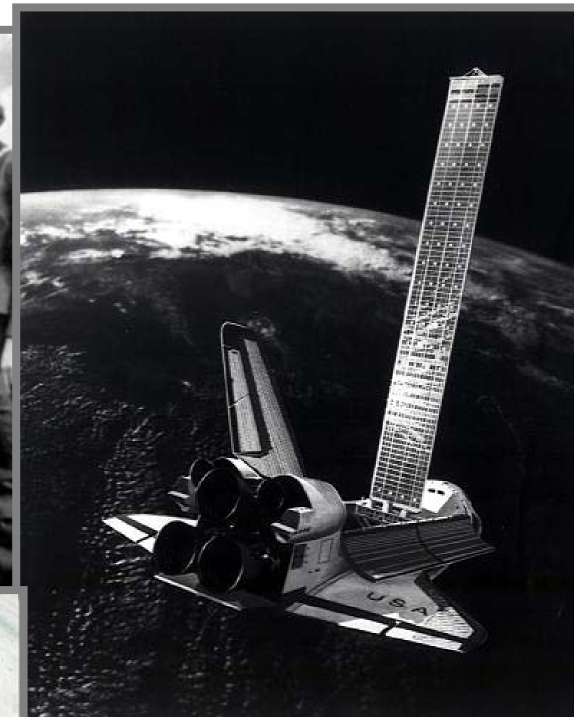
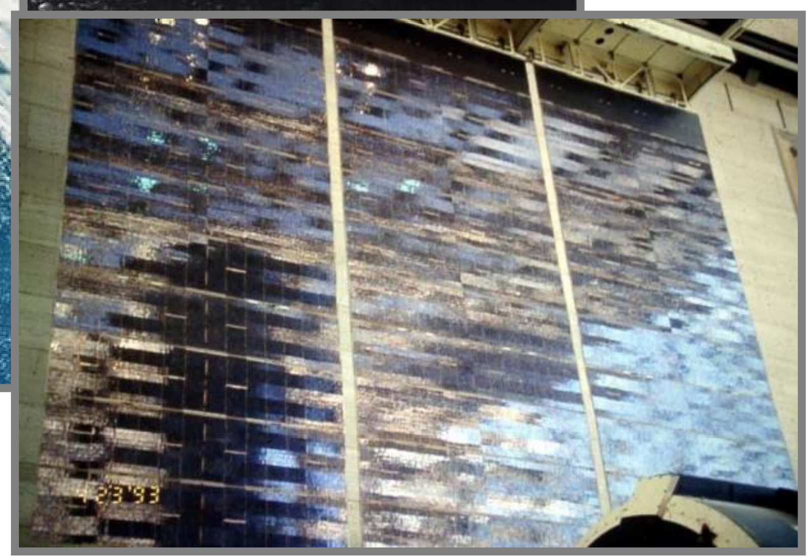
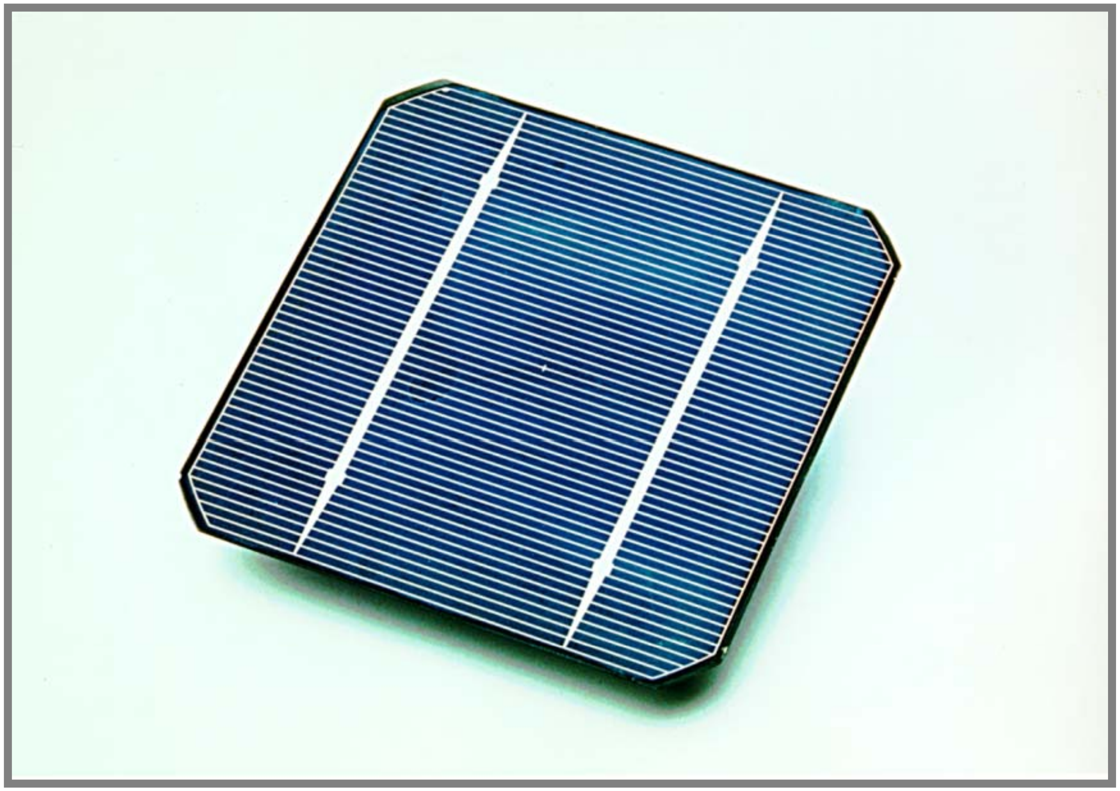
Solar Electric Technologies

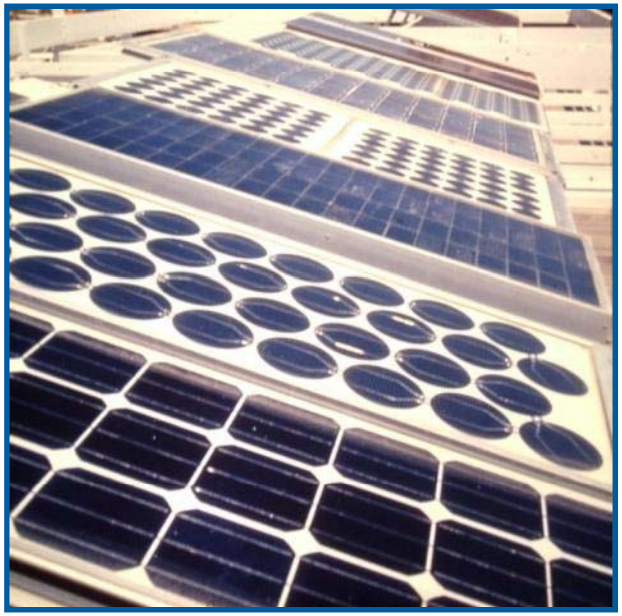

USA

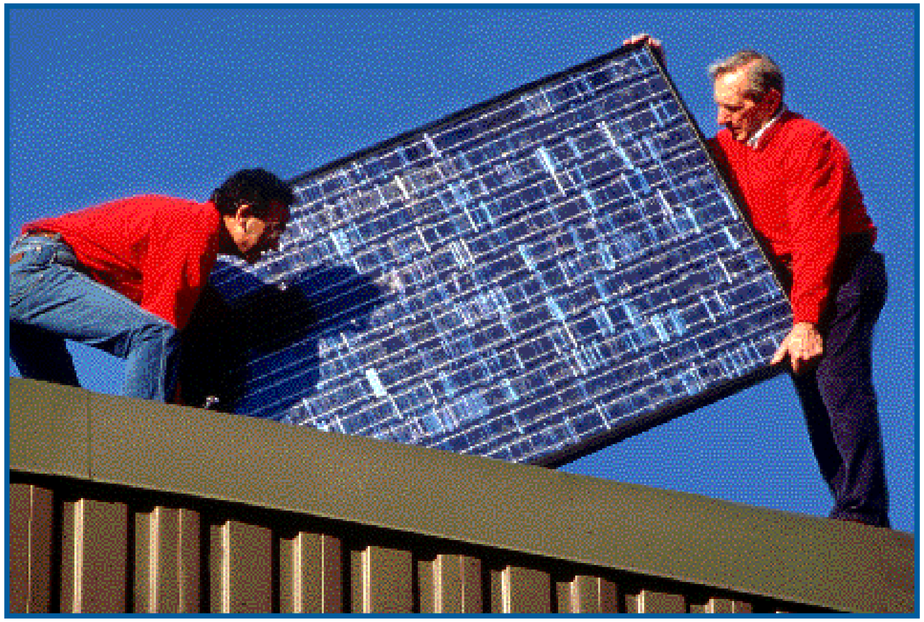


A typical solar cell (10cm x 10cm) generates about 1W at about 0.5V.

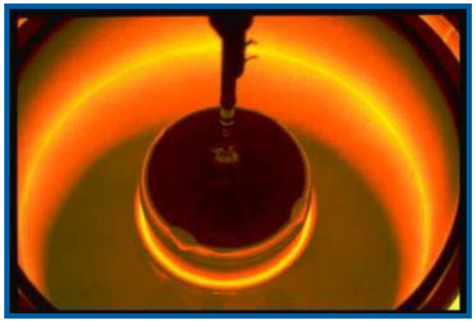


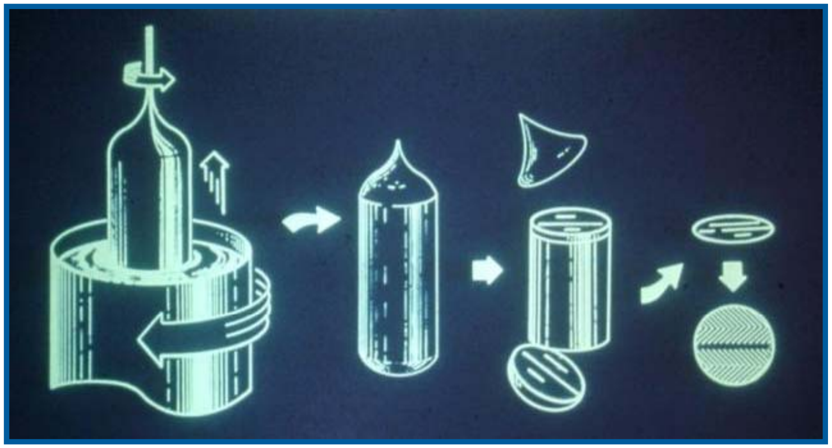
Individual cells are connected in series (increases the voltage) and in parallel (increases the current) into a module.

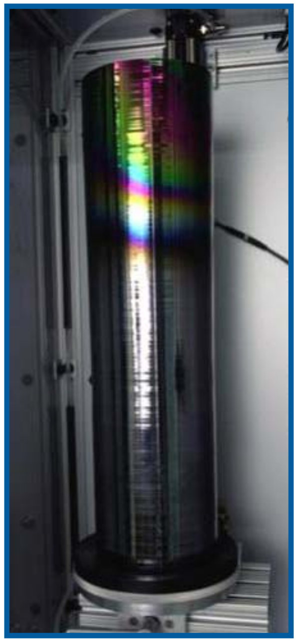


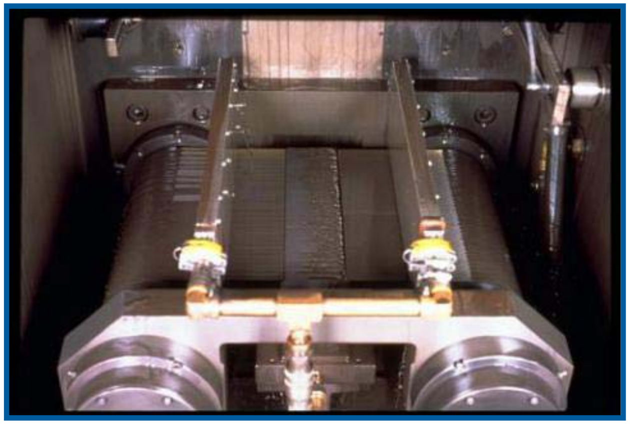


“Czochralski” Technology

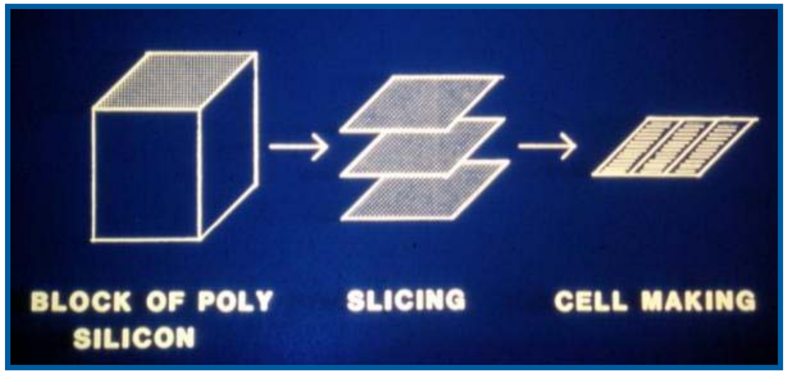


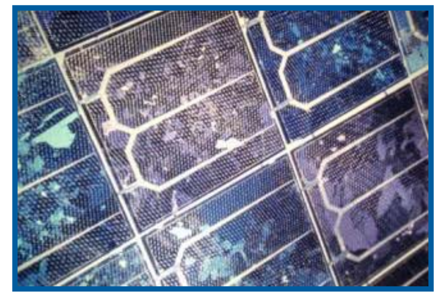


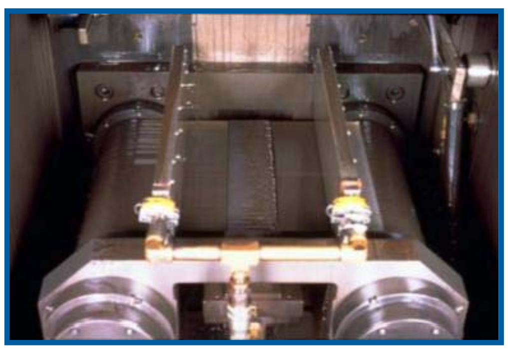




Cast Polycrystalline Technology



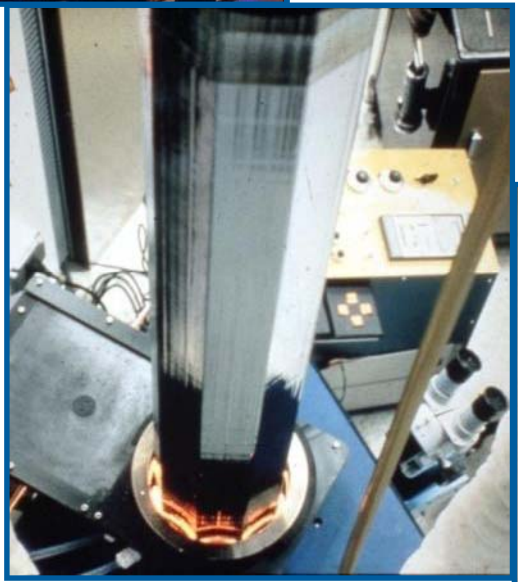


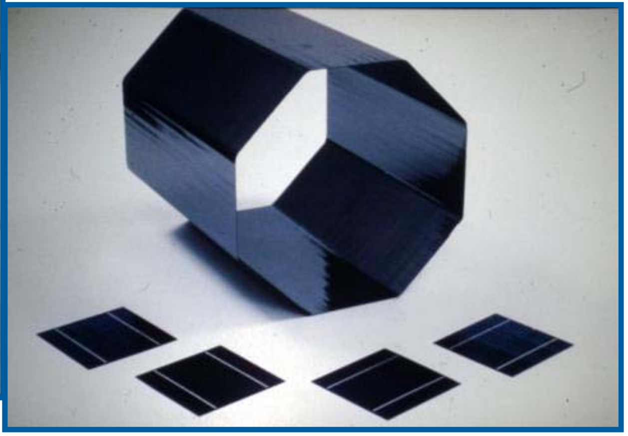


“Sheet” Technologies

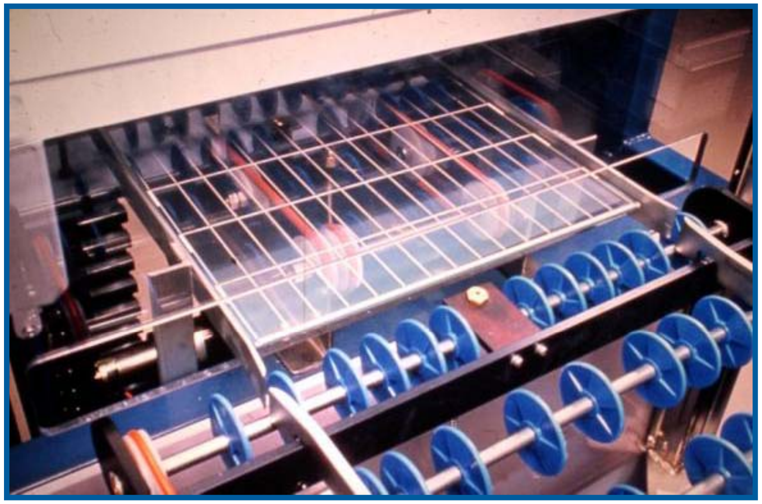
“Thin film” Silicon

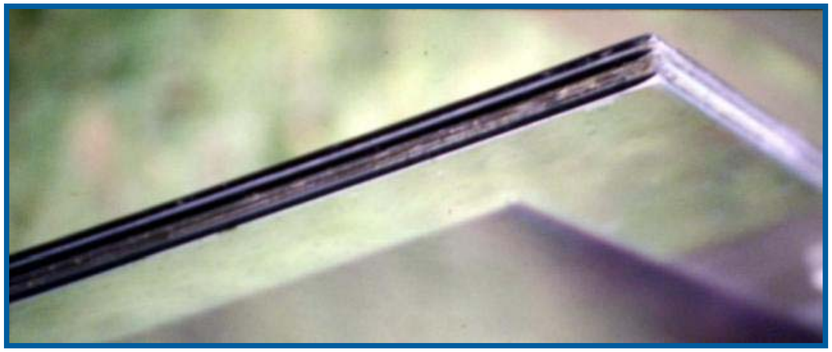
Edge-defined
Film-fed
Growth
(EFG)

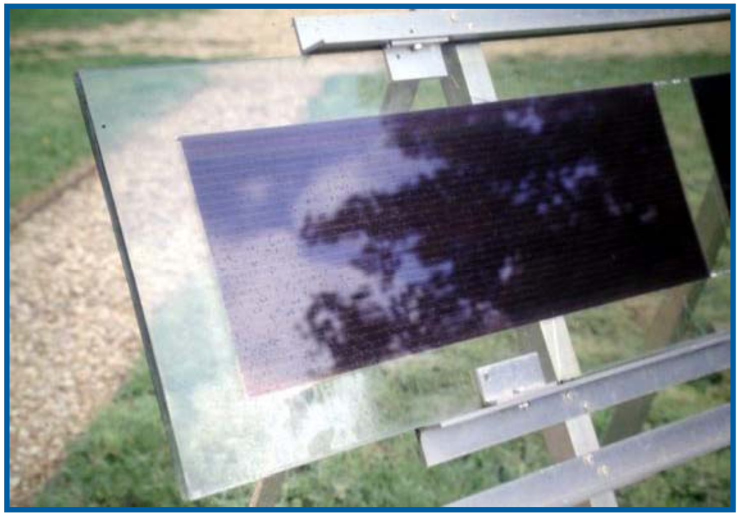




Thin Film Technologies On Glass

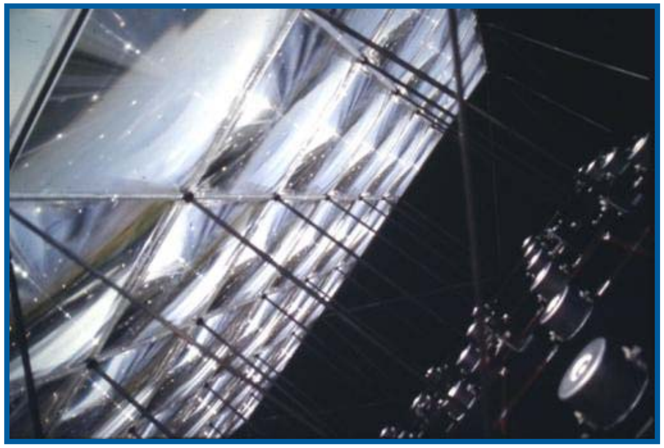






Thin Film Technologies On Flexible Substrates

Concentrating PV Systems

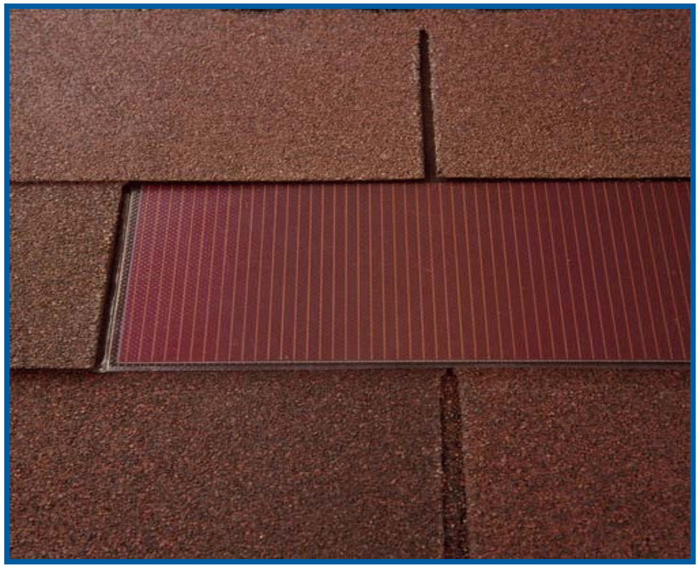


Point
Focus
100-1000X

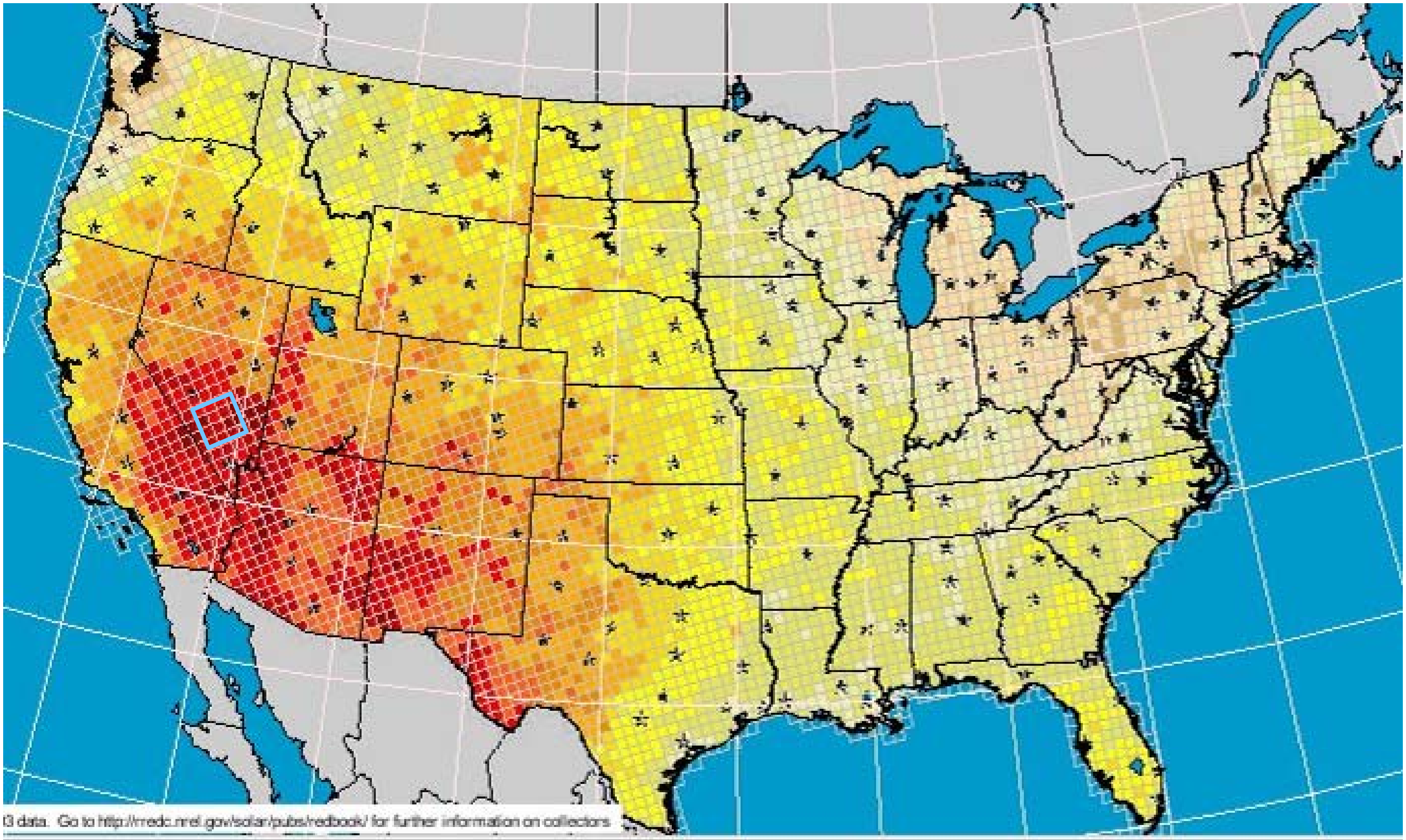
Line
Focus
30-50X

Photovoltaic Markets: Very diverse > Large (GWs) Market Potential

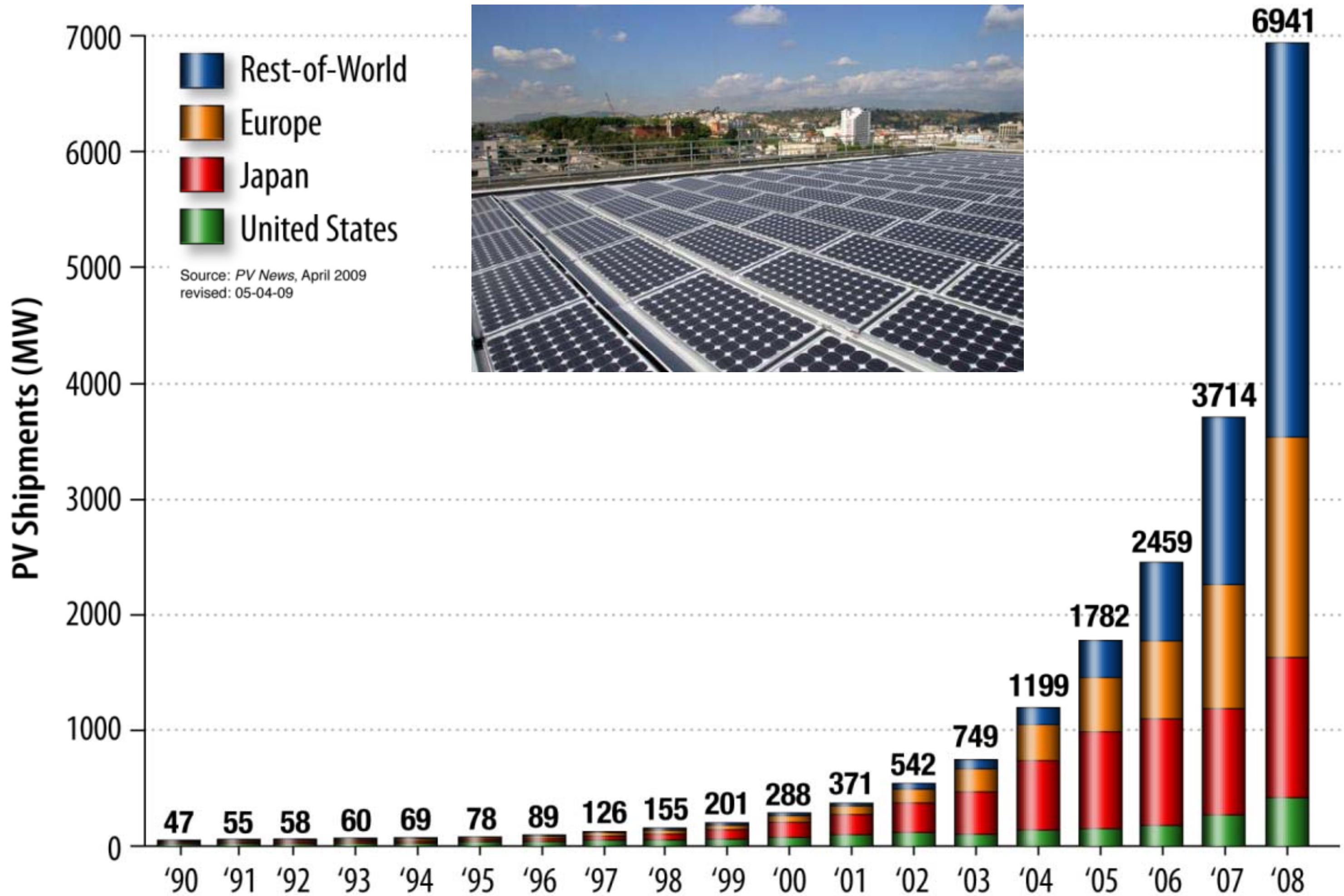
Building-Integrated PV (BIPV)



A Plot of Land, 100 Miles on a side, in Nevada could provide all the kWh consumed by the U.S.



Growth of Global PV Industry



0.01%-0.1% of electricity now comes from PV - extrapolates to > 5% in 2020

competitive with conventional electricity for 0.1% - 1% of market; more in future

Challenges for Photovoltaics

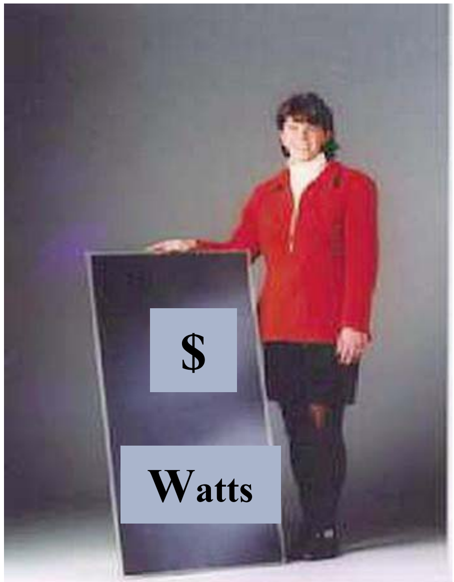
Continue to drive down costs and develop sufficient product diversity to address and maximize all market segments

Ensure adequate supply chain for a large and rapidly growing industry

Continue to provide reliable products with 30 yr lifetimes (both actual and perceived)

Fundamental Targets Leading to U.S. PV Deployment Success

Module	System	Electric Power Source



$ 1/Wp

$ 2 to 3/Wp

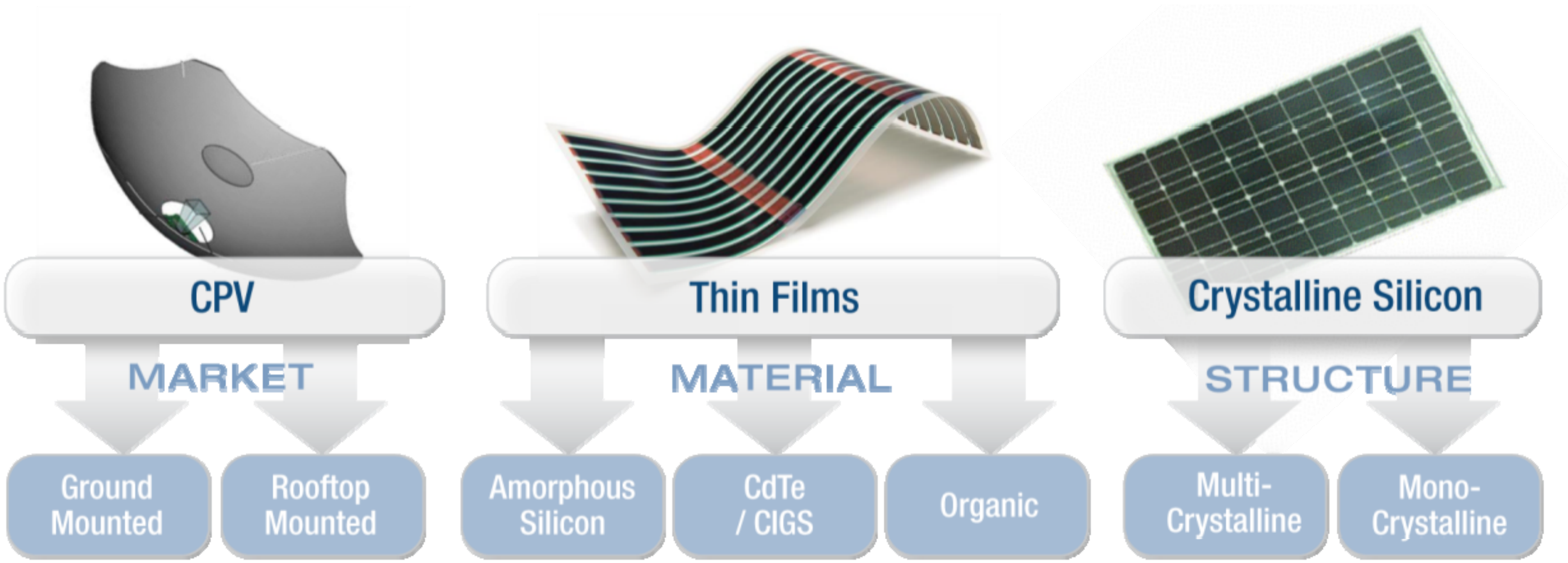
Manufacturing Scale Up

- ❑Supply Chain (gigawatt scale).
- ❑Meeting efficiency & $\$/m^2$ cost targets.
- ❑Maintain Performance/Quality.
- ❑Energy Payback & Environmental .

$cents/kWhr

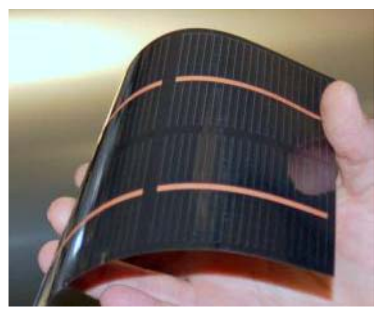
- ❑System Installation Costs
- ❑Grid Integration
- ❑20 to 30 yr. lifetime/reliability
- ❑1 to 2% Degradation
- ❑ Low Operating Costs

Photovoltaic (PV) technologies



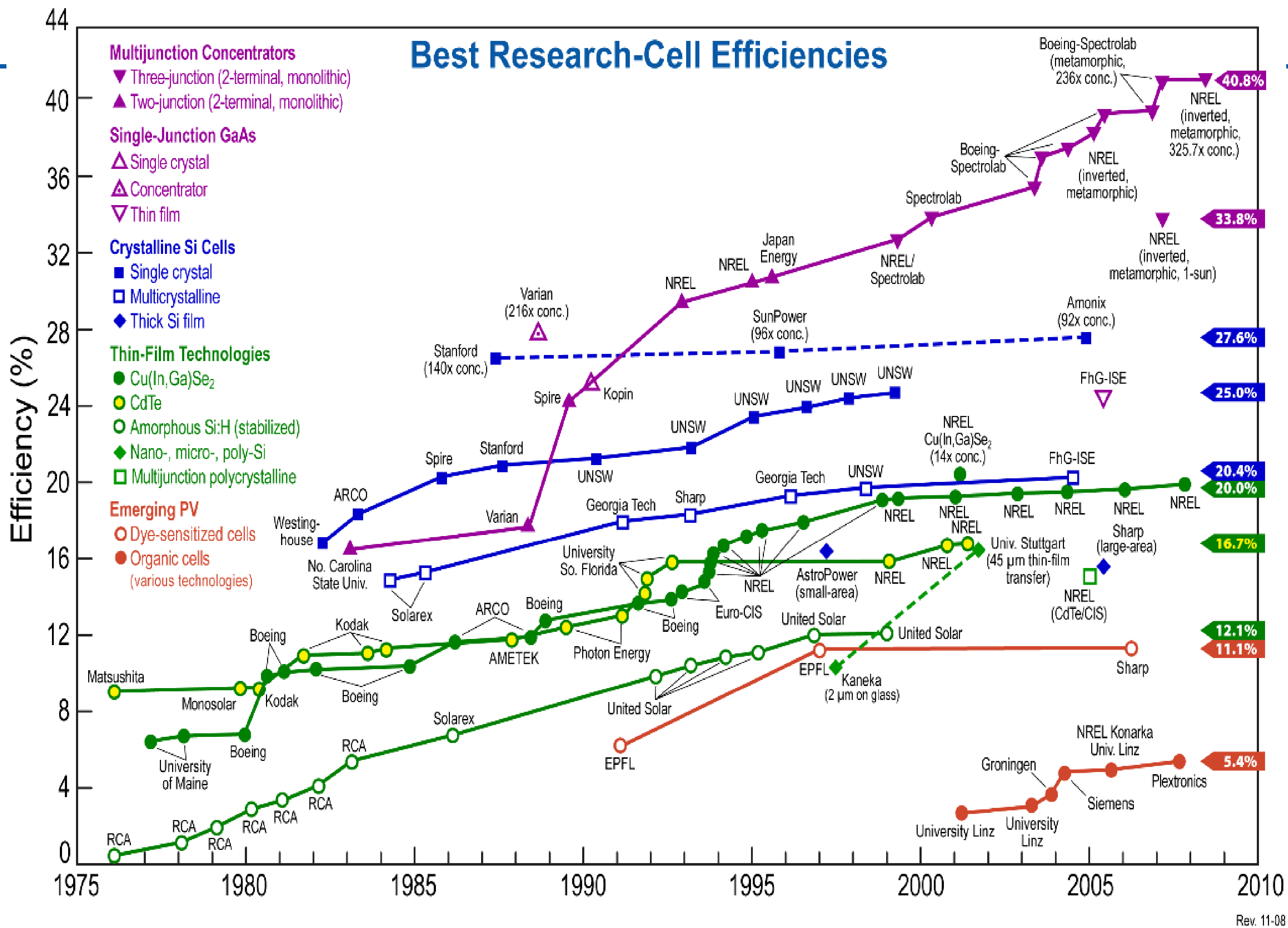
20x-100x

500x



$Cu(In,Ga)Se_2$ ~ 1-2 um

c-Si ~ 180 um



Best Research-Cell Efficiencies
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
Efficiency (%)
40.8%
33.8%
27.6%
25.0%
20.4%
20.0%
16.7%
12.1%
11.1%
5.4%
Boeing-Spectrolab (metamorphic, 236x conc.)
NREL (inverted, metamorphic, 325.7x conc.)
NREL (inverted, metamorphic)
NREL (inverted, metamorphic, 1-sun)
Boeing-Spectrolab
Spectrolab
NREL/Spectrolab
Japan Energy
NREL
Varian (216x conc.)
Stanford (140x conc.)
SunPower (96x conc.)
Amonix (92x conc.)
FhG-ISE
Spire
Kopin
Varian
Stanford
ARCO
Westing-house
No. Carolina State Univ.
UNSW
Georgia Tech
Sharp
Solarex
University So. Florida
Euro-CIS
AstroPower (small-area)
Univ. Stuttgart (45 µm thin-film transfer)
Sharp (large-area)
NREL (CdTe/CIS)
NREL Cu(In,Ga)Se2 (14x conc.)
United Solar
Kaneka (2 µm on glass)
EPFL
Sharp
Boeing
Kodak
AMETEK
Photon Energy
Matsushita
Monosolar
University of Maine
RCA
NREL Konarka Univ. Linz
Groningen
Siemens
Plextronics
University Linz
1975
1980
1985
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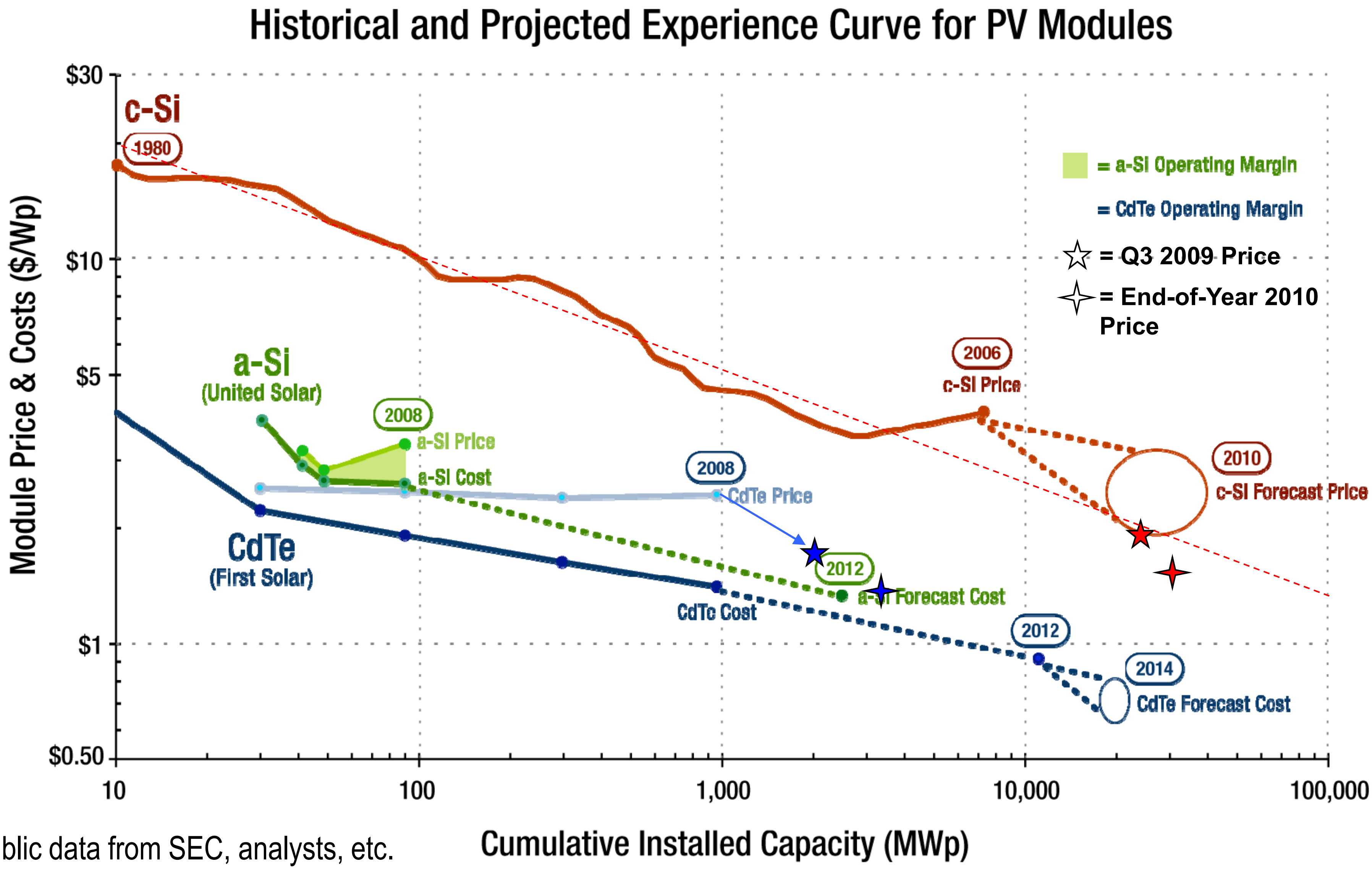
Rev. 11-08

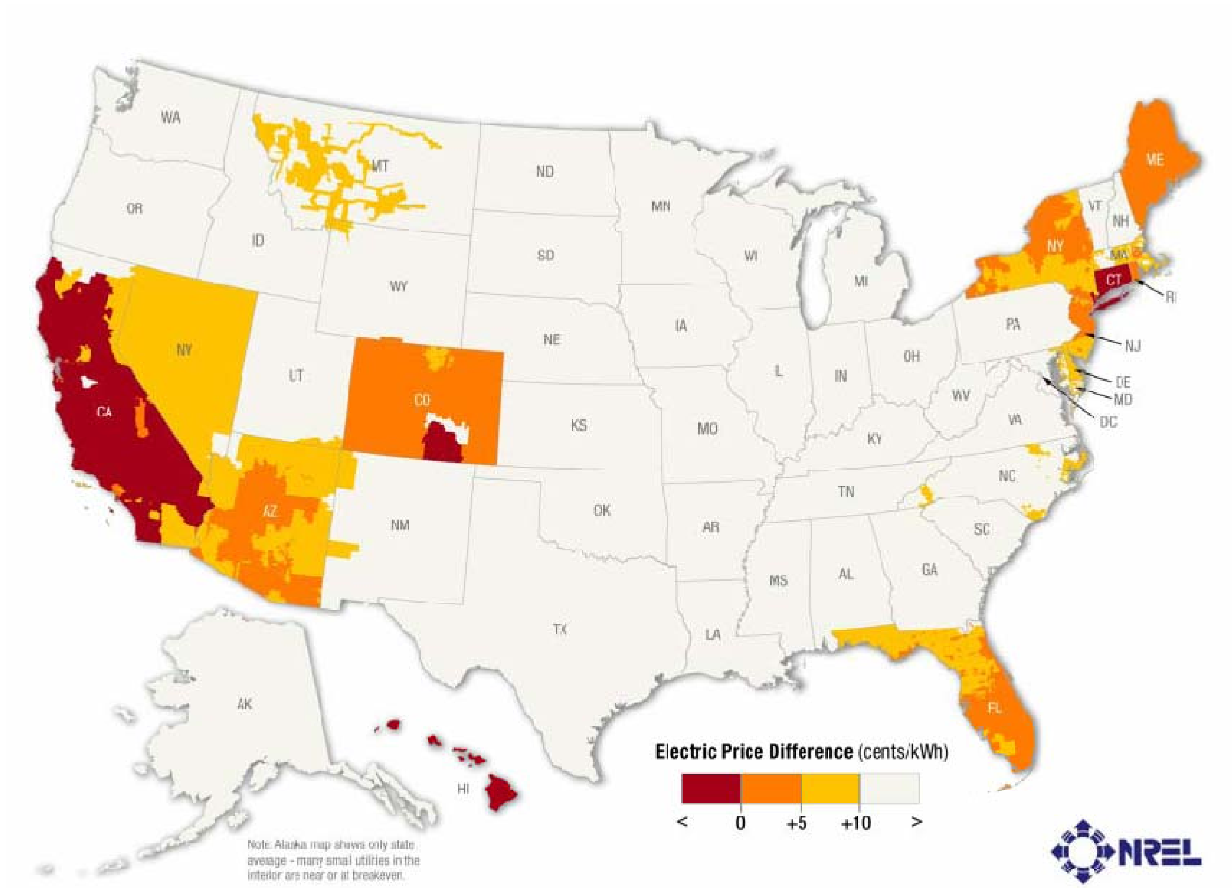
Costs have been dramatically reduced across vastly different technologies



Public data from SEC, analysts, etc.

Market penetration begins - 2007 residential PV and electricity price differences with existing incentives

Currently PV is financially competitive where there is some combination of high electricity prices, excellent irradiance and/or state/local incentives.

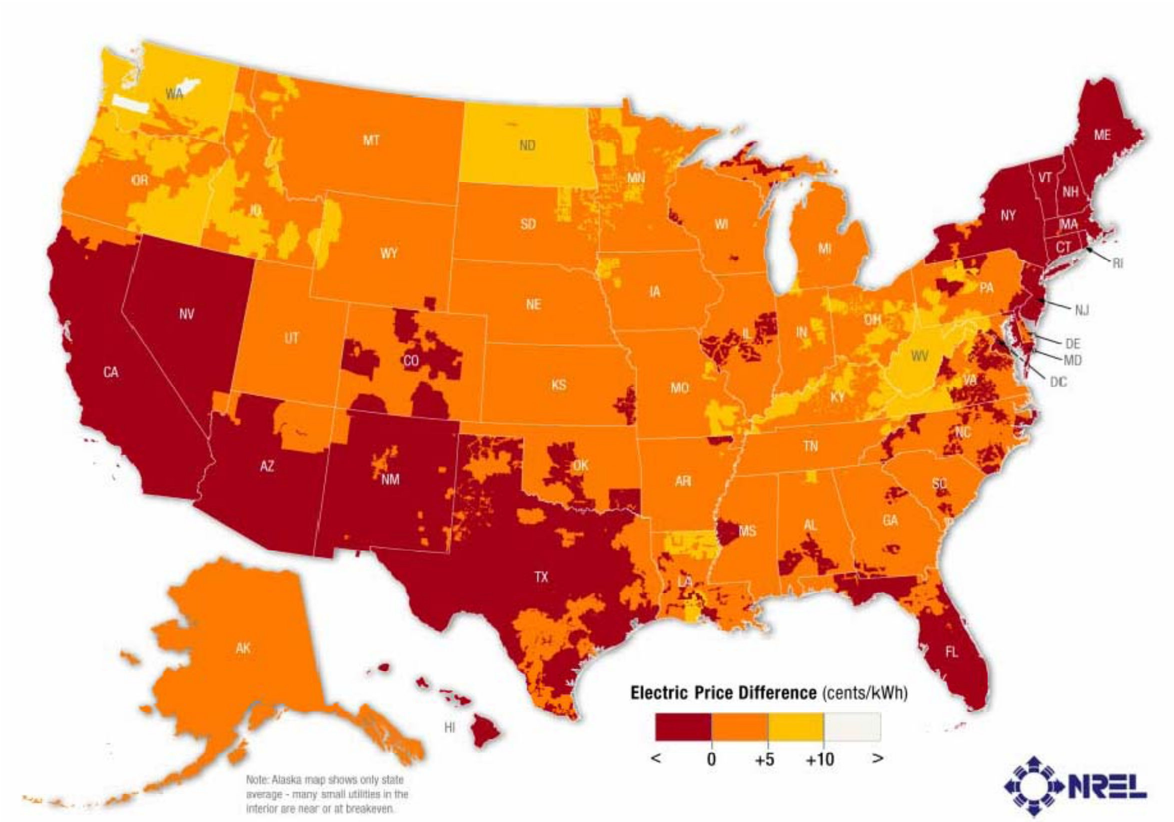


Assumptions: For the price of electricity, the average electricity price for the 1000 largest utilities in the U.S. based on EIA data for 2006 (except CA, where existing tiered rates structures were used). **The installed system price is set at $8.5/Wp** in the current case and is assumed to be financed with a home equity loan (i.e., interest is tax deductible), with a 10% down payment, 6% interest rate, with the owner in the 28% tax bracket, and a 30 year loan/30 year evaluation period. Incentives included are the Federal ITC worth $500/kW due to $2000 cap and individual state incentives as of December 2007.

The conservative forecast - 2015 residential without incentives and moderate (1.5% PA) increase in real electricity prices

PV is less expensive in 250 of 1,000 largest utilities, which provide ~37% of U.S. residential electricity sales

85% of sales (in nearly 870 utilities) are projected to have a price difference of less than 5¢/kWh between PV and grid electricity

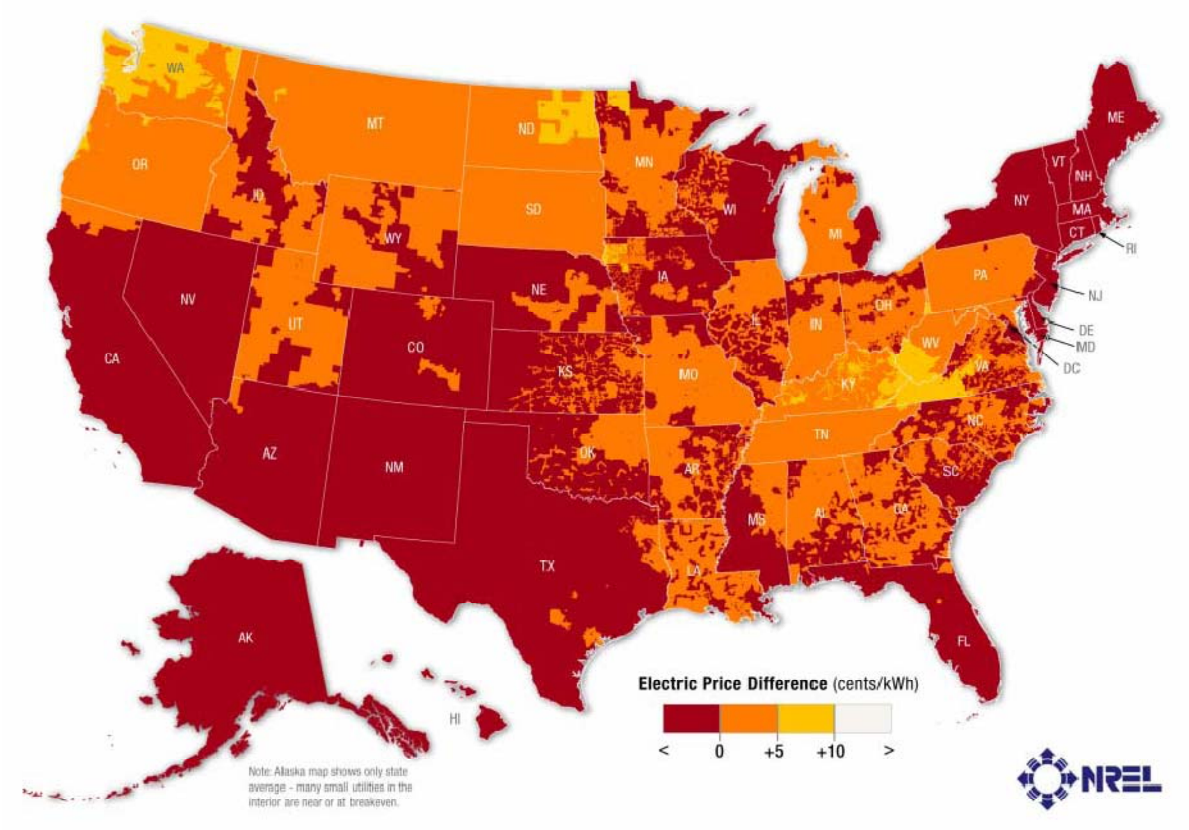


Notes: **The installed system price is set at $3.3/Wp.**

The realistic forecast - 2015 residential installations without incentives and aggressive (2.5% PA) increases in real electricity prices

PV is less expensive in 450 of the 1,000 largest utilities, which provide ~50% of U.S. residential electricity sales

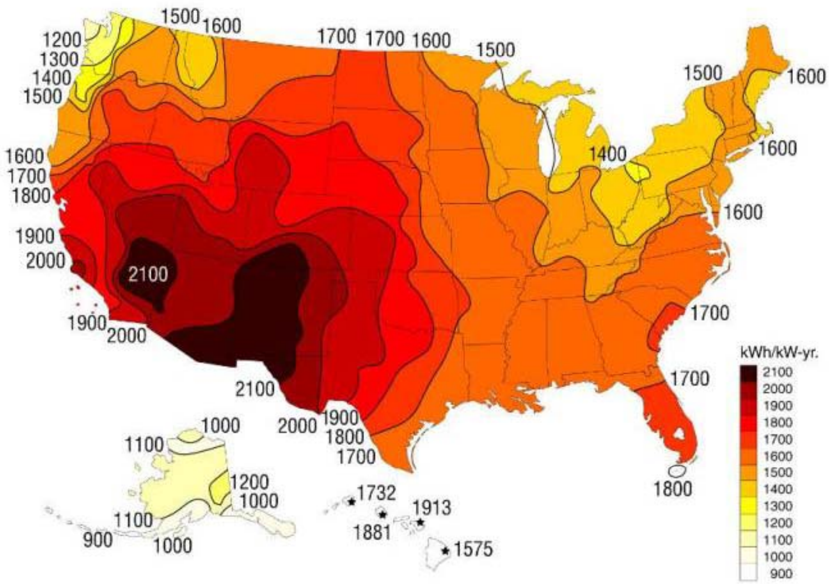
91% of sales (in nearly 950 utilities) have a price difference of less than 5¢/kWh between PV and grid electricity



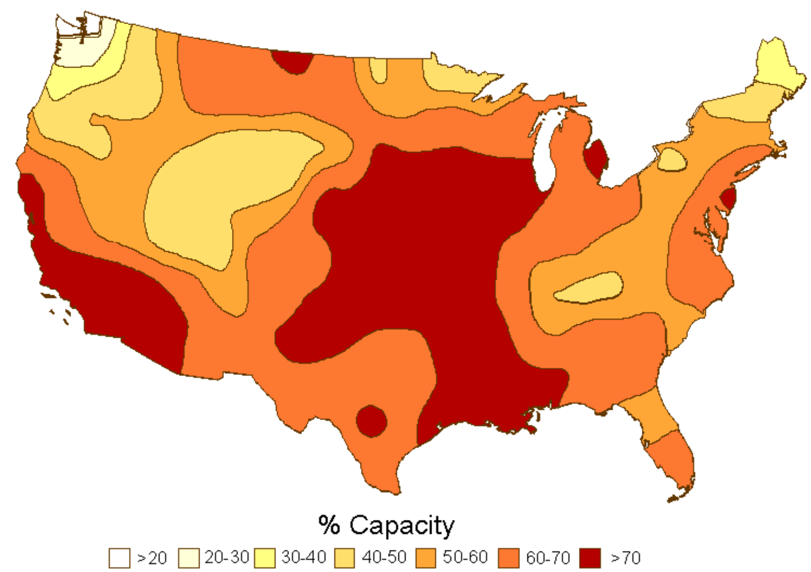
Notes: **The installed system price is set at $3.3/Wp**.

PV can provide peak shaving in many parts of U.S.

PV Energy kWh/kW-yr



Effective Load Carrying Capacity



Source: Christy Herig (NREL) and Richard Perez (SUNY/Albany)

Technical Challenges for High-Penetration PV

- Ensure safe and reliable two-way electricity flow
- Develop smart grid interoperability
- Develop advanced communication and control functionalities of inverters
- Integrate renewable systems models into power system planning and operation tools
- Integrate with energy storage, load management, and demand response to enhance system flexibility
- Understand high-penetration limiting conditions
- Understand how various climates and cloud transients affect system reliability

Topics

- Solar Resource Overview
- Solar Hot Water Systems
- Solar Photovoltaic Systems
- **Concentrating Solar Power Systems**

CSP Technologies and Market Sectors

CSP w/ Storage* (Dispatchable)

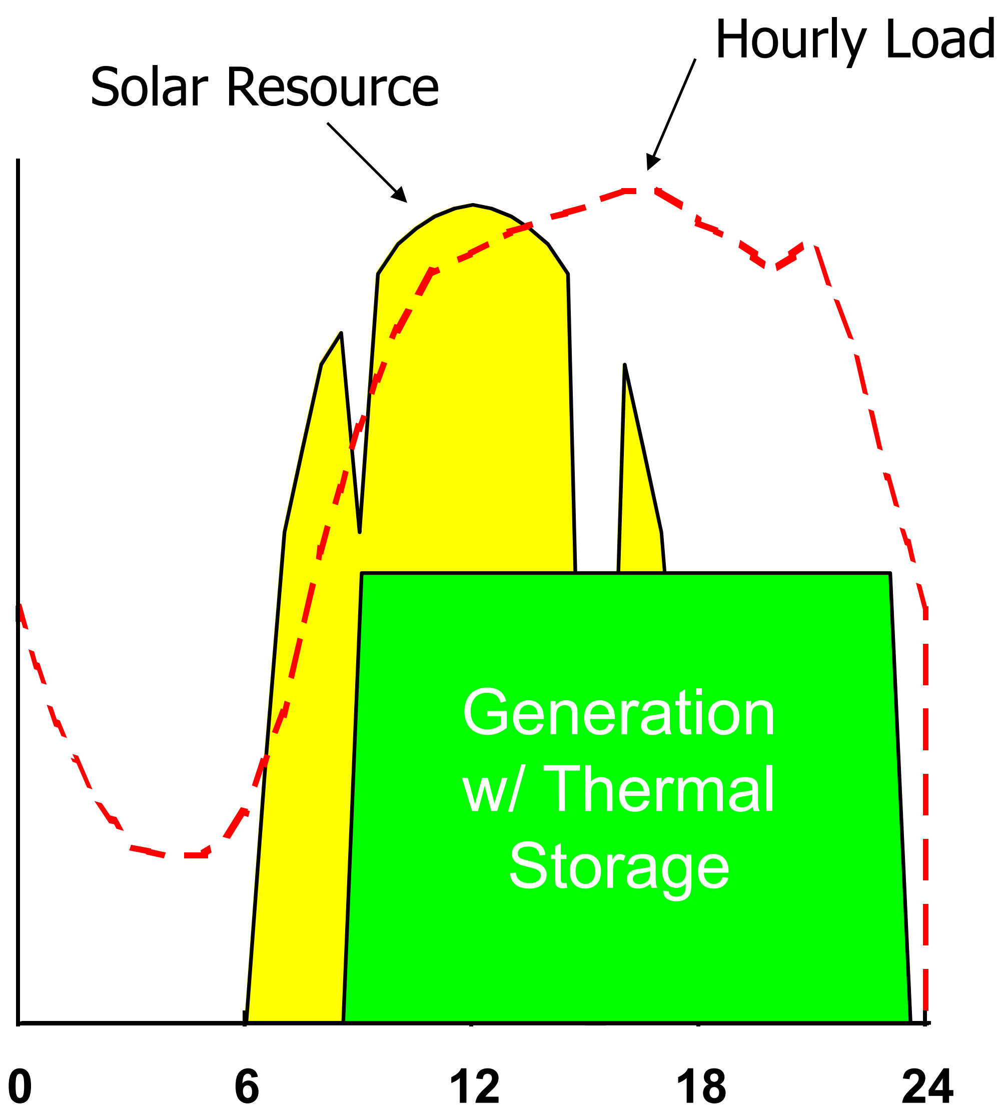
- Parabolic trough
- Power tower
- Linear Fresnel

*for non-steam heat transfer fluids

CSP w/o Storage (Non-Dispatchable)

- Dish/Engine

Value of Dispatchable Power?
Meets Utility Peak Power Demands



Storage provides

– higher value because power production can match utility needs

– lower energy costs if storage is less expensive than incremental turbine costs

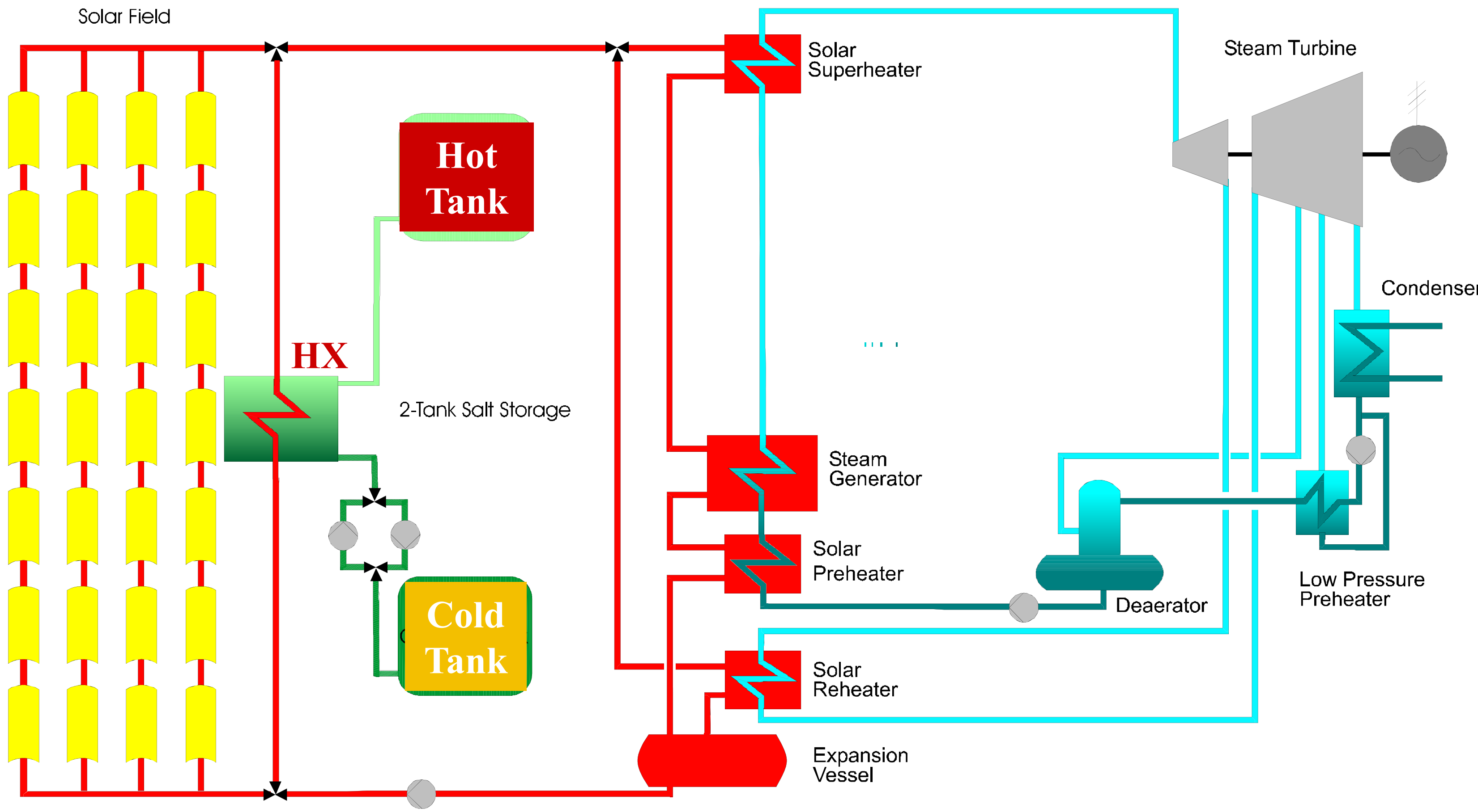
Concentrating Solar Power:
Dispatchable Power

Parabolic Troughs: Commercial, utility-scale deployments

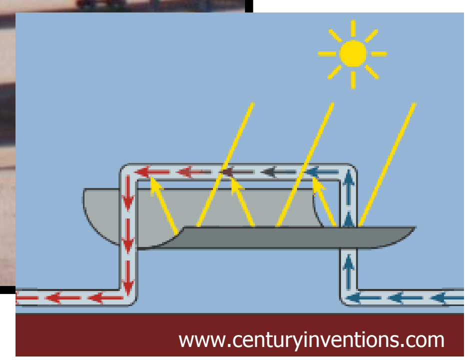
Central Receiver: Pre-commercial, pilot-scale deployments

- Up to 250MW plants (or multiple plants in power parks) for intermediate and baseload power
- Moderate solar-to-electric efficiency
- Thermal storage offers load following and capacity factors up to 70%

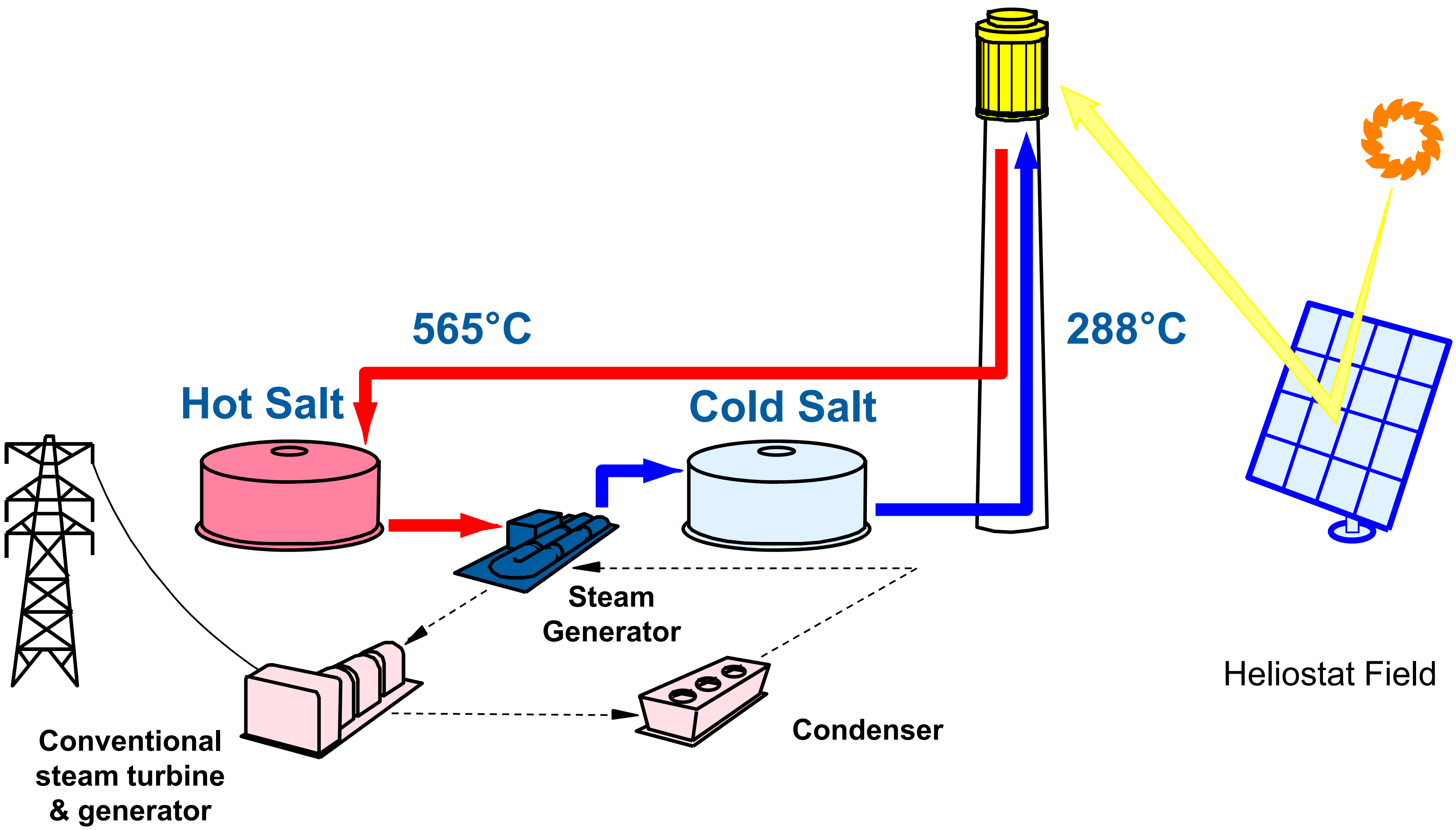
Parabolic Trough Power Plant
w/ 2-Tank Indirect Molten Salt Thermal Storage



Parabolic Trough



Molten Salt Power Towers



Power Tower (Central Receiver)

Different design approaches:

- Direct Steam Generation
  - Abengoa PS10 (Spain)
  - Abengoa PS20 (Spain)
  - BrightSource (USA/Israel)
  - eSolar (USA)
- Molten Salt
  - Gemasolar (Spain)
  - SolarReserve (USA)
- Air Receiver
  - Jülich (Germany)

Concentrating Solar Power:
Non-Dispatchable Central Station/Distributed Power

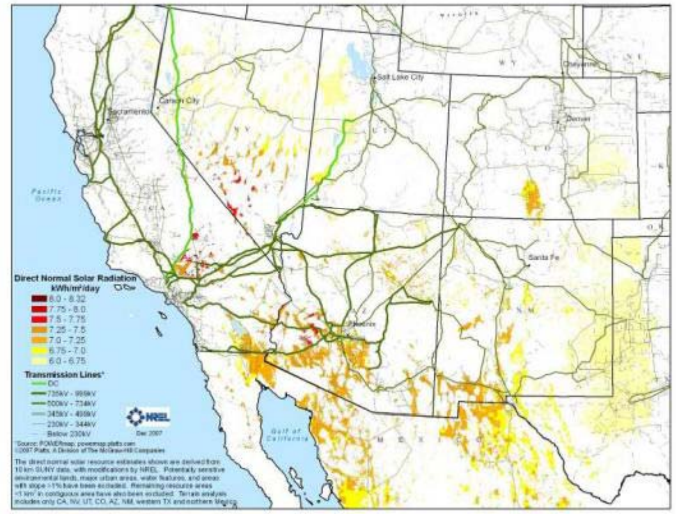
Dish/Stirling: Pre-commercial, pilot-scale deployments

Concentrating PV: Commercial and pre-commercial pilot-scale deployments

- Modular (3-25kW)
- High solar-to-electric efficiency
- Capacity factors limited to 25% due to lack of storage capability

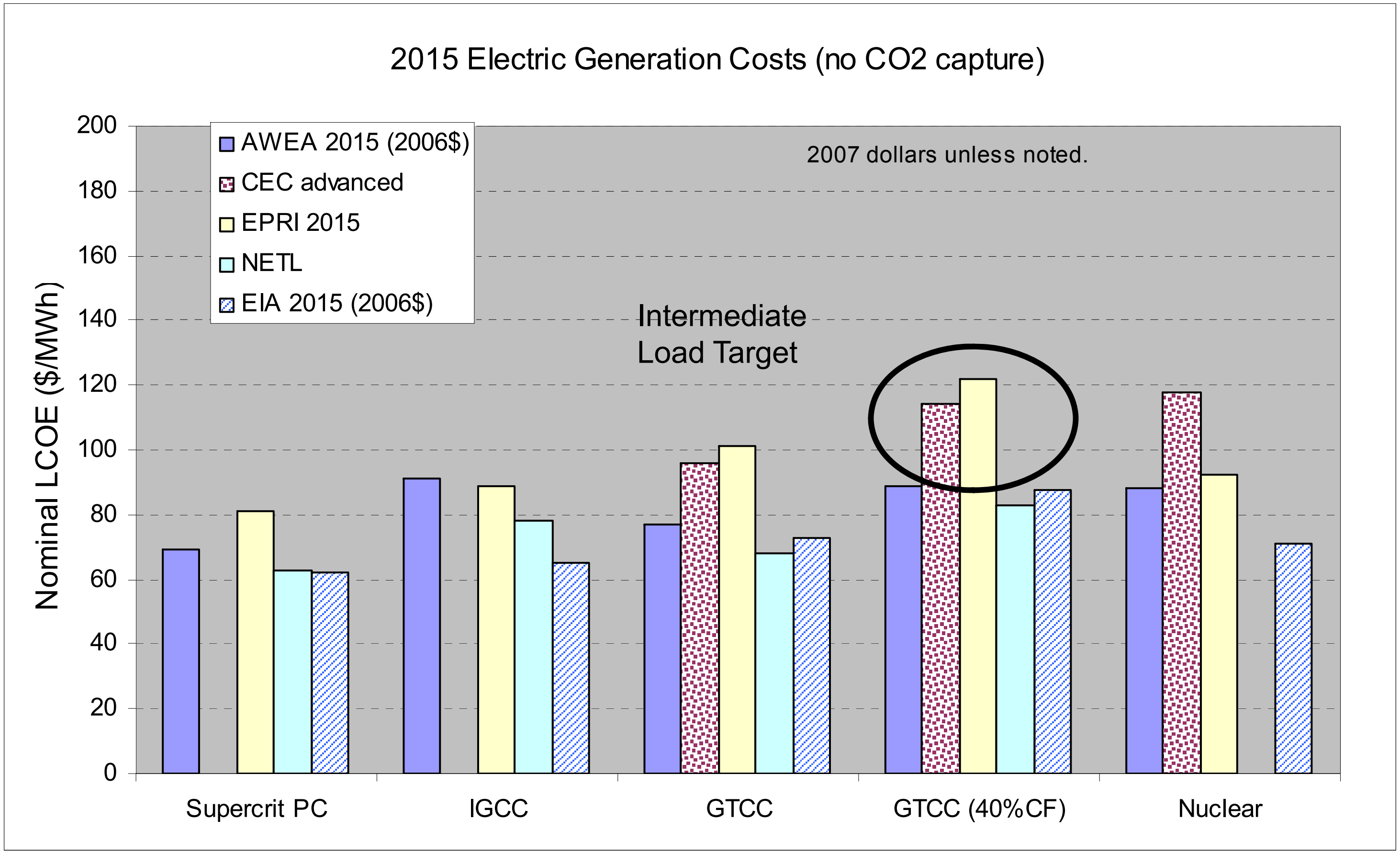
CSP Market Goals

– Competitive in southwest intermediate load power markets ($.12/kwh nominal LCOE) by 2015



– Expand access to include carbon constrained baseload power markets ($.10/kwh nominal LCOE) by 2020

2015 Cost Target Analysis

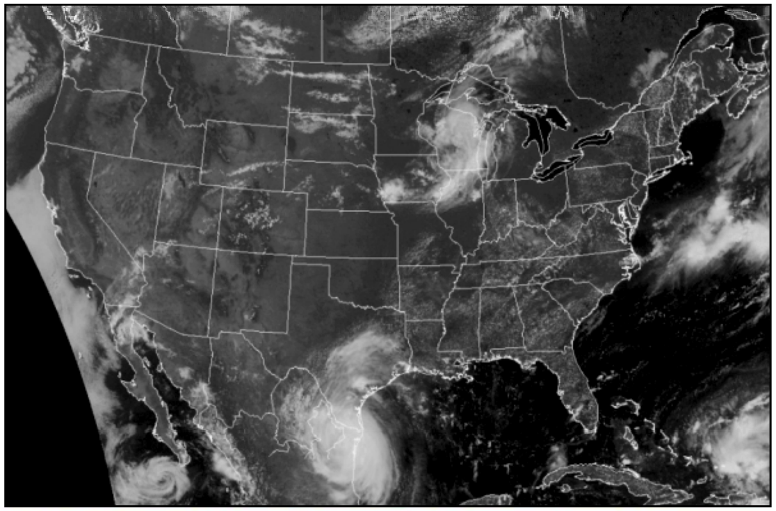


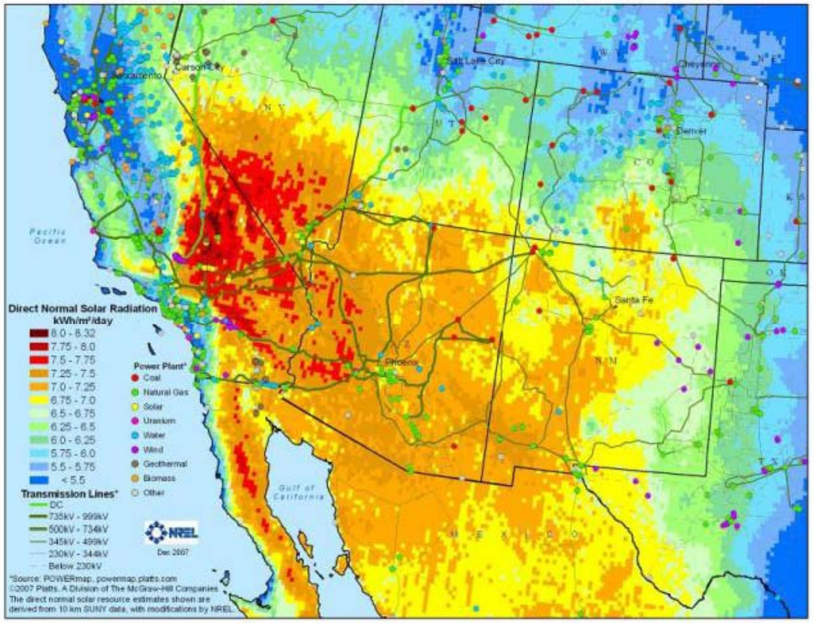
U.S. Southwest GIS Screening Analysis for CSP Generation

Screening Approach

- Initial solar resource and GIS screening analysis used to identify regions most economically favorable to construction of large-scale CSP systems

- GIS analysis used in conjunction with transmission and market analysis to identify favorable regions in the southwest





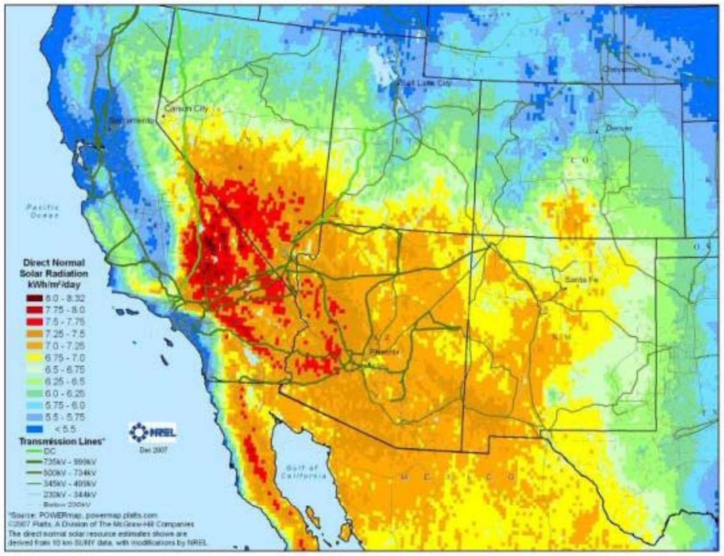
Solar Resource Screening Analysis

All Solar Resources

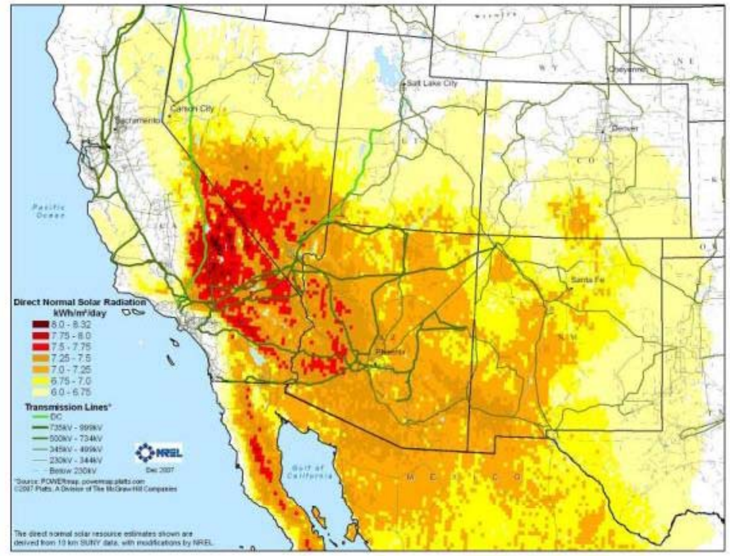
Locations Suitable for Development

1. Start with direct normal solar resource estimates derived from 10 km satellite data.
2. Eliminate locations with less than 6.0 $kWh/m^2/day$.
3. Exclude environmentally sensitive lands, major urban areas, and water features.
4. Remove land areas with greater than 1% (and 3%) average land slope.
5. Eliminate areas with a minimum contiguous area of less than 1 square kilometers.

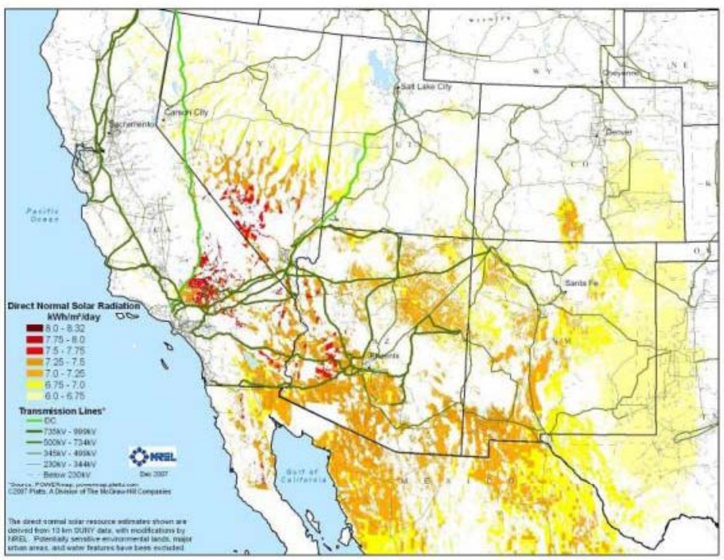
GIS Solar Resource Screening Analysis



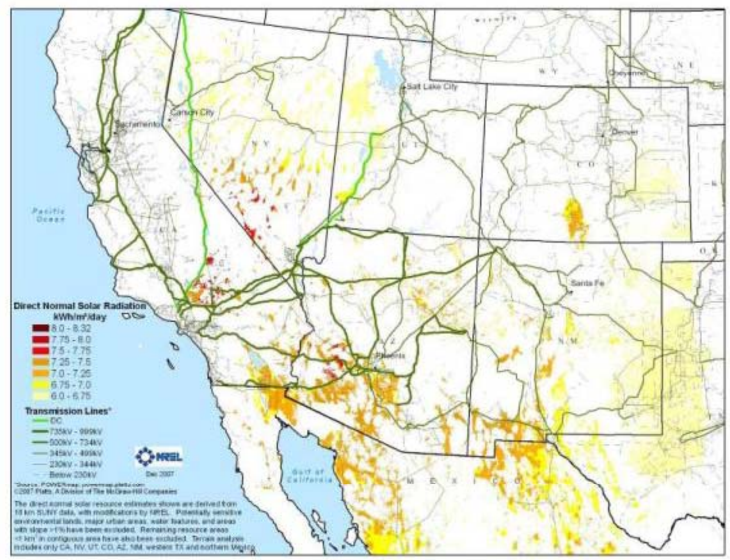
Unfiltered Resource



Solar > 6.0 kwh/m²-day



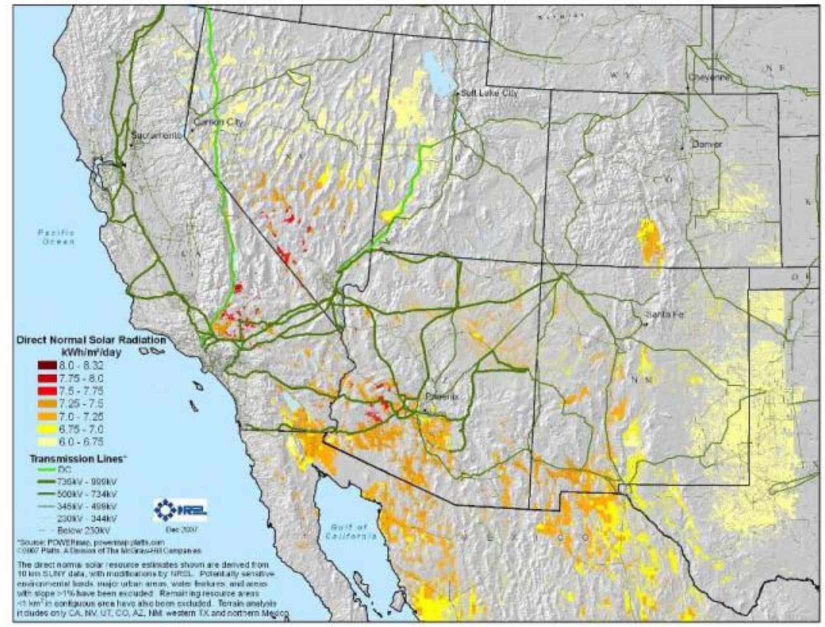
Land Exclusions



Slope Exclusions

Resulting CSP Resource Potential

State	Land Area (mi^2)	Solar Capacity (MW)	Solar Generation Capacity GWh
AZ	13,613	1,742,461	4,121,268
CA	6,278	803,647	1,900,786
CO	6,232	797,758	1,886,858
NV	11,090	1,419,480	3,357,355
NM	20,356	2,605,585	6,162,729
TX	6,374	815,880	1,929,719
UT	23,288	2,980,823	7,050,242
Total	87,232	11,165,633	26,408,956



The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.

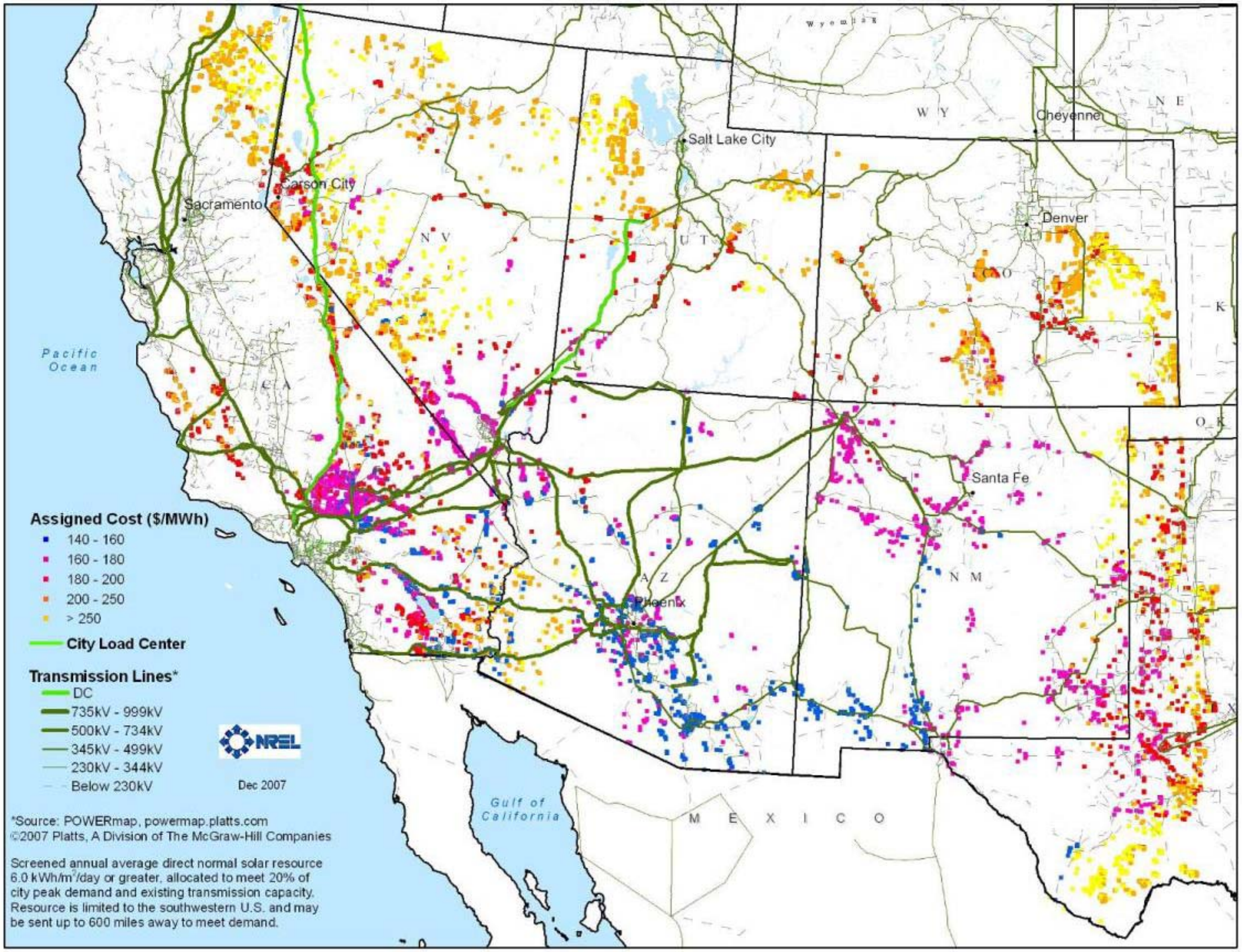
Solar Energy Resource ≥ 6.0

Capacity assumes 5 acres/MW

Generation assumes 27% annual capacity factor

Current total nameplate capacity in the U.S. is 1,000GW w/ resulting annual generation of 4,000,000 GWh

Optimal CSP Sites from CSP Capacity Supply Curves



354 MW Luz Solar Electric Generating Systems (SEGS)
Nine Plants built 1984 - 1991

1-MW Arizona Trough Plant, Tucson, AZ

64 MWe Acciona Nevada Solar One
Solar Parabolic Trough Plant

50 MW AndaSol One and Two
Parabolic Trough Plant w/ 7-hr Storage, Andalucía

Abengoa 50MW Trough Plants
Seville, Spain

50 MW Iberdrola Energia Solar de Puertollano
Puertollano (Ciudad Real)

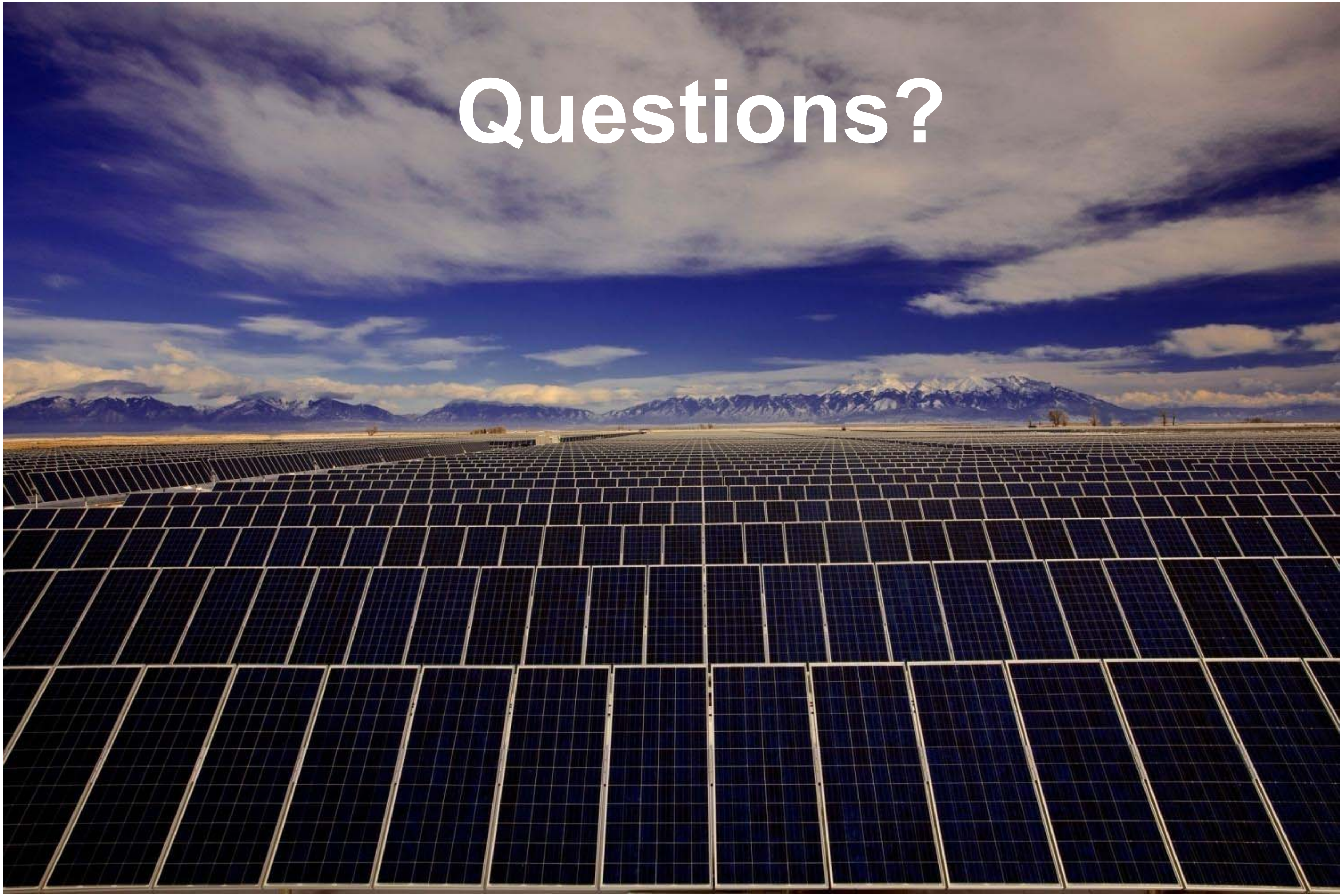
Abengoa PS10 and PS 20
Seville, Spain

Power Tower Pilot Plants

6 $MW_{thermal}$ BrightSource
Negev Desert, Israel

5 MWe eSolar
California, USA

1MW Dish Demonstration – Phoenix, AZ



SunEdison 8MW, San Louis Valley, CO