SOLAR ENERGY AND OUR ELECTRICITY FUTURE

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Outline of Today's Discussion

- Background
- Solar Cells and the Photoelectric Effect
- From Cells to PV Systems
- Modeling PV Performance
- Concentrating Solar Power (CSP)

Some things not addressed in this presentation:

Organics, Dye-sensitized, nanomaterials, quantum dots, etc.

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Solar Energy Fun Facts

➔More energy from sunlight strikes the Earth in one hour than all the energy consumed on the planet in one year (13 TerraWatts).

➔Carbon “free” energy source

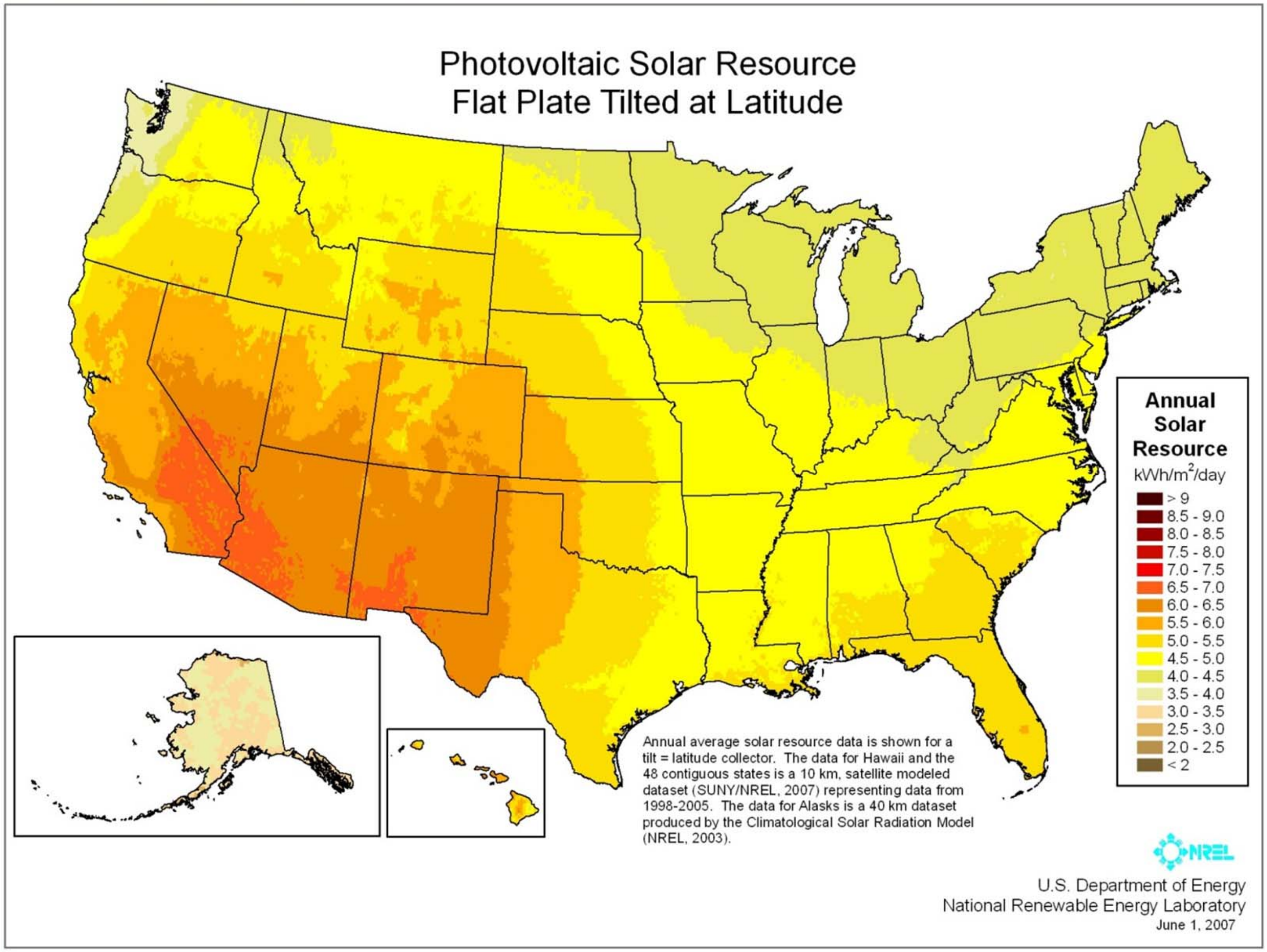
➔Solar energy is the only long-term option capable of meeting the energy (electricity and transportation fuel) needs of our planet.

- Solar	7,500 TW
- Wind	14 TW
- Hydro	1 TW
- Ocean	0.6 TW
- Geothermal	2 TW

Estimated
Extractable
Resource (DOE-OS-BES)

In the U.S. solar resources significantly outweigh energy use

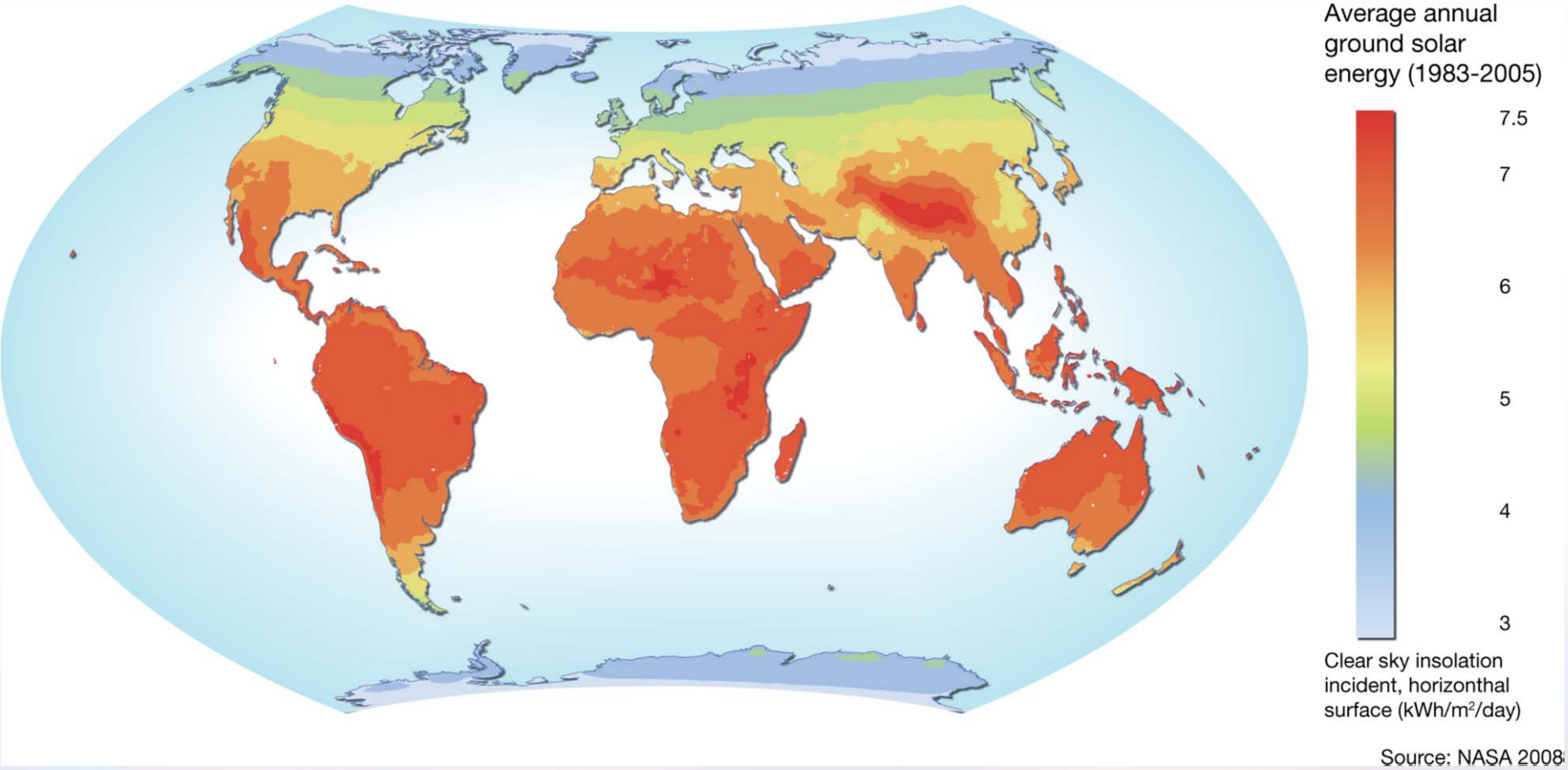
- **Currently, solar provides less than 0.1% of the electricity used in the U.S.**
- **All of the electricity in the U.S. could be provided using:**
  - Less than 2% of the land dedicated to cropland and grazing.
  - Less than the current amount of land used for corn ethanol production.



Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alasks is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

Source: Margolis, NREL 2009

Also globally solar resources significantly outweigh energy use



Source: NASA 2008

- **Covering less than 0.2% of the land on the earth with 10%-efficient solar cells would provide twice the power used by the world.**

Source: Margolis, NREL 2009

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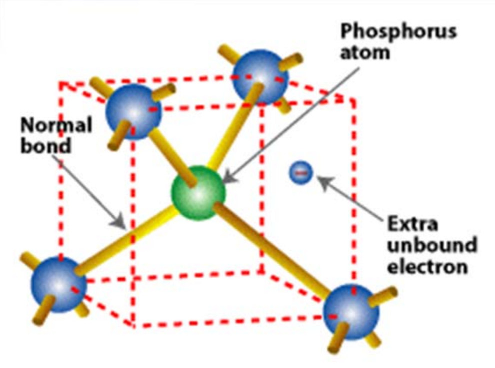
The photoelectric effect has been known for some time

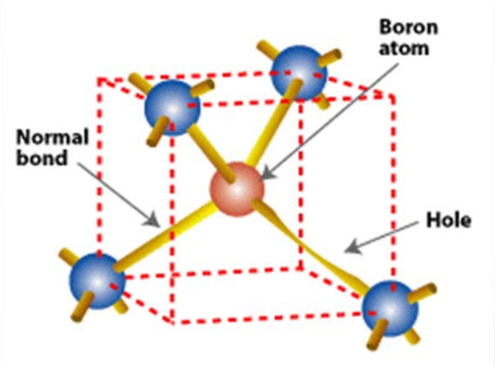
- 1839: Edmond Bequerel, French physicist discovers photoelectric effect
- 1904: Albert Einstein theoretically describes photovoltaic effect, for which he won the Nobel Prize in 1921
- 1916: Robert Millikan practically demonstrates Einstein's theory
- 1918: Jan Czochralski, Polish physicist discovers method of producing monocrystalline silicon – still in use today
- 1941: first monocrystalline silicon cell produced
- 1954: AT&T Bell Labs publishes reports on solar cells with 4.5% efficiency

http://www.pvresources.com/en/history.php

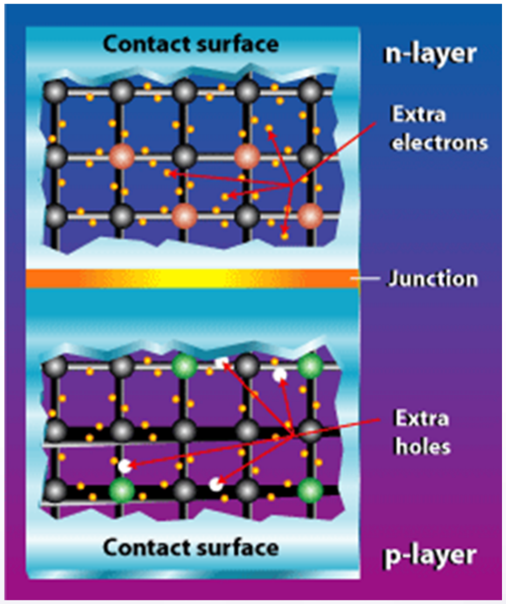
The concept of a simple crystalline solar cell



Substituting a phosphorus atom (with five valence electrons) for a silicon atom in a silicon crystal leaves an extra, unbonded electron that is relatively free to move around the crystal.



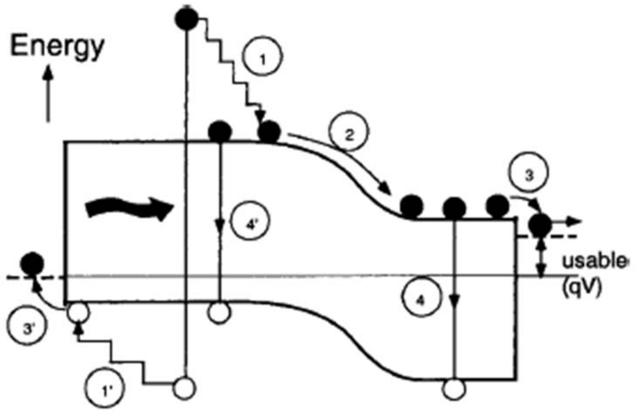
Substituting a boron atom (with three valence electrons) for a silicon atom in a silicon crystal leaves a hole (a bond missing an electron) that is relatively free to move around the crystal.



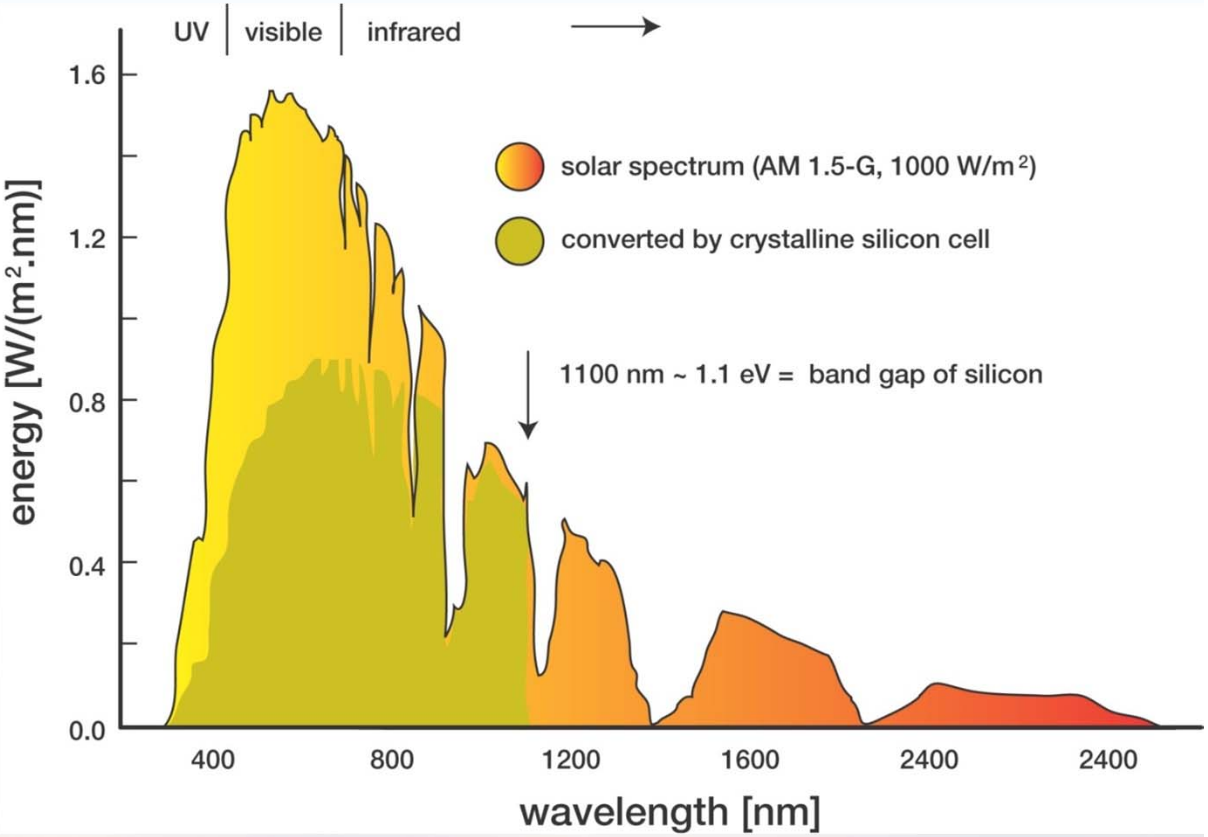
Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.

http://www1.eere.energy.gov/solar

The Photoelectric Effect



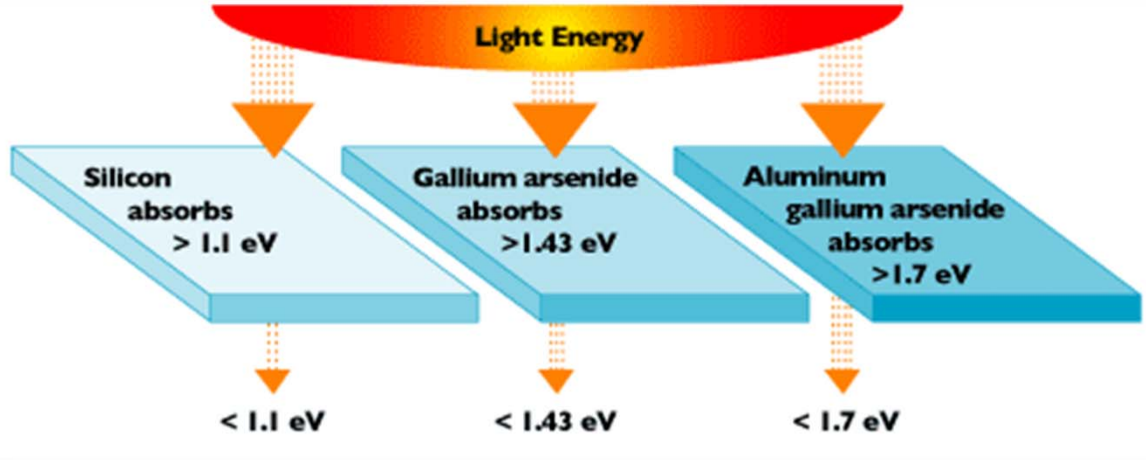
Excitation and loss processes in a standard solar cell: (1) thermalization loss; (2) and (3) junction and contact voltage loss; (4) recombination loss.



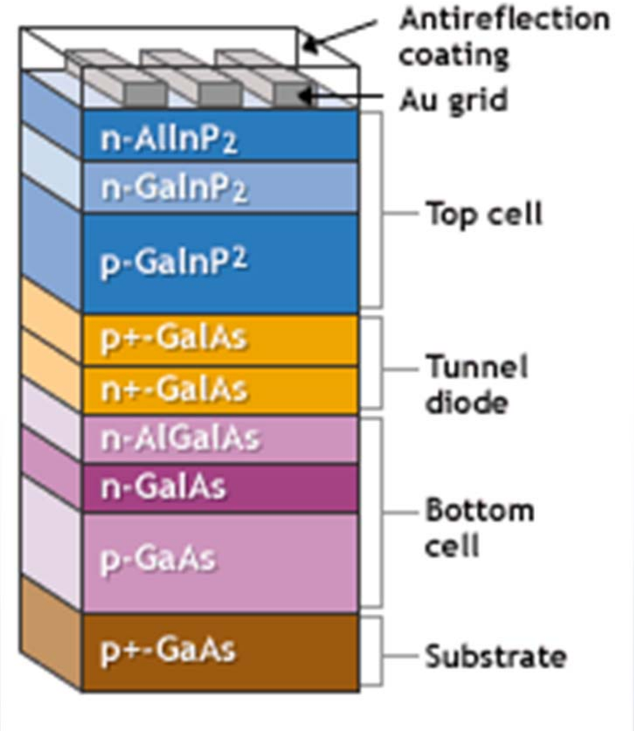
http://www.vicphysics.org/documents/events/stav2005/spectrum.JPG

(Courtesy of Feng Shi, Northern New Mexico College)

Multi-junction cells absorb more photons for higher efficiencies



Different PV materials have different energy band gaps. Photons with energy equal to the band gap energy are absorbed to create free electrons. Photons with less energy than the band gap energy pass through the material.

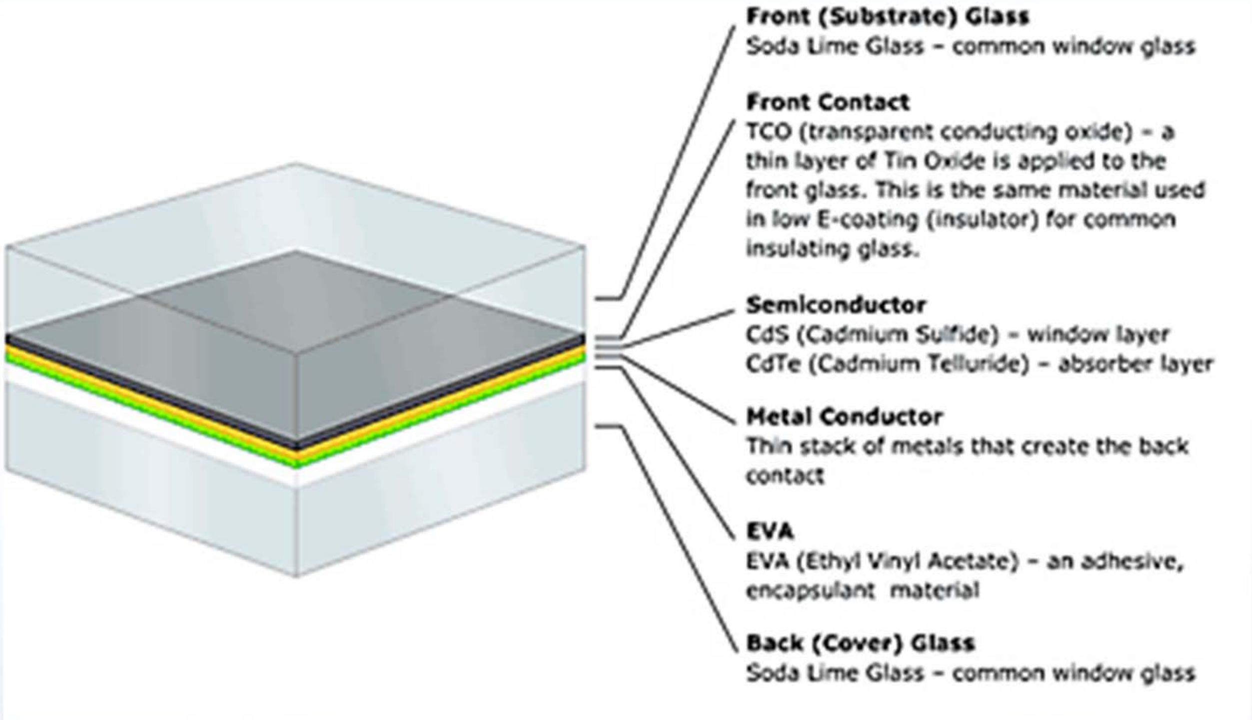


This multijunction device has a top cell of gallium indium phosphide, then a "tunnel junction" to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

- Complex, high manufacturing cost
- Used in concentrating systems for high output

http://www1.eere.energy.gov/solar

Thin Film Devices Use Much Less Semiconductor Material



Front (Substrate) Glass
Soda Lime Glass – common window glass

Front Contact
TCO (transparent conducting oxide) – a thin layer of Tin Oxide is applied to the front glass. This is the same material used in low E-coating (insulator) for common insulating glass.

Semiconductor
CdS (Cadmium Sulfide) – window layer
CdTe (Cadmium Telluride) – absorber layer

Metal Conductor
Thin stack of metals that create the back contact

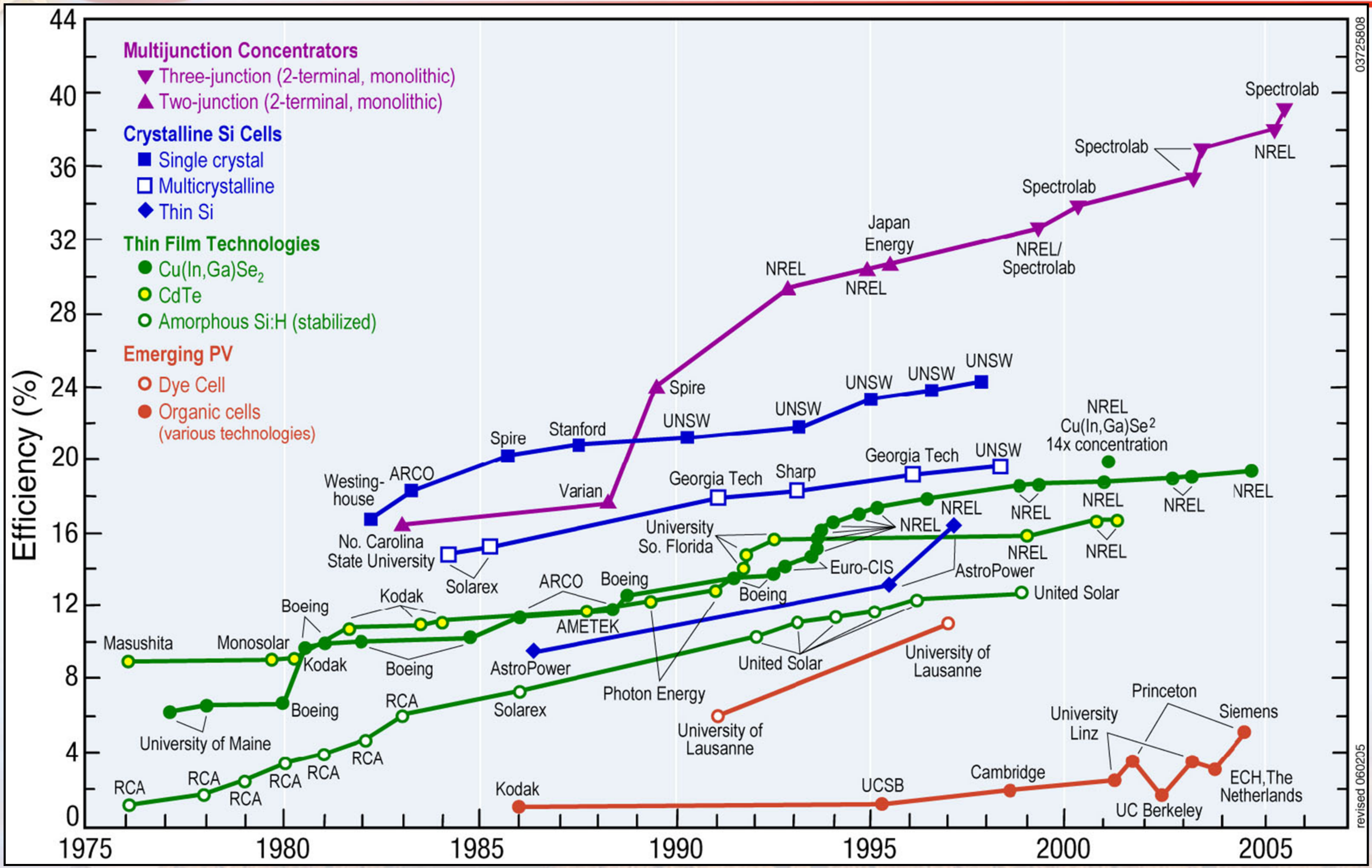
EVA
EVA (Ethyl Vinyl Acetate) – an adhesive, encapsulant material

Back (Cover) Glass
Soda Lime Glass – common window glass

- 1-2 microns thick vs. ~180 microns for c-Si
- Lower efficiencies mean more balance-of-system
- Glass substrate limits usability (weight, flexibility)

Source for figures: www.firstsolar.com

Best Research-Cell Efficiencies



<u>Lewis et al, Basic Research Needs for Solar Energy Utilization</u> Department of Energy Paper, 4.18.05 (courtesy F. Shi, NNMC))

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PV Conversion Technology Tradeoffs

Technology	Advantages	Disadvantages
Mono-Crystalline Silicon	Proven technology Higher Efficiency (22%)	High material usage
Poly-Crystalline Silicon	Proven technology Lower cost than mc-Si	Lower efficiency (13-16%) High material usage
Amorphous Silicon Thin Film	Proven roll-to-roll high throughput manufacturing Low materials usage	Low efficiency (~7%) High Cap-Ex Costs
CdTe Thin Film	Low manufacturing cost Low materials usage	Lower efficiency (~10%) Lifetime not demonstrated Glass required
CIGS Thin Film	High Thin Film Efficiency (~12-13%) Low materials usage	Currently expensive & difficult to manufacture Lifetime not demonstrated
Multi-junction concentrators	High efficiency (~36%) Very low material usage	Expensive to manufacture Need for high tracking accuracy Expensive balance-of-system Thermal management issues
Organics (not yet commercial)	Very low cost to produce	Low efficiency (~4-6%) Unstable

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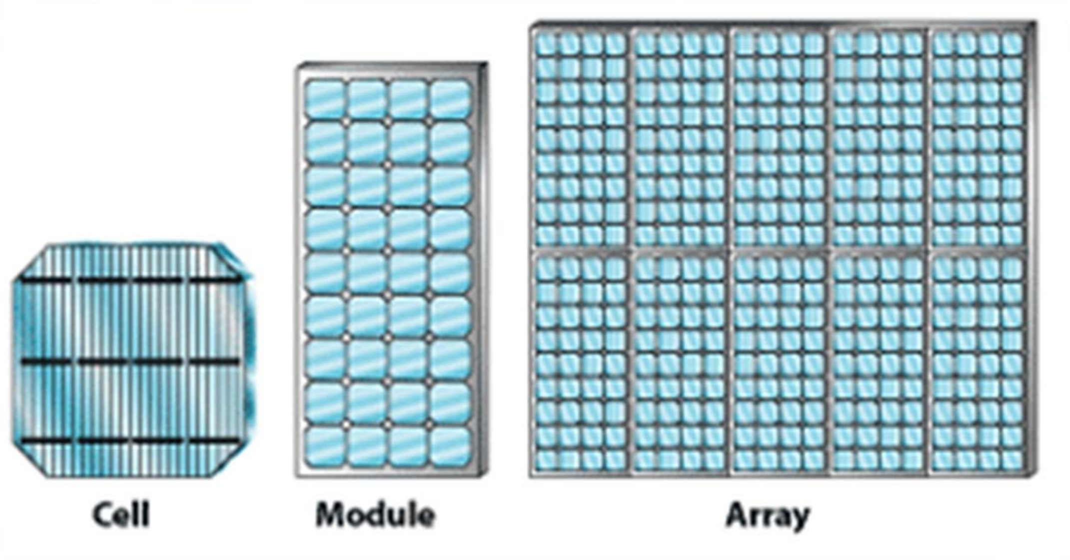
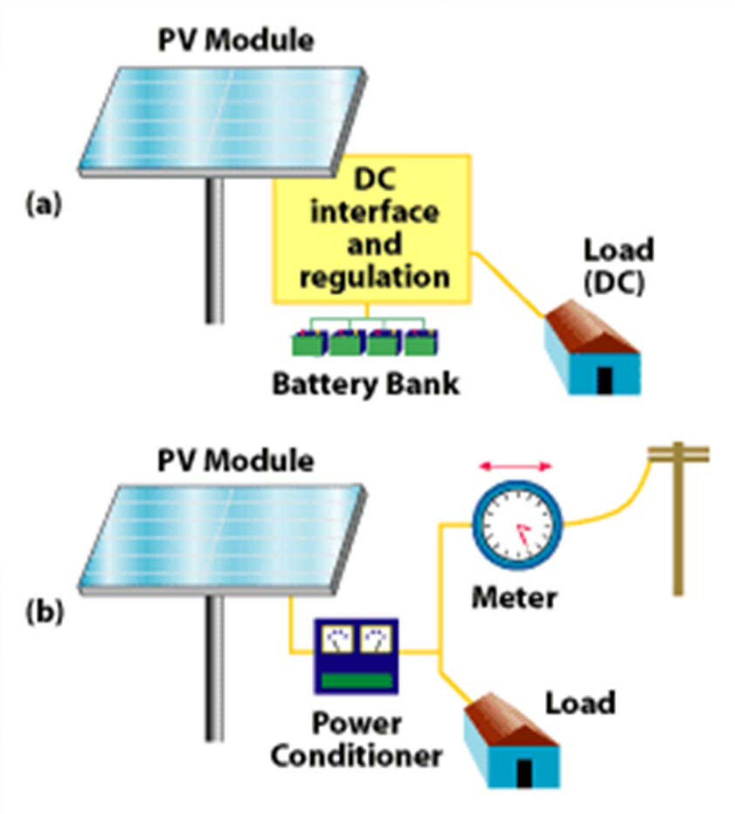
The Photovoltaic System Slide

(in lieu of “The Photovoltaic System Presentation”)



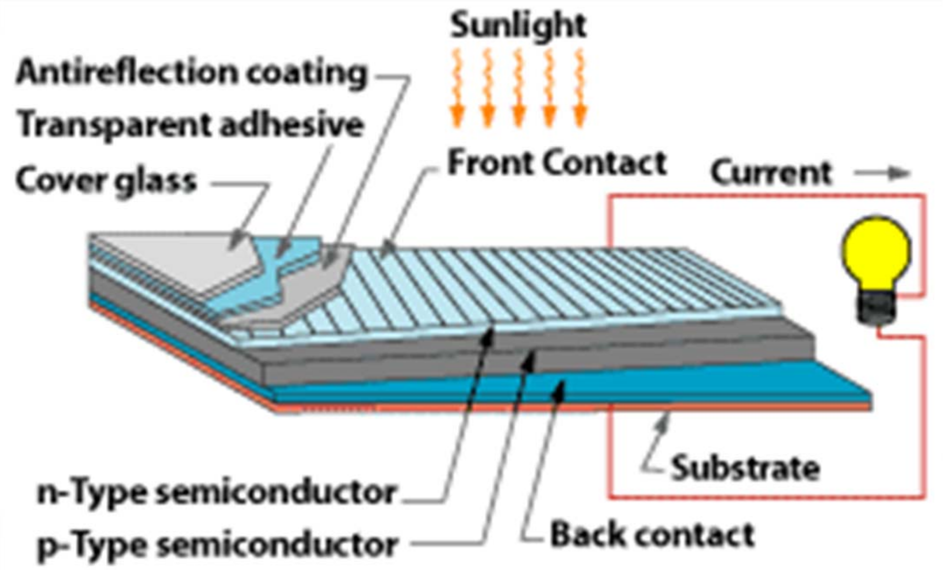
The basic photovoltaic or solar cell typically produces only a small amount of power. To produce more power, cells can be interconnected to form modules, which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small.



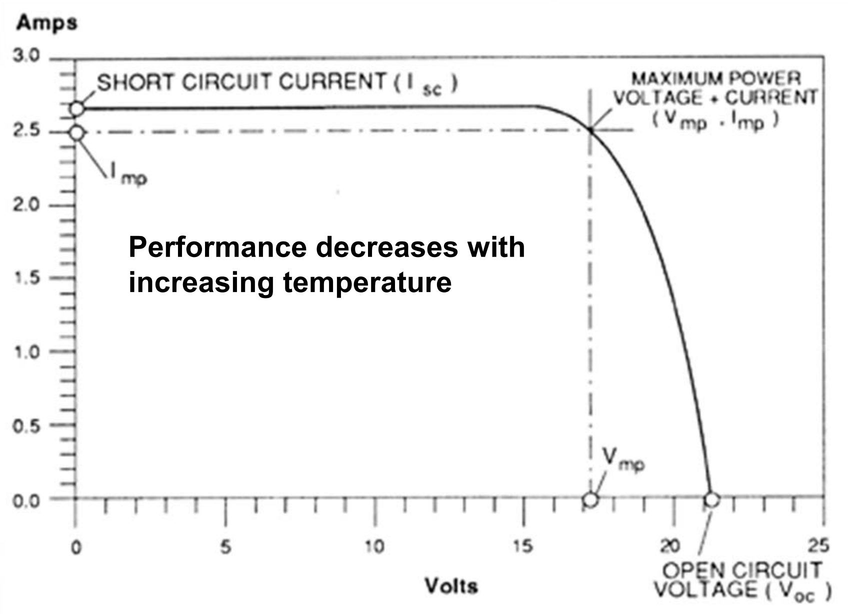
This simple illustration shows the elements needed to get the power created by a PV system to the load (in this example, a house). The stand-alone PV system (a) uses battery storage to provide dependable DC electricity day and night. Even for a home connected to the utility grid (b), PV can produce electricity (converted to AC by a power conditioner) during the day. The extra electricity can then be sold to the utility during the day, and the utility can in turn provide electricity at night or during poor weather.

http://www1.eere.energy.gov/solar

The Photovoltaic Module

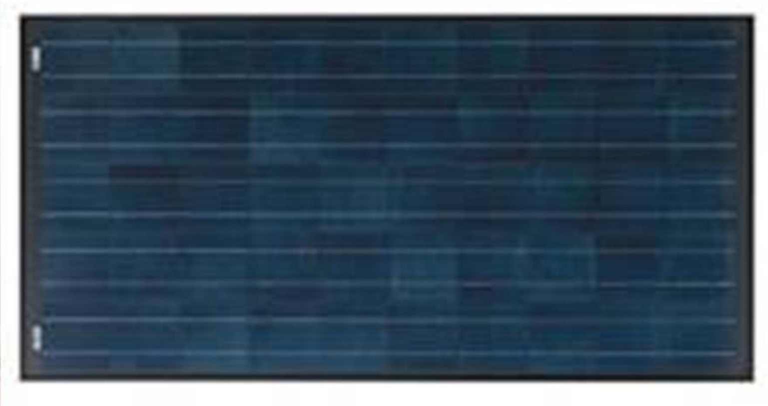


http://www1.eere.energy.gov/solar



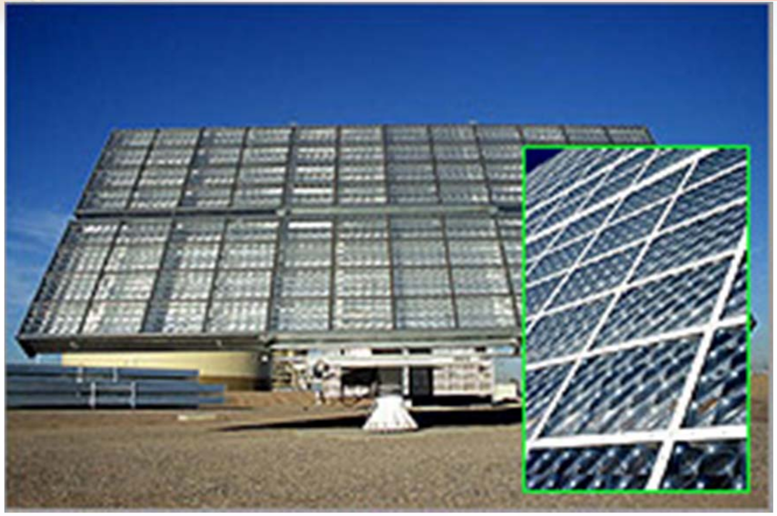
Performance decreases with increasing temperature

http://www.daviddarling.info/encyclopedia

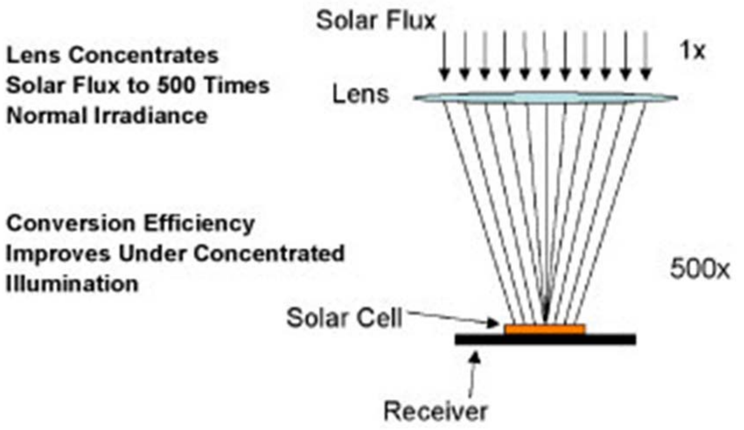


- One typical flat-plate module design uses a substrate of metal, glass, or plastic to provide structural support in the back; an encapsulant material to protect the cells; and a transparent cover of plastic or glass.

Concentrating Photovoltaic (CPV) Modules

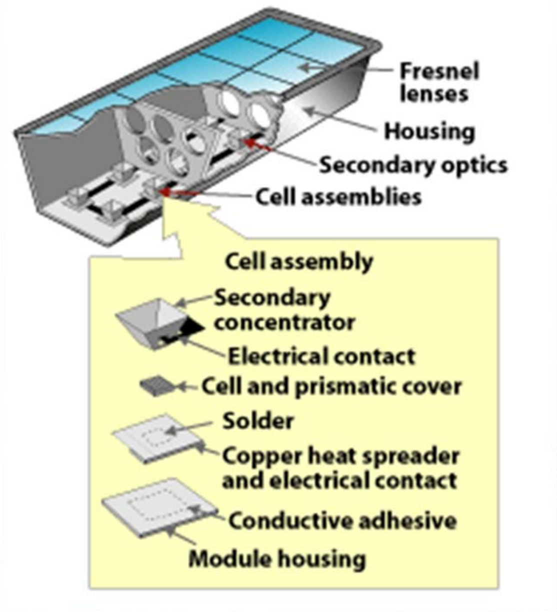


500 Times Normal Irradiance



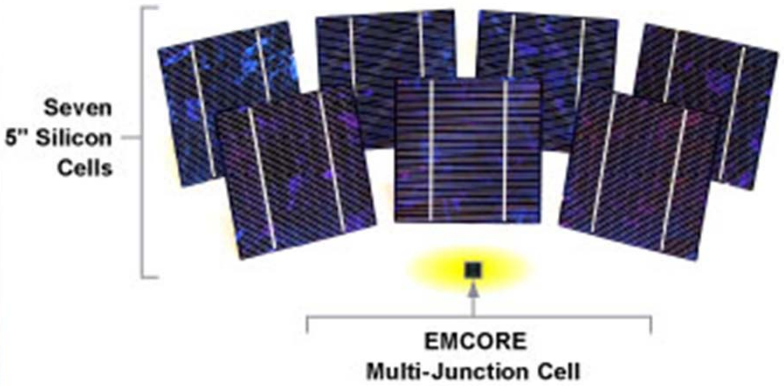
Lens Concentrates Solar Flux to 500 Times Normal Irradiance

Conversion Efficiency Improves Under Concentrated Illumination



Equal Power Output

Concentration Enables the Use of Very Small Solar Cells

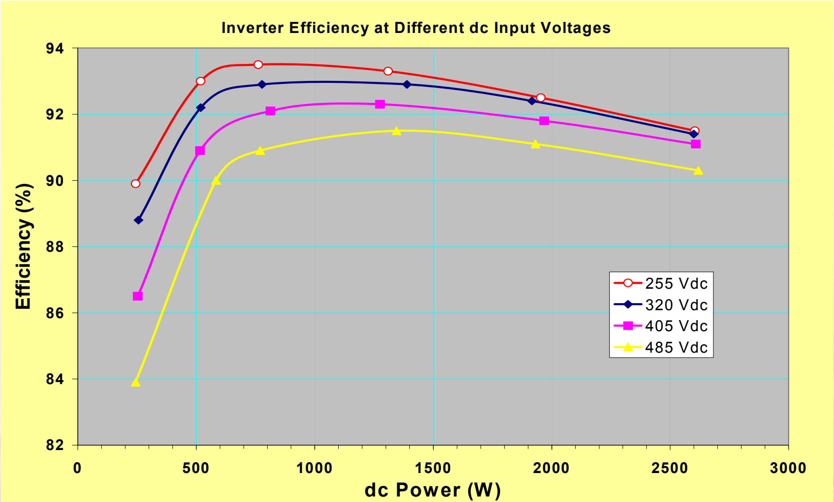


www.emcore.com

PV Inverters and Balance-of-Systems

- **Convert DC to AC**
- **Available at module-scale (200W) up to 2 MW**
- **Principal hardware:**
  - High power transistor bridges for conversion
  - Transformer for isolation of AC signal
  - Capacitors for signal smoothing
- **Principal software:**
  - Maximum Power Point Tracking (for optimum module utilization)
  - Anti-islanding (to detect grid loss)
  - Signal detection (turn on/off)
- **Reliability: viewed as the weak link in the system**
- **Additional BOS: AC, DC disconnects; wiring, fuses, racks, meters, …**

Residential inverters and related disconnects/meters at Sandia’s PV Systems Optimization Laboratory



Typical inverter efficiency plot (from SNL DETL)

PV Applications

- Residential
- Commercial
- Utility
- Off-grid

San Francisco's Moscone Center

East Africa - Solar-cooled vaccine delivery (photo courtesy of Shell Solar)

Building-Integrated PV (BIPV)

3kW a-Si rooftop at Sandia's Distributed Energy Technologies Laboratory (DETL)

- Take advantage of architectural characteristics of a building
- Integrally mounted as part of structure
- Can be difficult to access for maintenance
- Can have higher operating temperatures (low air flow) and lower performance

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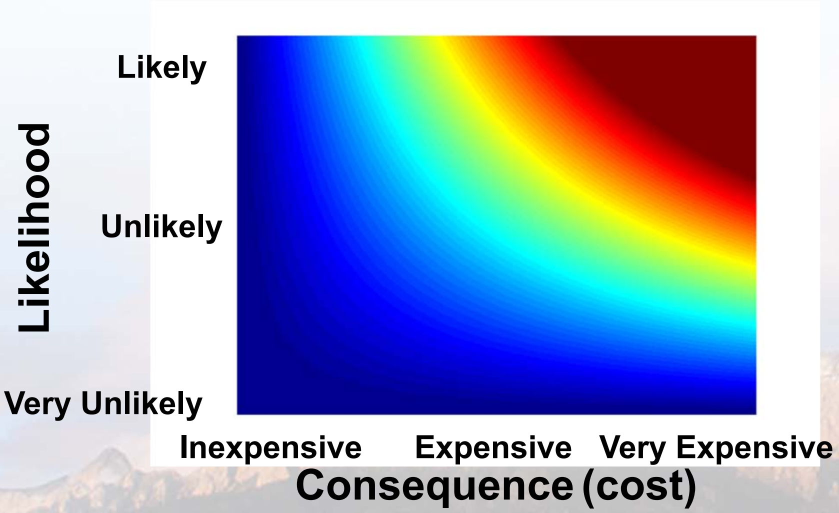
Design Issues

- **Goal is to maximize investment return while minimizing risk**
  - Multivariate, nonlinear optimization problem with considerable uncertainties
  - Risk can be defined as the probable frequency and probable magnitude of future loss
    - Product of probability and consequence



Other Examples of Risks:

- **Irradiance lower than expected**
- **Soiling worse than expected**
- **Components fail sooner than expected**
- **Degradation faster than expected**
- **Warranty not honored**
- **Design flaws**

Design Options

1. **Site (weather data availability, uncertainty)**
2. **Technology (module, inverter, and BOS)**
3. **Orientation (fixed tilt, tracking, roof or ground mount, ground coverage ratio, shading)**
4. **System configuration (central or distributed power conversion, module and string layout)**
5. **Operation (monitoring, cleaning, preventative maintenance, etc.)**
6. **Modeling of expected system performance**

1. Site Choice

- **What type of weather data is available?**
  - Typical Meteorological Year (TMY)
    - TMY (1952-1975); TMY2 (1961-1990); TMY3 (1991-2005)
    - Not available everywhere (how to interpolate between sites?)
    - Variable data quality
  - Field Data
    - Expensive, Short duration, data quality
  - Satellite Data
    - Free and for a fee depending on period and supplier
- **Uncertainties**
  - TMY annual uncertainties are typically +/- 9% (95% CI). Approximately equal to +/- 1% for 25 yr average (4.5%/sqrt(25))

2. Technology Choices

- **Efficiency vs. area-related costs (a balancing act)**
  - High efficiency modules more expensive per watt
    - Typically mounted on trackers to increase energy yield
  - Lower efficiency modules less expensive per watt
    - Require longer wire runs (greater DC losses), more racking, ground prep, O&M, etc.
- **Reliability track record**
- **Financial health of company (warranty risk)**
- **Installer experience**
- **Equipment availability**
  - Characterization and testing data

3. Orientation Choices

- **Tracking vs. fixed tilt**
- **Mounting options (thermal consequences)**
  - Roof mount
    - Ballasted vs. penetrations
    - Flat or tilted (soiling)
    - Access to fix leaks, replace roof
  - Shade Structure (parking garages)
  - Ground Mount
    - Vegetation/animal control
- **Time of Use Rates**
  - Trade total energy for energy at peak periods
  - Battery storage options?

4. Operational Decisions

- Level of Monitoring
  - Inverter level
    - Least expensive, hard to identify incremental problems
    - Usually combined with a PM cycle (how often?)
    - Accuracy concerns unless revenue grade meter is used (extra expense)
  - String Level
    - Uses smart combiner boxes or alternatives
    - Can be combined with string-level power conversion
    - Extra communications overhead (reliability)
  - Module Level
    - Microinverter or DC/DC converters
- Preventative Maintenance
  - What to do? How often? Contract or in-house?
- Utility Interactions
  - Large systems are being asked to coordinate with utilities, provide forecasts, etc.

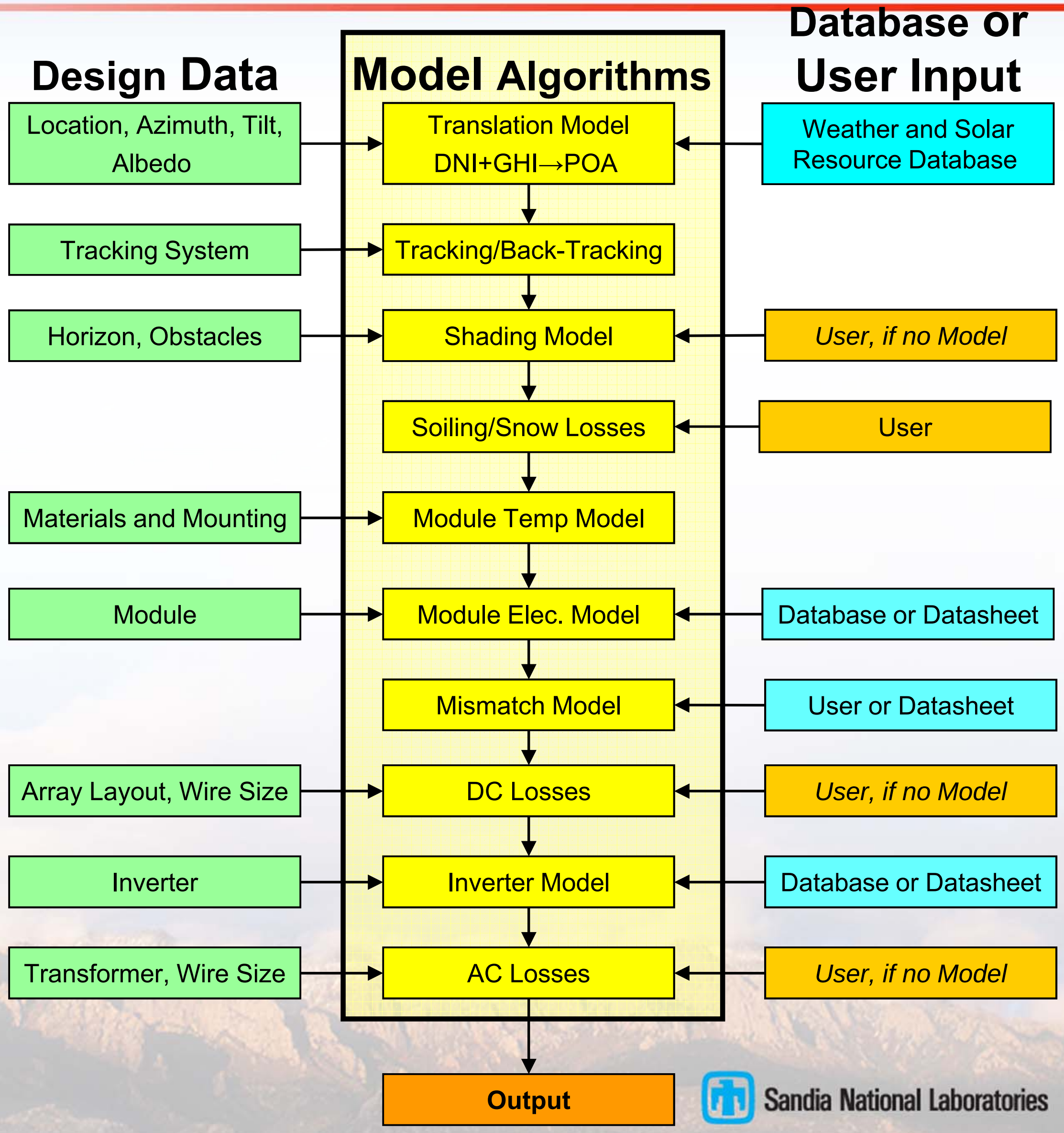
5. Modeling Issues

- **PV performance models are being used to assess design issues.**
  - Are they up to it?
- **Sandia organized a workshop to begin to address these issues:**
  - PV Performance Modeling Workshop September 23-24, 2010, Albuquerque, NM
  - Attended by 50 including Modelers, Manufacturers, Integrators, Independent Engineers, Analysts, Universities, and National Labs

PV Performance Modeling Steps

Modeling Process

- How much light enters module?
- What is the spectral content of the light?
- What is cell temperature?
- String Mismatch
- Balance of system
  - Wiring losses
- Inverter performance
  - MPPT
  - Efficiency



Design Data	Model Algorithms	Database or User Input
Location, Azimuth, Tilt, Albedo	Translation Model DNI+GHI→POA	Weather and Solar Resource Database
Tracking System	Tracking/Back-Tracking	
Horizon, Obstacles	Shading Model	*User, if no Model*
	Soiling/Snow Losses	User
Materials and Mounting	Module Temp Model	
Module	Module Elec. Model	Database or Datasheet
	Mismatch Model	User or Datasheet
Array Layout, Wire Size	DC Losses	*User, if no Model*
Inverter	Inverter Model	Database or Datasheet
Transformer, Wire Size	AC Losses	*User, if no Model*

Output

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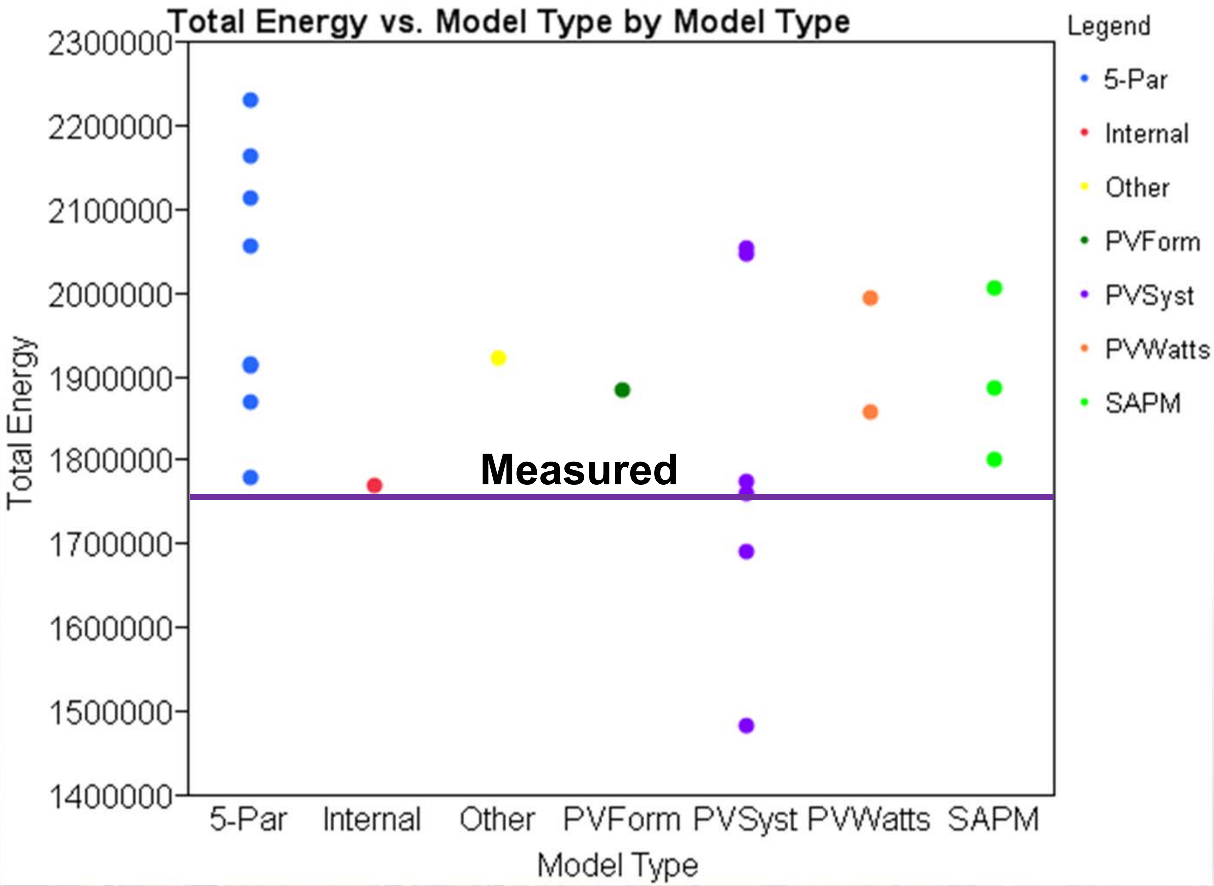
Current Status of PV Performance Modeling

- **Models Do Not Agree**
  - Even the same model, applied by different users may produce different answers
- **Model accuracy and uncertainty, in general, have not been independently verified**
  - Uncertainty (x ± y) generally not stated
  - No accepted validation process
- **Potential impacts include**
  - Choosing a technology because the model associated with an incentive treats it favorably
  - Choosing a technology based on performance that is not a better value when uncertainty is considered.
  - High market hurdles for new technologies lacking extensive field performance data to justify tweaking models
  - A decrease in investor confidence, leading to higher financing costs

Model Results Can Vary

- **Blind study**
  - 20 modelers
  - 7 models
- **Results differ within and between models**
  - Losses are hard to estimate
  - Assumptions are necessary



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Preliminary Summary of Outcomes

- Model developers are improving their models to boost accuracy for all technologies
- All models, even the simplest, require user estimates for some inputs, e.g. derate factors in PVWatts
  - Modelers in same company using same model may get significantly different results
  - Experienced project developers have tuned models to match output of fielded systems and/or have developed internal models
  - Model tuning and validation requires data on fielded system performance with accompanying weather data
    - Public data is not available, especially for larger systems
- Modelers who lack system data for model tuning and/or who are modeling new technologies will likely produce varying estimates of annual output, as illustrated by analysis of the workshop pre-work.
- Needs
  - Validated data for model inputs, e.g. from 3rd parties
  - Standard sets of data from public installations of a variety of systems types and locations for use in model validation and improvement
  - Characterization of model uncertainty, including which inputs have greatest effect.

Model Development Issues

- **Existing spec sheet data are insufficient for building a sophisticated model**
  - Multiple irradiance and temperature conditions (more than two) are needed (proposed for IEC 61853-1)
  - Adequate sampling of modules (how many is enough?)
  - Third party testing (auditing?)
  - Stability of characterization data between technology (light induced changes: Are IEC 61215 and 61646 adequate for new technology?)
- **Agreement on modeling losses is needed**
- **New module and BOS components difficult to assess (e.g. BIPV, Solyndra, bifacial, DC-DC converters)**

Large Systems Issues

- **Certain factors need to be represented differently for large and small systems.**
  - Irradiance issues (point vs. array measurements)
  - Module Temperature issues (spatial fluctuations, Heat Island effect, etc.)
  - Reliability Issues (O&M strategy is important)
  - DC Loss Issues (longer wire runs, uneven soiling)
  - Tracking issues (backtracking algorithm, failures, parasitic loads)
  - Inverter issues (MPPT performance, multiple inverters)
- **Industry knows how to do this for their systems**
- **Customers/Financiers need independent tools to validate performance estimates**

Current Efforts and Next Steps

- **Guide industry to adopt standards that allow more accurate modeling of performance**
  - Better characterization at different irradiance and temperature conditions on spec sheets
- **Develop publically-available resources for PV modeling**
  - PV Performance Modeling Collaborative
    - Launch website and resources
    - Documented and validated modeling functions (Matlab)
    - Host 2nd PV Performance Modeling Workshop (Fall 2012)
- **Regional Validation Test Centers**
  - Test and validate U.S. PV technology in different climates

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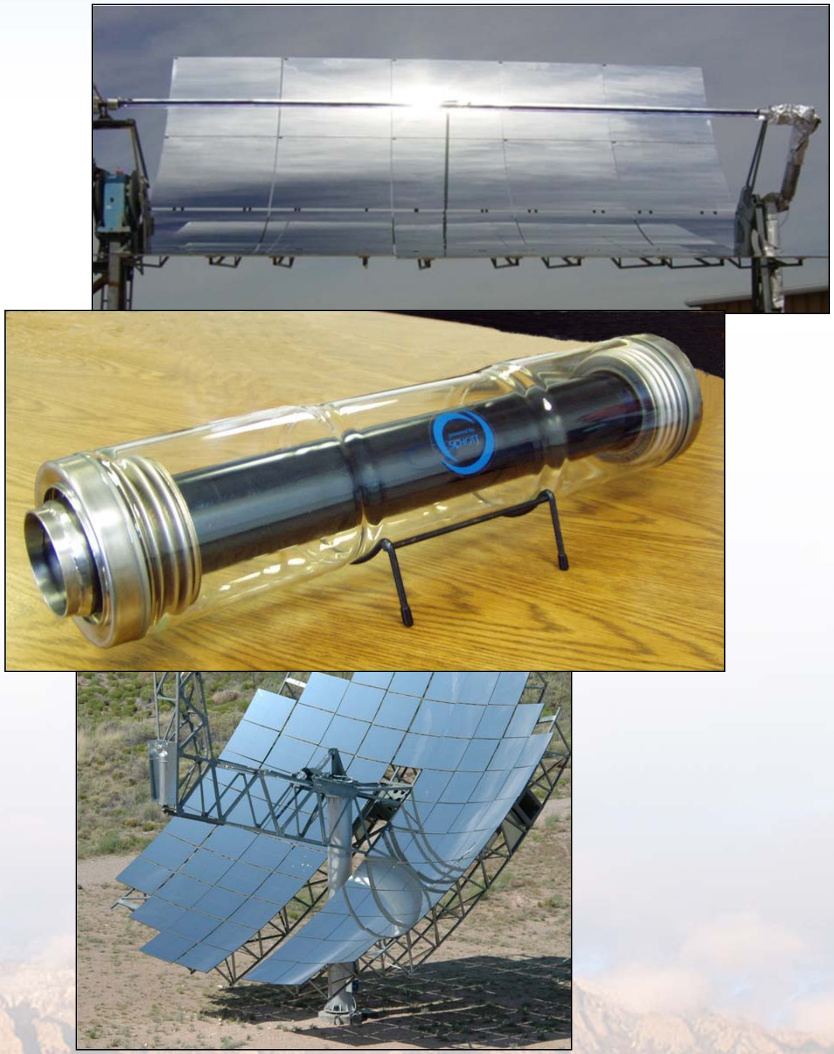
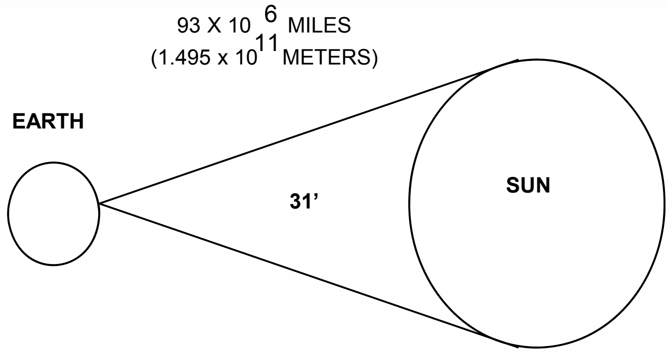
Heat Transfer Fundamentals

- **The solar energy resource**
  - Sunshape and solar energy spectrum
- **Heat transfer issues**
  - Conduction, convection, radiation
  - Absorption and IR emission
- **Solar concentrator optics**
  - Single-axis tracking trough collectors
  - Double-axis tracking heliostats and dishes
  - Specular reflection
- **Power cycles**

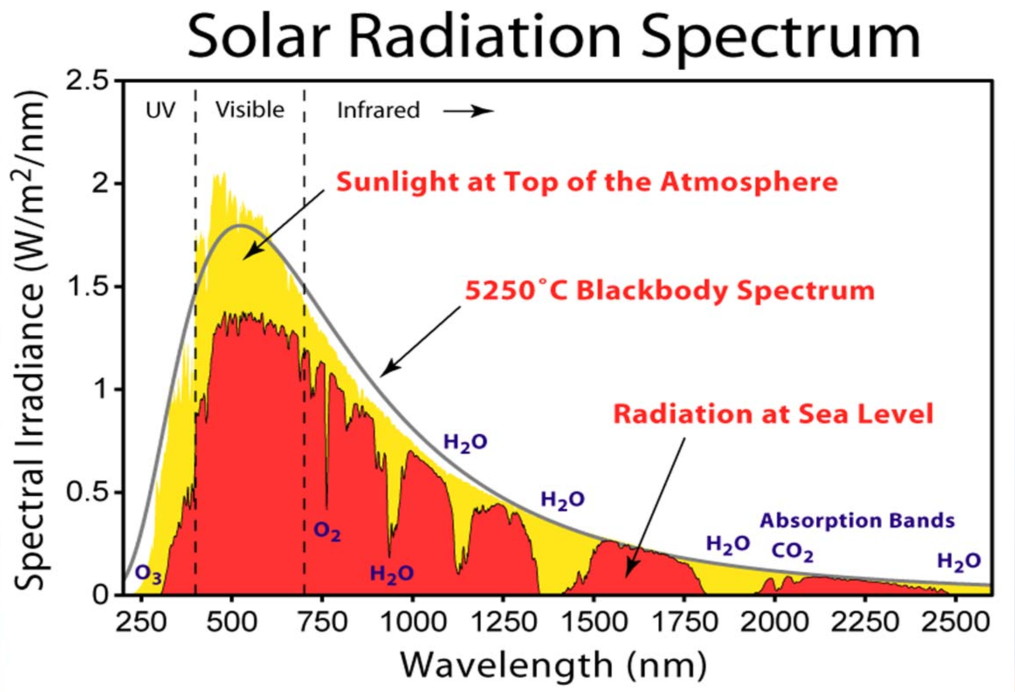


Spectrum and Sunshape

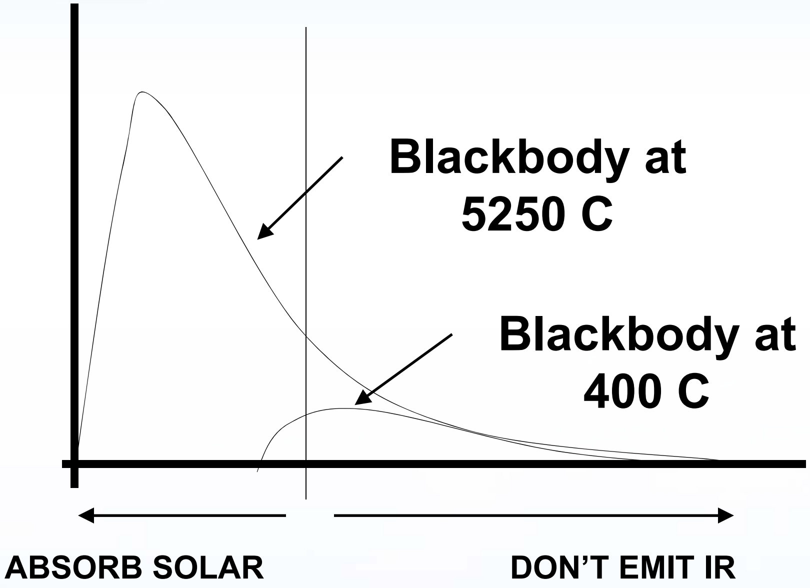
- The visible spectrum is from 400 nm to 700 nm
- Note 5250 C Blackbody spectrum



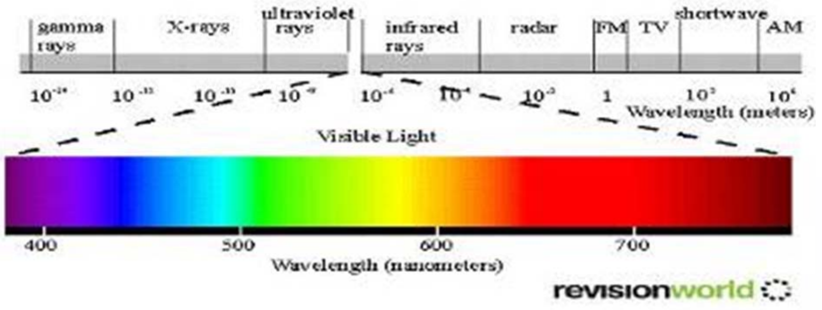
- Unlike PV, CSP responds to the full spectrum of the sunlight (“Broadband”)
- CSP only uses the “direct” component of the light
  - Flat-plate PV can use the direct and diffuse components



Absorption and emission

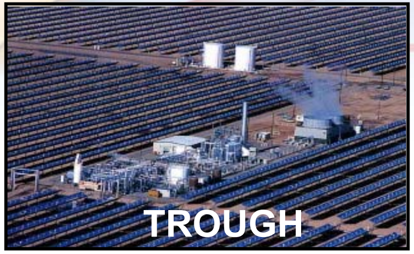


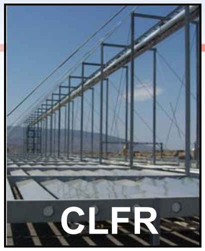
Solar energy is part of the electromagnetic wave spectrum.



- The first objective is to capture all of the solar energy
- The second objective is not to lose it
- Surface characteristics of absorptivity (α) and emissivity (ε) vary with wavelength
- It is desirable to have a high solar α and a low IR ε

What can CSP do?





- **Convert the sun's energy to heat and use that heat to power and engine/generator.**
- **Are utility-scale solar power (> 100 MW).**
- **Comprise three generic system architectures: line focus (trough and CLFR), point focus central (power tower), and point focus distributed (dish engine).**
- **More than 140 plant-years of commercial operation (10 plants, 400MW) in the Southwest.**
- **Capable of providing dispatchable power for peaking and intermediate loads (storage or hybridization).**
- **Mostly uses commodity items (turbines, glass, steel, aluminum, piping, controls, etc)**

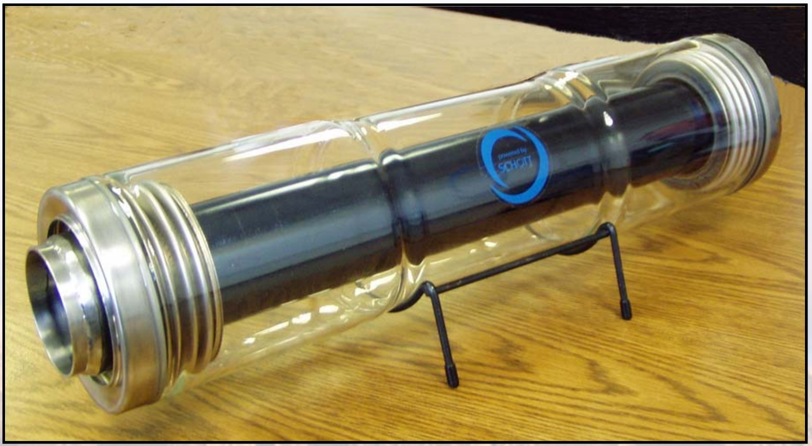
Trough Components

Drive

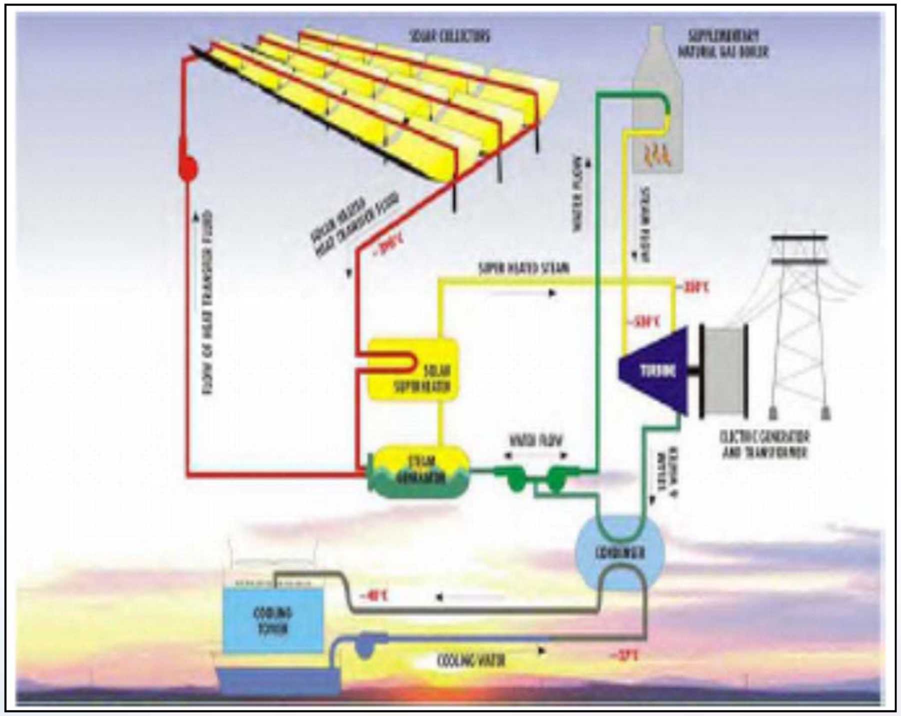
Trough Collector

Controller

Receiver



How a Trough System Works



- **Synthetic Oil circulated through the collectors and heated from 290 to 390 C.**
- **Hot oil circulated through the steam generator to produce superheated steam.**
- **Steam routed through the turbine generator producing electricity.**
- **Steam condensed using water cooled in cooling tower.**

CLFR Designs

- Continuous Linear Fresnel Reflector
- Approximates a line-focus trough collector
- May be lower cost because it doesn't use curved mirrors and places the reflectors near ground level -- reducing wind loads

SEGS Plants

- Solar Electric Generating Stations
- Total annual ave. solar-to-electric efficiency at 12%.
- Plants use conventional equipment and are “hybridized” for dispatchability (25% Natural gas)

30 MW increment based on regulated power block size

Nevada Solar One

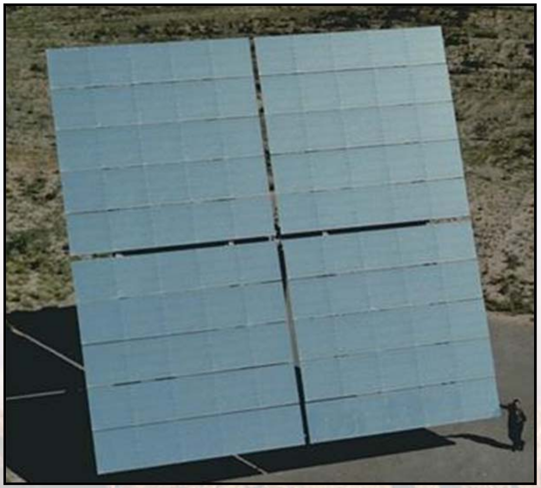
- 64 MW Capacity
- 357,200m² Solar Field
- 30 Minutes Thermal Storage
- Minimal Fossil fuel
- Long term PPA signed with Nevada Power
- EPC Notice to Proceed – January 2006
- Startup April 2007

Power Tower Components

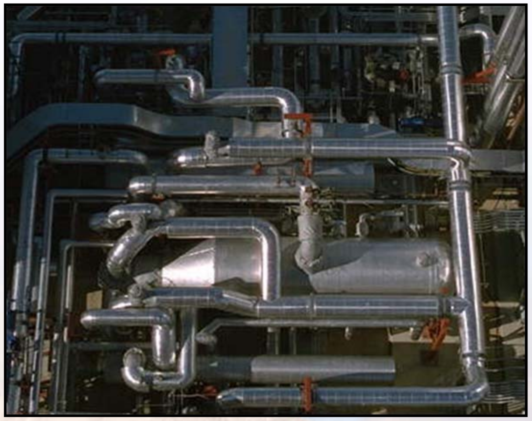
Receiver

Storage Tanks

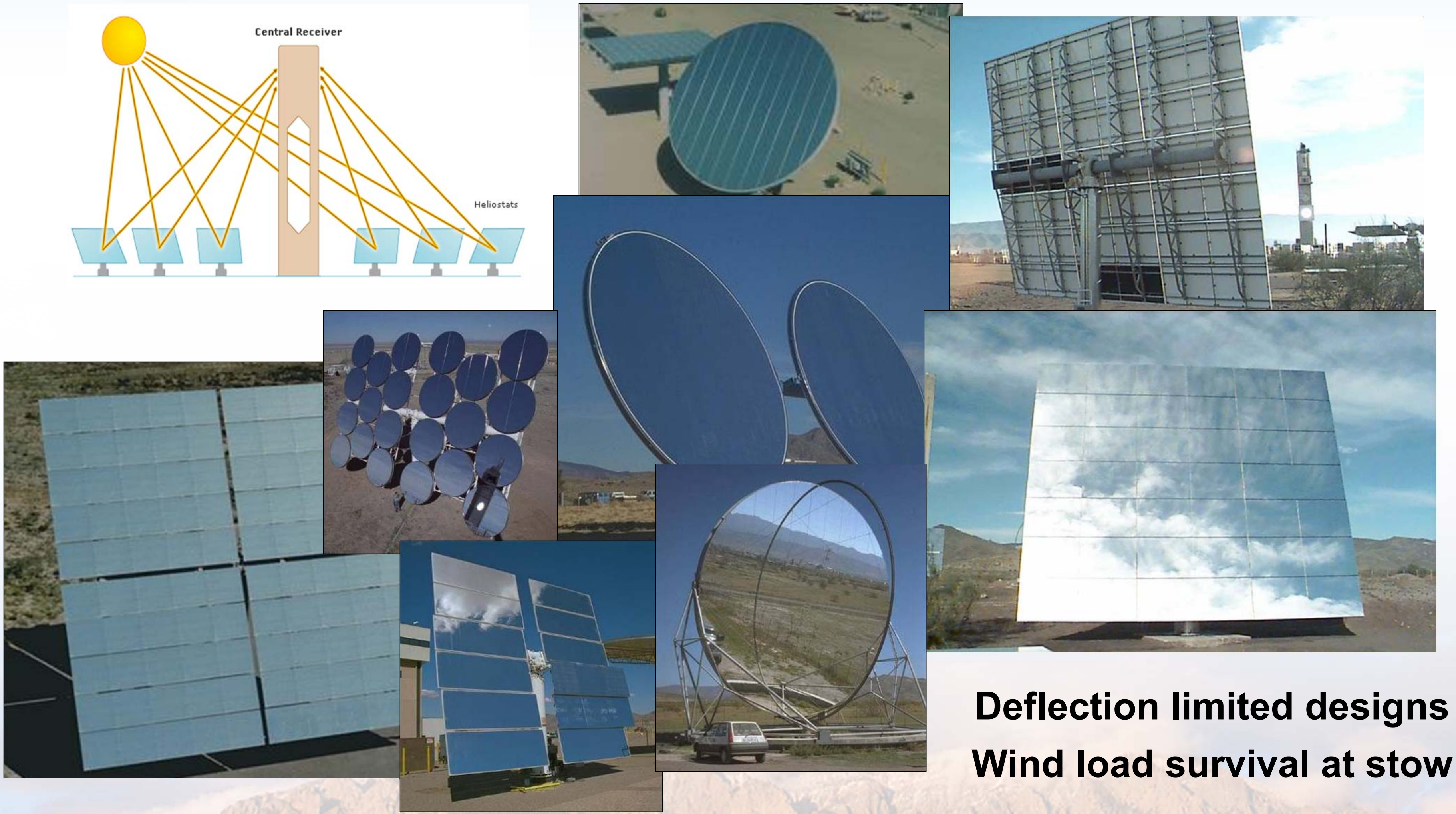
Heliostat



Steam Generator



Heliostat Designs



Deflection limited designs

Wind load survival at stow

Central Receiver Receivers


CAVITY MOLTEN SALT RECEIVER


SOLAR 2 MOLTEN SALT RECEIVER


WINDOWED BEAM DOWN AIR RECEIVER

- **Central Receivers are**
  - Cavity receivers
  - Windowed
  - Direct steam generators
  - Can use Molten-Salt working fluids
- **Design Considerations**
  - Inlet/Outlet Temperatures
  - Materials
  - Pressure
  - Low volatility working fluids

Power Towers

PS 10 (2006) PS 20 (2009)

11 MW & 20 mw Capacity

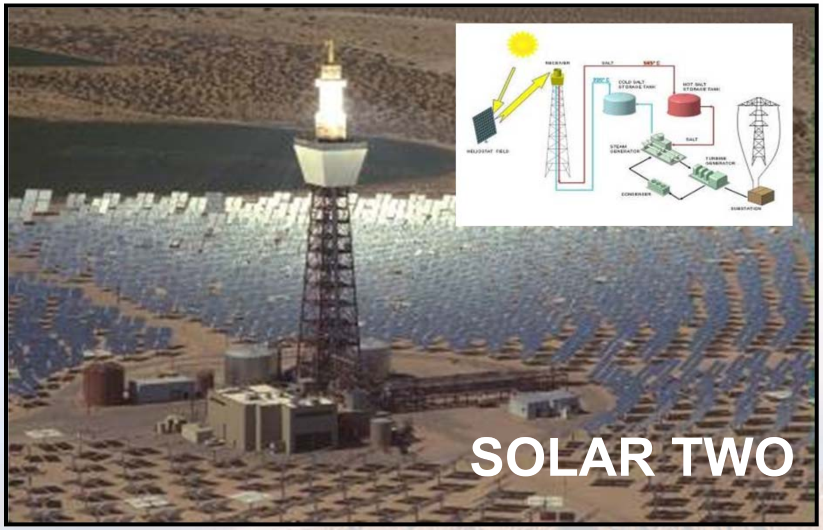
Once-through steam boiler

1 Hour thermal storage (steam)

1878 heliostats (120 m² each)

Towers height 100 m and 160 m

73 GWhr/annually



Solar Two Experiment (1995 – 1997)

10 MW Capacity

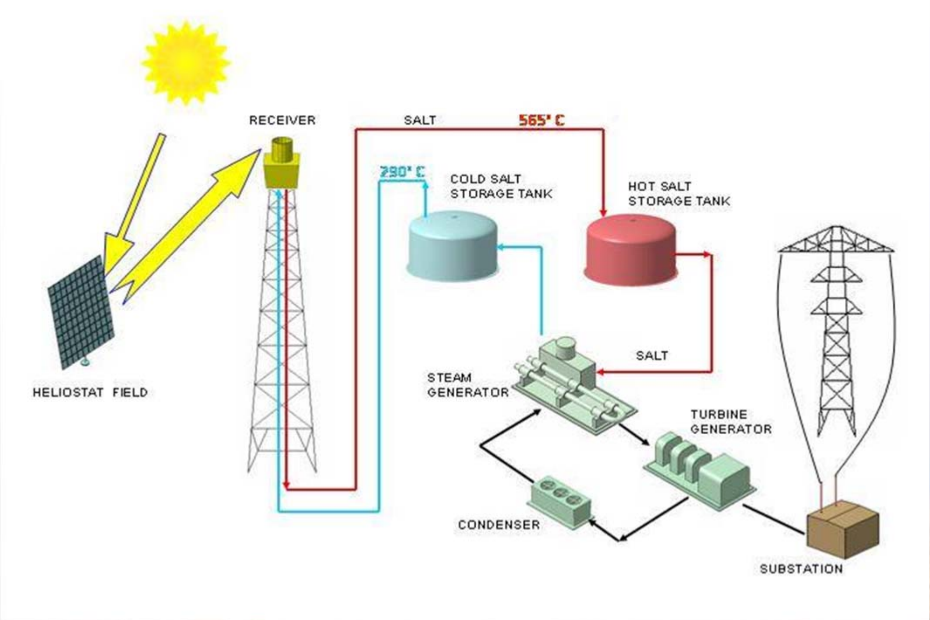
Molten Salt working fluid/thermal st.

Receiver η = 88%

η of Storage > 98%

Dispatchability demonstrated

Molten-Salt Power Tower



In a Molten Salt Tower

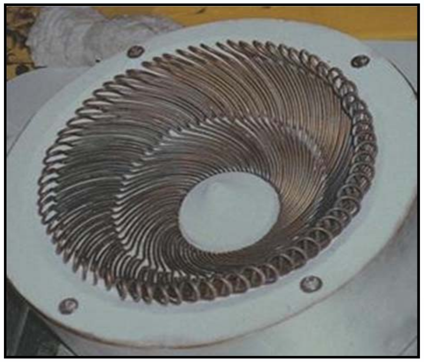
cold salt (265C) is pumped to the receiver, heated to 565 C, and returned to the Hot Tank

To generate power, hot salt is removed from the hot tank, passed through the steam generator, and returned as cold salt to the cold tank.

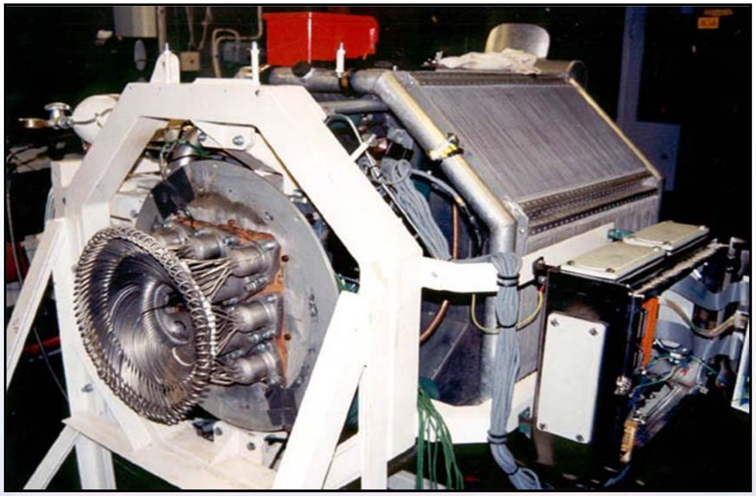
Energy collection is uncoupled from power production

Dish Stirling Components

Receiver

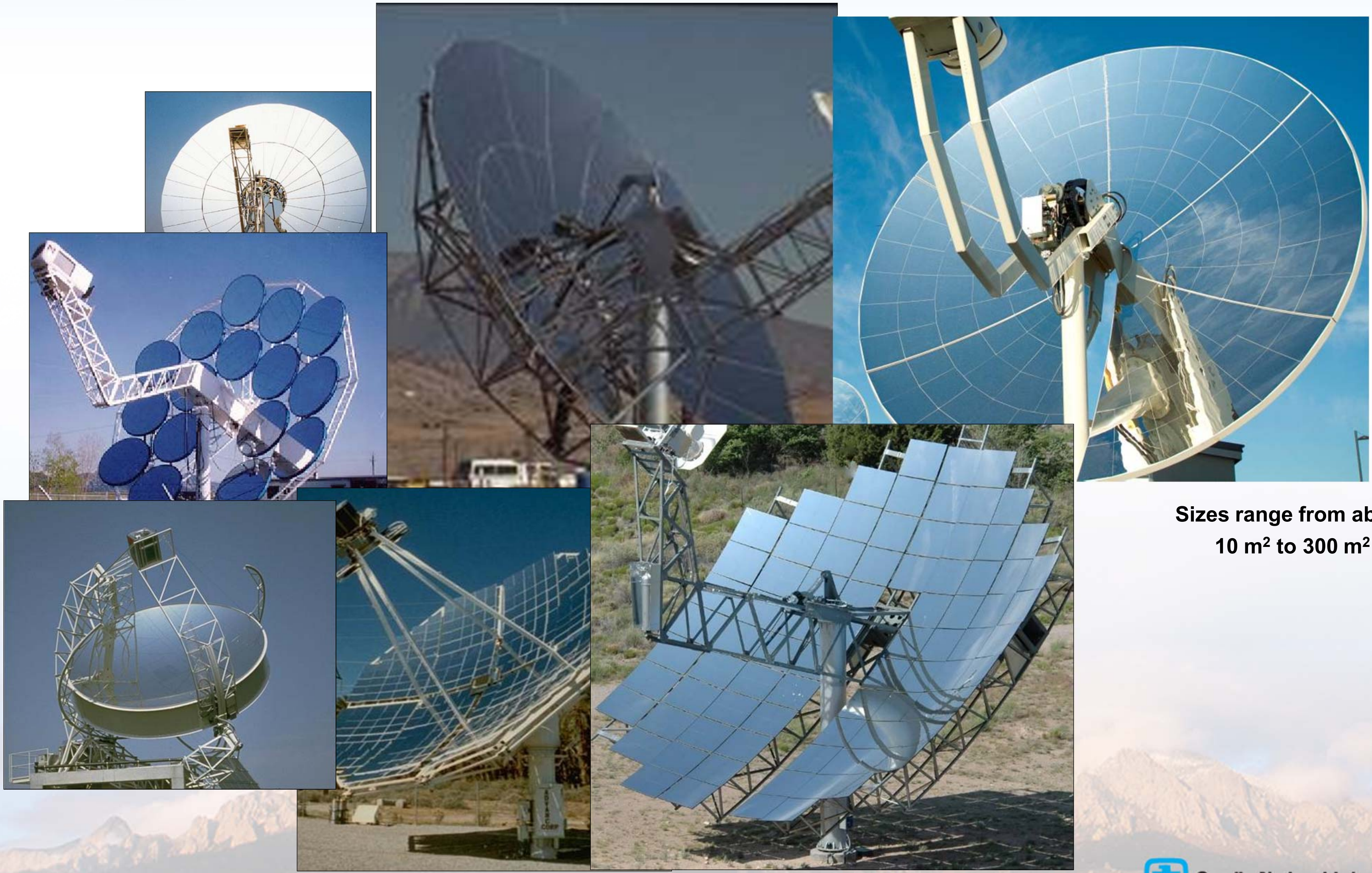


Dish



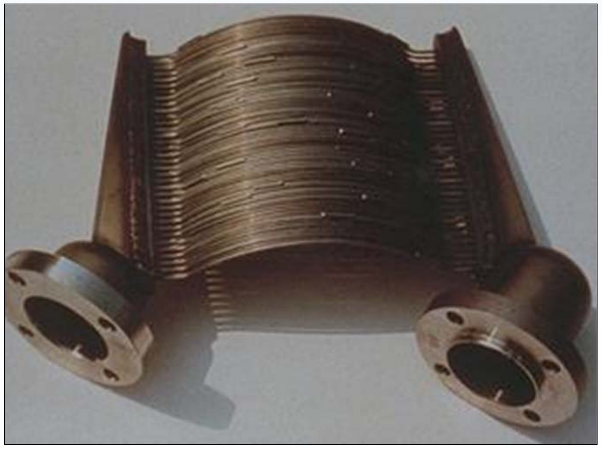
Engine/Generator

Dish Designs



Sizes range from about
10 m^2 to 300 m^2

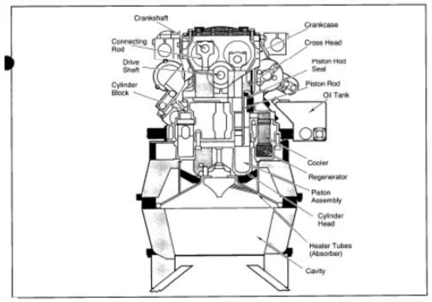
Dish Stirling Receivers

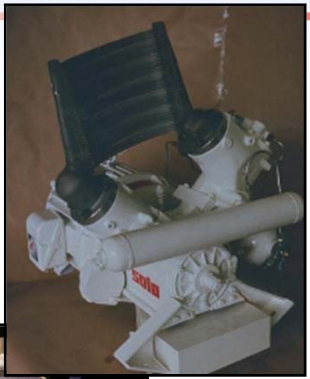


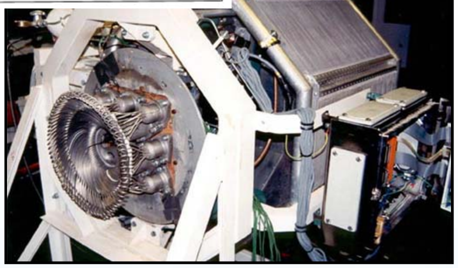
The receivers transfer the solar-generated heat to the engine. This is done indirectly; by heating tubes that transfer the heat to the engine working fluid (hydrogen or helium) or by transferring the heat to an intermediate fluid (like sodium) that heats the tubes.

CSP Dish Stirling Systems

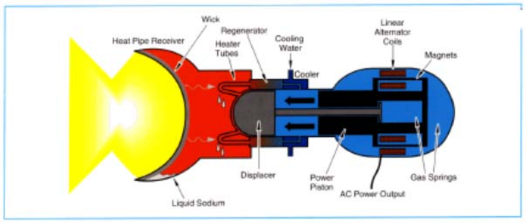
Kinematic







Free Piston



Kinematic engines operate similar to an automobile to produce mechanical power by moving pistons, driving a crankshaft, and spinning a generator.

Free-piston engines have only two moving parts – a power piston and a displacer piston. The power piston moves back and forth driving the displacer piston. The displacer piston has a permanent magnet that moves back and forth in coils located in the engine housing, operating as an alternator.

CSP Dish Stirling Systems

- High efficiency (Peak > 30% net solar-to-electric)
- Annual Efficiency ~ 22 – 25%
- Modular (3, 10, 25kW)
- Utility-scale plants would have 1000s
- Small system for DG applications
- No commercial plants built yet

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Summary

- Solar resource and potential is huge in all parts of the U.S.
- Many PV technology and design options
- Characterization and prediction of PV system performance needs improvement
- CSP offers options with energy storage, which makes integration easier, but costs are still high