SOLAR ENERGY
Introduction

- With the exception of nuclear power, all of the energy we use is “solar” in origin-
  - wind and hydro are driven by solar heating.
  - wood and other bio-fuels are solar energy converted and stored by plants
  - coal, oil, natural gas are fossilized bio-fuels.
- Solar energy refers to the direct use of the energy contained in sunlight.
- The power flux of direct, normally incident sunlight averages about 1 kW/m² (≈ 100 W/ft²).
Not all of the sunlight entering the atmosphere gets used by a solar energy system.
Map shows kWh/m² of solar energy incident on a horizontal surface in month of June.
Two Categories of Solar Energy

- **Active Solar**: A method specifically designed to acquire energy from sun and move it to where needed, including:
  - photovoltaic electric power generation
  - solar thermal electric power generation
  - active solar heating using solar collectors

- **Passive Solar**: a design (usually of buildings) that inherently takes advantage of the sun for daylighting and winter heating, and avoids solar gain in summer to minimize need for cooling.
PASSIVE SOLAR

- Passive solar architecture has been practiced by people living in hot regions of the world for millennia, e.g., adobe style.
- A good example of contemporary passive solar design is the UA Student Recreation Center (old part with gym).
Original UA Recreation Center

- Solar Eyebrow:
  - Eyebrow shades summer sun to reduce cooling load
  - Winter sunlight passes through window

- Translucent Skylights:
  - Heavy interior of building stores solar heat in winter
SOLAR HEATING

- Probably the most economical use of active solar energy at present is for heating—both space heating and hot water heating.
- This technology saw big surge in late 1970s because of high tax credits, but tapered back due to declining energy prices, end of tax incentives, and bad publicity resulting from fly-by-night shady operators.
Collector Types

- **Flat plat** - flat, blackened Cu or Al plate with soldered or welded tubes - usu. for water.
- **Modified flat plate** - corrugated, triangular folds, etc., - usually for air.
- **Concentrator** - use mirror or lens system to focus sun and achieve high temperature - usually for water.
Domestic hot water heating system

Water is circulated through collector when $T_c > 32^\circ F$, $T_t < 180^\circ F$ and $T_c$ is $10^\circ F$ hotter than $T_t$.

3-way valves for draining tank

Collector circulation pump

Collector

Hot out

Cold in

Drain

Hot water tank

Temp Pressure Relief Valve

$T_c$

$T_t$
Domestic hot water heating, Sussex, England
Solar Thermal Electric and Heating

- After a big surge because of LUZ plant (described later), solar heating unit sales have reached about $28 million/yr or a collector area of $7 \times 10^6$ ft$^2$/yr.

- At present, the biggest single market (over half) is for swimming pool heaters.

- Solar water heating can achieve collector efficiency $> 50\%$, but cost and inconvenience cannot compete at present except where fossil fuel supplies are expensive (e.g., Hawaii) or not easily obtained (remote areas).
PV systems near point of use are usually more economical than large arrays that supply a grid.

Another technology for producing electricity from solar energy is solar thermal power.

Electricity produced much like conventional method- solar heat powers a Rankine or Stirling cycle- although an intermediate heat transfer fluid (like an oil) may be used to collect heat.

Actual operating efficiencies of most developed system is about 12%, similar to crystalline PV.
Three Types of Solar Thermal Power Systems

- All systems concentrate sunlight onto receiver (boiler) to achieve high turbine inlet temperature /pressure (recall $\eta_{\text{Carnot}} = 1 - T_c/T_H$).
- **Trough-electric** uses a long parabolic mirror to focus sunlight on a cylindrical receiver.
- **Dish/Stirling** systems use a parabolic dish to focus sunlight onto a receiver containing a piston-based Stirling cycle.
- **Power Towers** use a field of mirrors (heliostats) to focus intense heat on a large central receiver.
Trough Electric

- Receiver tube
- Concentrator reflecting surface
- Tracking Mechanism
LUZ Solar Thermal Plants

- 354 MW total are delivered to So. Cal. Edison.
- LUZ did not profit because of dropping energy prices and failure to receive sufficient tax credit for environmental benefits.
- Troughs concentrate by factor of 80 into vacuum-jacketed cylindrical receiver- up to 730°F turbine inlet temperature.
- Electricity is produced at about 15¢/kWh.
Testing a LUZ trough collector at Sandia National Lab.
Trough collectors at the LUZ site.
The LUZ plants in Kramer Junction, California
Parabolic Dish System

Concentrator reflector surface

Receiver or engine/receiver
Dish Systems

- Parabolic dish technology is much less developed than trough electric or power tower.

7.5 kW (10 hp) dish/Stirling system being developed by DOE and Cummins.
Power Tower

- A power tower receives reflected sunlight from many tracking mirrors (heliostats).
- Concentration of 800 suns; $\eta_{\text{solar}} = 15$ to $20\%$; $T_H \approx 1000^\circ\text{F}$.
- DOE has built Solar One and Solar Two.
Solar One Tower

- 250 ft above ground
- 23 ft dia.
- Receiver panels
- Each panel has 70 tubes
- 45 ft receiver height
Mirror modules are 3.6 ft x 10.2 ft

Solar One Heliostat

Foundation and support pedestal
Azimuth and elevation drive
Heliostat electronics
Power box
Solar One and Solar Two

- Solar One was a 10 MW\textsubscript{electric} power tower located near Barstow, CA that supplied electricity to the grid from 1983 - 1988, but was not economical.
- Used power tower directly as boiler to feed turbine-no thermal storage, so no sun means no power.
- Solar Two was a project to convert Solar One so that primary heat transfer fluid is molten nitrate salt. Heat was stored so plant could keep operating during cloudy weather or at night.
- Solar Two completed its operation successfully in April 1999. Current estimated power cost is 15¢/kWh.
Molten Nitrate Salt Tanks for Solar II

Source: US DOE – Sandia Nat’l Lab
Solar Two

Source: US DOE – Sandia Nat’l Lab
Solar II Technology

Source: US DOE – Sandia Nat’l Lab
Solar II Typical Operation

11.6 MW max peak generation

Source: US DOE – Sandia Nat’l Lab
# Solar Thermal Power Status

## Concentrating Solar Power Technology Status and Projected Cost

<table>
<thead>
<tr>
<th>Technology</th>
<th>Status</th>
<th>Unit Capacity</th>
<th>Capital Cost ($/kW)</th>
<th>O&amp;M (¢/kWh)</th>
<th>LEC (¢/kWh) Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Troughs</td>
<td>Early commercial evolution</td>
<td>30 MW to 80 MW</td>
<td>$2,900</td>
<td>1.0</td>
<td>6.8 – 11.2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.6 – 9.1</td>
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<tr>
<td>Power Towers</td>
<td>Demonstrated technical feasibility</td>
<td>30 MW to 200 MW to $2,900</td>
<td>0.7</td>
<td>5.2 – 8.6</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>3.3 – 5.4</td>
</tr>
<tr>
<td>Solar Dish/Engines</td>
<td>Early technical feasibility</td>
<td>5 kW to 50 kW</td>
<td>$2,900</td>
<td>2.0</td>
<td>8.6 – 13.0</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>4.0 – 6.0</td>
</tr>
</tbody>
</table>

*Source: US DOE – Sandia Nat’l Lab*
Projected Solar Thermal Costs

Source: US DOE – Sandia Nat’l Lab
A solar cell uses junctions of an $n$-type semiconductor (freely moving electrons) with a $p$-type semiconductor (freely moving “holes”), which creates a type of diode which is in electric equilibrium in the dark (no current).

See how a cell works: http://www.eere.energy.gov/solar/
PV Operation

- Photons (electromagnetic radiation) from sunlight free electrons and holes and cause a DC current from the *n*- to the *p*-type material.
- Several **cells** are placed in series in **modules** to achieve higher voltages and power.
PV History

- Photoelectric effect discovered in 1839.
- Einstein received his Nobel prize for explaining how light and the photoelectric effect worked.
- Bell Labs made first solar cell in 1954.

Mid-50’s *Nat’l Geographic* ad
Two Photovoltaic Cell Types

- **Single crystal or polycrystalline cells** use "doped" crystals for making the cells, much like computer chips.
- This is most common technology.
- Crystalline cells are expensive, but last many years with little degradation.
- Silicon is the most common material, though others are under development, such as gallium arsenide.
Single-crystal PV array (~250 W)
Four Crystalline Cell Production Steps

- Wafer production- a crystalline silicon ingot is produced from molten silicon, then sawed into thin wafers- costs about $200/m² cell area.
- Cell fabrication- uses doping and etching technologies similar to computer chip making- costs about $100/m².
- Encapsulation- laminate cells into weather-resistant materials- costs about $100/m².
- Attachment- cells attached to rigid structural framework for mounting- costs about $100/m².
Crystalline PV Cell Economics

- Total cost of conventional crystalline PV cells is about $500/m² ($50/ft²) of collector area.
- Total average power flux is 1000 W/m², so 1 m² of cells produces 125 W at cost of $500, which corresponds to $4/W of electric generating capacity (note: this is only cost of PV cells and does not include necessary auxiliary components.
- Lowest reported costs were $3/W for photovoltaic cells in 2002 (IEA). Crystalline silicon cells accounted for 80% of total worldwide in 2002.
Thin Film PV Cells

- Thin film cells are made by vapor-deposition of 1 mm thick layers of semi-conductor material onto a glass substrate.
- Materials used are silicon, cadmium telluride, or copper indium diselenide.
- The continuous manufacturing cost can result in $/W costs significantly lower than crystalline.
- Efficiencies are also much lower, about 6%, so about twice the cell array area is required.
- Efficiencies are expected to improve to > 10%
## Photocell Efficiencies

<table>
<thead>
<tr>
<th>Type</th>
<th>Typical module efficiency [%]</th>
<th>Maximum recorded module efficiency [%]</th>
<th>Maximum recorded laboratory efficiency [%]</th>
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</thead>
<tbody>
<tr>
<td>Single crystalline silicon</td>
<td>12-15</td>
<td>22.7</td>
<td>24.7</td>
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<tr>
<td>Multicrystalline silicon</td>
<td>11-14</td>
<td>15.3</td>
<td>19.8</td>
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<tr>
<td>Amorphous silicon</td>
<td>5-7</td>
<td>-</td>
<td>12.7</td>
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<tr>
<td>Cadmium telluride</td>
<td>-</td>
<td>10.5</td>
<td>16.0</td>
</tr>
<tr>
<td>CIGS</td>
<td>-</td>
<td>12.1</td>
<td>18.2</td>
</tr>
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*Source: International Energy Agency, 2002*
Figure 1: Cumulative installed PV power by application area in the reporting countries

Source: International Energy Agency, 2004
U.S. Installed Photovoltaic Capacity

Source: International Energy Agency, 2004
Figure 4: PV module production and module production capacity between 1993 and 2002

Source: International Energy Agency, 2004
# PV Cell Manufacturing - 2002

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Japan</td>
<td>244</td>
<td>261</td>
<td>260</td>
<td>405</td>
</tr>
<tr>
<td>USA</td>
<td>121</td>
<td>177</td>
<td>81</td>
<td>148</td>
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<td>Europe</td>
<td>134</td>
<td>226</td>
<td>133</td>
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<tr>
<td>Rest</td>
<td>21</td>
<td>37</td>
<td>8</td>
<td>22</td>
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<tr>
<td>TOTAL</td>
<td>520</td>
<td>801</td>
<td>482</td>
<td>792</td>
</tr>
</tbody>
</table>

*Source: International Energy Agency, 2004*
PV Power Systems for Buildings- 6 Components:

- Solar array for primary power, plus backup, which could be grid, wind, or engine gen-set.
- Array mounting system- fixed or movable.
- Battery storage for electricity at night.
- Charge controller and safety disconnect system for batteries.
- Metering panel.
- An inverter to go from DC to AC.
Mounting an Array

- Solar array can be fixed or movable.
- An array that directly tracks the sun is 30% more efficient than optimal fixed array.
- Compromise: fixed array that is tilted every few weeks to keep best orientation.
Sun-tracking arrays on the big island of Hawaii
This home in Brookline, Mass collects heat through southern windows and produces electricity and hot water from roof-mounted collectors (fixed array).
Home Electric Systems

- Batteries and a considerable set of controls, etc., must be used to store electricity.
- Home PV cells generally rated at ~14 V and are good for charging a 12 VDC battery system.
- Home can use DC, AV with inverter, or both.
- DC appliances and lighting are readily available.
- Energy efficiency is critical because of high cost of producing electricity with solar PV cells.
- 12 VDC power uses large current so requires BIG wires to avoid high $I^2R$ losses.
(a) A pure DC system with battery storage

(b) An AC system with an inverter but no storage because connected to grid.
Solar home in North Carolina
Power room in North Carolina solar home
Figure 5: PV system and module price trends in selected reporting countries
Applications for PV Cells NOW

- Remote or temporary operations where it’s not cost effective to connect to the grid, like flashing highway signs, well pumps or in space.

A 4.5 kW telecommunications signal booster in a remote area of Nevada.
A solar powered path light is a simple collection and storage system.

200 W pump for village without electricity in India.
NASA’s Mars Sojourner, 1997
The Pathfinder Plus—a lightweight, solar-powered, remotely piloted flying wing aircraft. The aircraft could stay airborne for months on scientific sampling and imaging missions. Solar arrays cover most of the upper wing to provide power for electric motors, avionics, communications, and other electronic systems. A backup battery system can provide power for 2 to 5 hours and allow brief flights after dark.

Source: NASA
Pump powered by 200 W in Arizona desert pumps > 100 gal/day of water from 560-ft deep well. System cost $8000, much cheaper than running power line.
More PV Applications NOW

- Power for light loads- like calculators.
- Off-grid living- in remote areas can’t hook-up to grid (power lines cost at least $20,000 per mile).

Off-grid house on Peace River, Florida
Another application for PV’s is the capability of setting up a power generation source very quickly in a remote or cut-off area.

Setting up power after Hurricane Andrew in Florida
Photovoltaic Roof Shingles

These roof shingles are coated with PV cells made of amorphous silicon. When installation is complete, the PV shingles look much like ordinary roofing shingles, but they generate electricity.

Source: US DOE – Sandia Nat’l Lab
California Dreamin’... a 2 MW PV array next to Rancho Seco nuclear plant (~1200 MW?), shut down by public referendum in 1990.
The sun is rising, not setting, on solar energy.