Sustainable Energy

Lecture 13: Solar Energy

Characteristics of Solar Energy

- Tribal peoples have used passive solar for thousands of years.
- Current technologies provide 3 main ways to access solar energy:
  - Thermal energy or heat collected passively or actively for space conditioning buildings.
  - Thermal energy that is collected and converted into electricity in solar collectors/concentrators.
  - Direct conversion of solar energy to electricity using photovoltaic cells.

Resource Assessment

- About half of the incident energy on the earth's upper atmosphere reaches the surface of the earth.
  - 21% of this solar flux is direct radiation
  - 29% is scattered or diffuse radiation
- 40,000 EJ (37,920 quads) are incident on the US each year.
- Thermal energy recovery efficiencies range from 30-60%; photovoltaic systems 8-15%.
- Variables that effect the amount of available radiation are:
  - Latitude
  - Season
  - Day length
  - Cloud cover/weather

Insolation in the US

Table 13.1. Representative Monthly Values for Total (Direct Plus Diffuse) Insolation. Based on 30-Year Averages

Location	Latitude	Total (direct and diffuse) insolation on horizontal surface in Btu/ft^2 per day (Langleys per day)											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Albuquerque, NM	35°	1151 (312)	1454 (394)	1925 (522)	2344 (635)	2560 (694)	2757 (747)	2561 (694)	2387 (647)	2120 (575)	1640 (444)	1274 (345)	1052 (285)
Atlanta, GA	33.5°	848 (230)	1080 (293)	1427 (387)	1807 (490)	2018 (547)	2103 (570)	2003 (543)	1898 (514)	1519 (412)	1291 (350)	998 (270)	752 (204)
Bismarck, ND	47°	587 (159)	934 (253)	1328 (360)	1668 (452)	2056 (557)	2174 (589)	2305 (625)	1929 (523)	1441 (391)	1018 (276)	600 (163)	464 (126)
Boston, MA	42°	505 (137)	738 (200)	1067 (289)	1355 (367)	1769 (479)	1864 (505)	1860 (504)	1570 (425)	1268 (344)	897 (243)	636 (172)	443 (120)
Boulder, CO	39°	750 (203)	1030 (279)	1390 (377)	1750 (630)	1960 (531)	2160 (585)	2120 (575)	1890 (512)	1580 (428)	1200 (325)	830 (225)	670 (182)
Ithaca, NY	42°	434 (118)	755 (205)	1074 (291)	1322 (358)	1779 (482)	2025 (549)	2031 (550)	1736 (470)	1320 (358)	918 (249)	466 (126)	370 (100)
Los Angeles, CA	25°	890 (241)	1150 (312)	1520 (412)	1920 (520)	2030 (550)	2090 (566)	2260 (612)	2070 (561)	1670 (453)	1320 (358)	1000 (271)	820 (222)
Miami, FL	25°	1292 (350)	1554 (421)	1828 (495)	2026 (549)	2068 (560)	1991 (540)	1992 (540)	1890 (512)	1646 (446)	1436 (389)	1321 (358)	1183 (321)
Washington, DC	39°	632 (171)	901 (244)	1255 (340)	1600 (434)	1846 (499)	2080 (564)	1929 (523)	1712 (464)	1446 (392)	1083 (293)	763 (207)	592 (161)

1 Langley = 3.69 Btu/ft^2 = 41.86 kJ/m^2 = 1 cal/m^2

Source: Renne, Stovall et al. (2002).

Passive and Active Solar

- About 1/3 the energy we consume is used to heat and cool the buildings we live and work in.
- Solar thermal energy utilization in buildings involves one or more of the following technologies:
  - Passive thermal gain and reuse
  - Active solar heat capture using solar collectors
  - Direct or indirect day lighting
- Passive Solar systems
  - Adobe and Tombe walls – usually used on the south-facing side of the building; black or darkened surface.
  - Floor heat sinks can be used; concrete, brick floors, rock bins, etc.

Trombe Wall Design

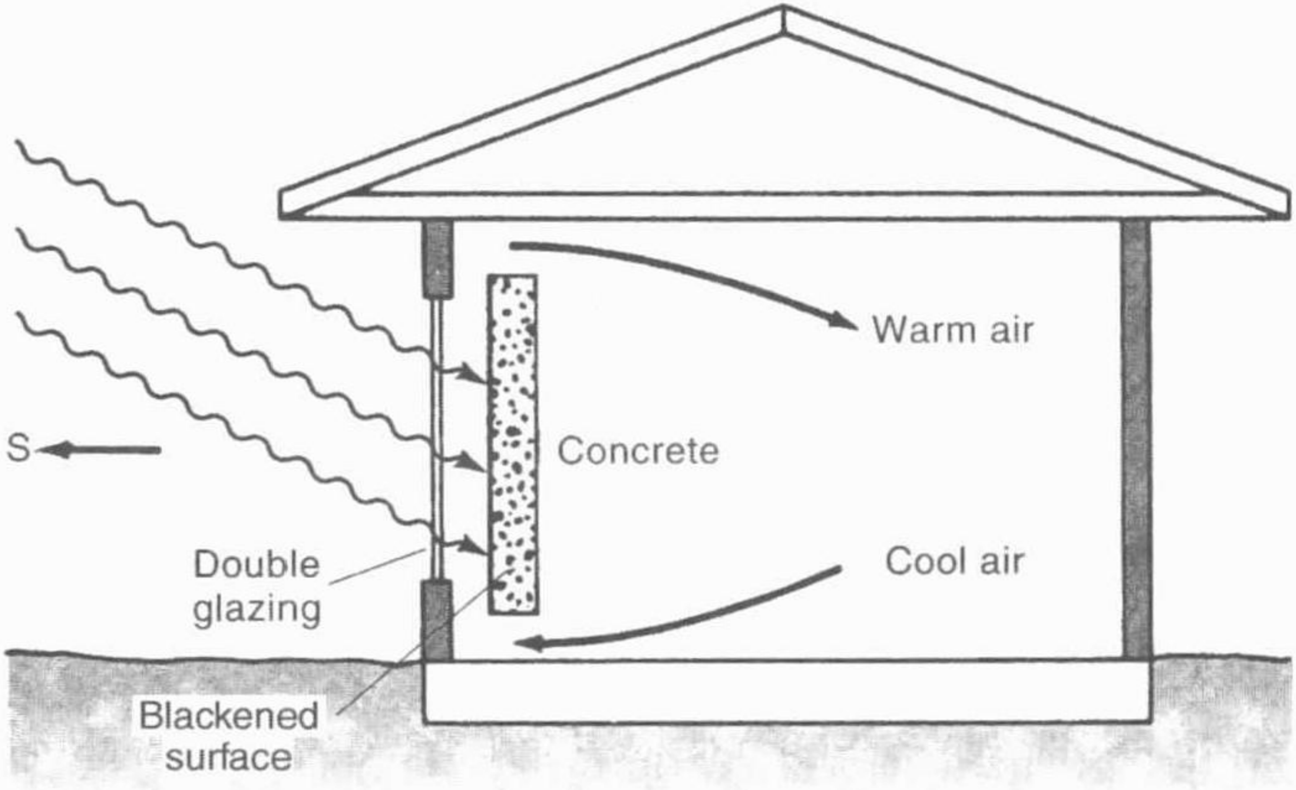


Figure 13.9. Schematic of a Trombe wall for passive capture of solar energy. Adapted from Hinrichs (1996). From *Energy* second edition by Hinrichs. © 1996. Reprinted with permission of Brooks/Cole, a division of Thomson Learning: www.thomsonrights.com.

Passive Solar Collector

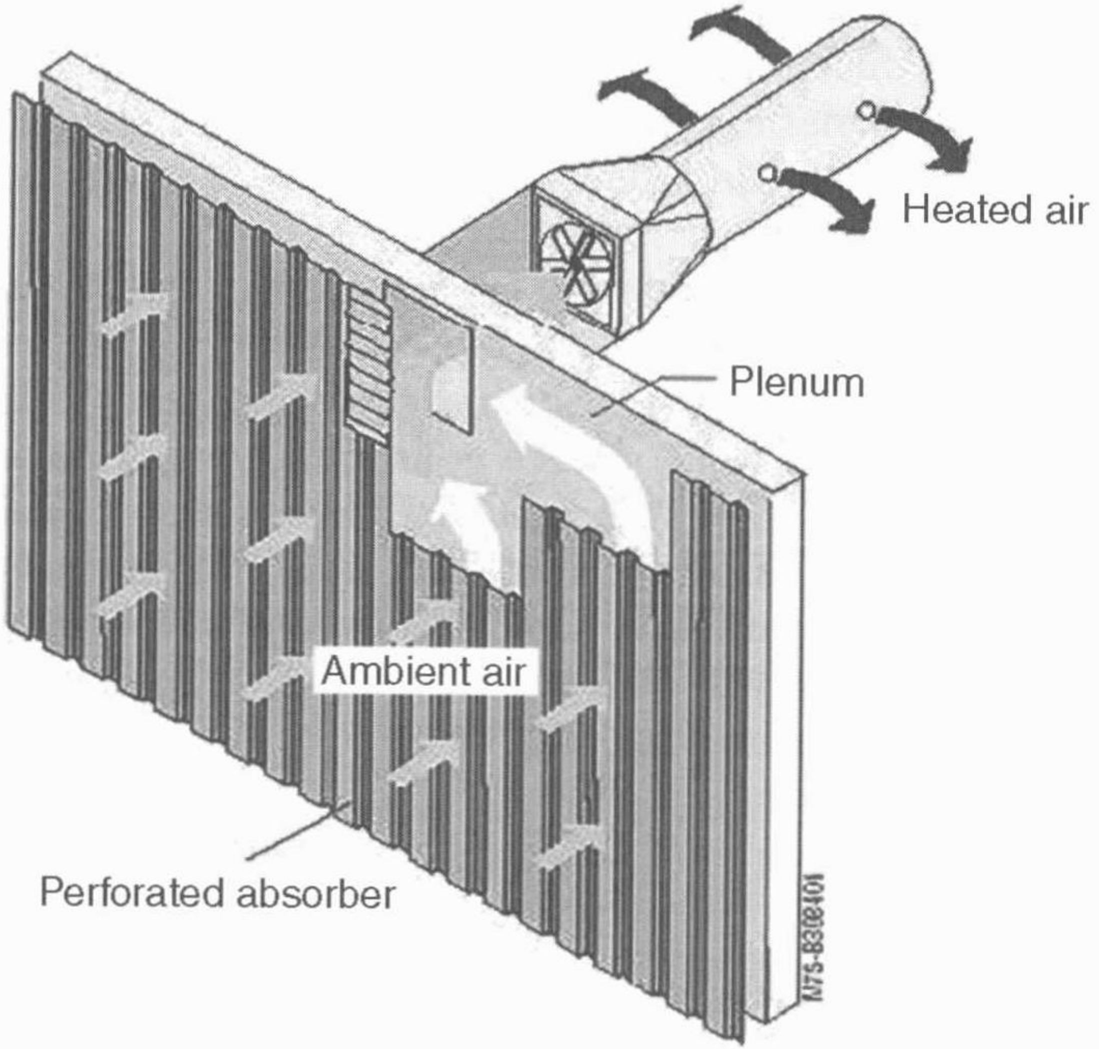


Figure 13.10. The NREL transpired passive solar collector configured as a vertical wall structure element. Source: Renne, Stovall et al. (2002).

Passive and Active Solar continued

- Active Solar Systems
  - Solar collectors are used with a fluid circulation system to capture the heat and move it to other areas of use.
  - Primary uses are water heating and space heating.

Active Solar Collector System

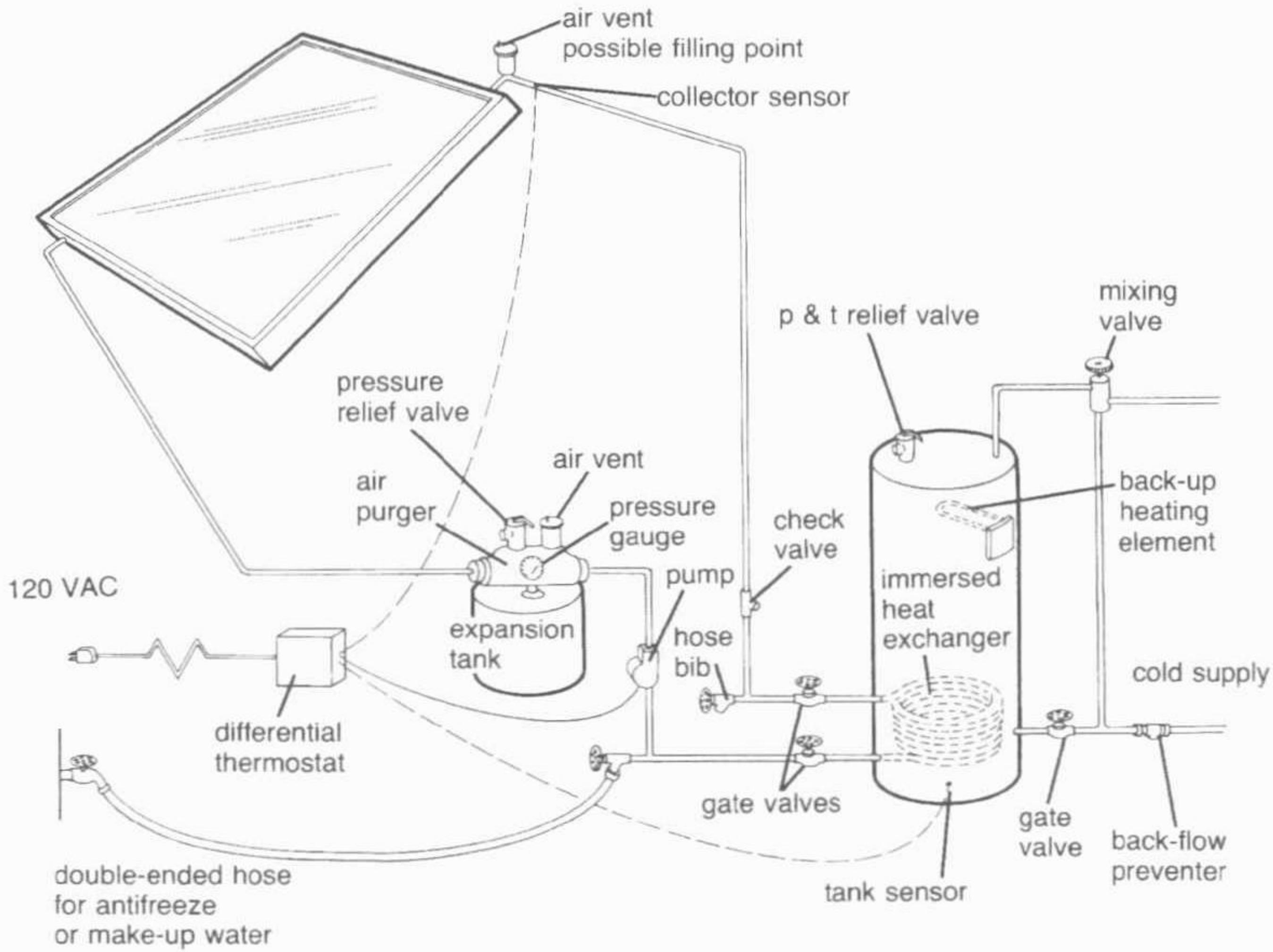


Figure 13.11. Typical active solar hot water system. Adapted from Keisling (1983).

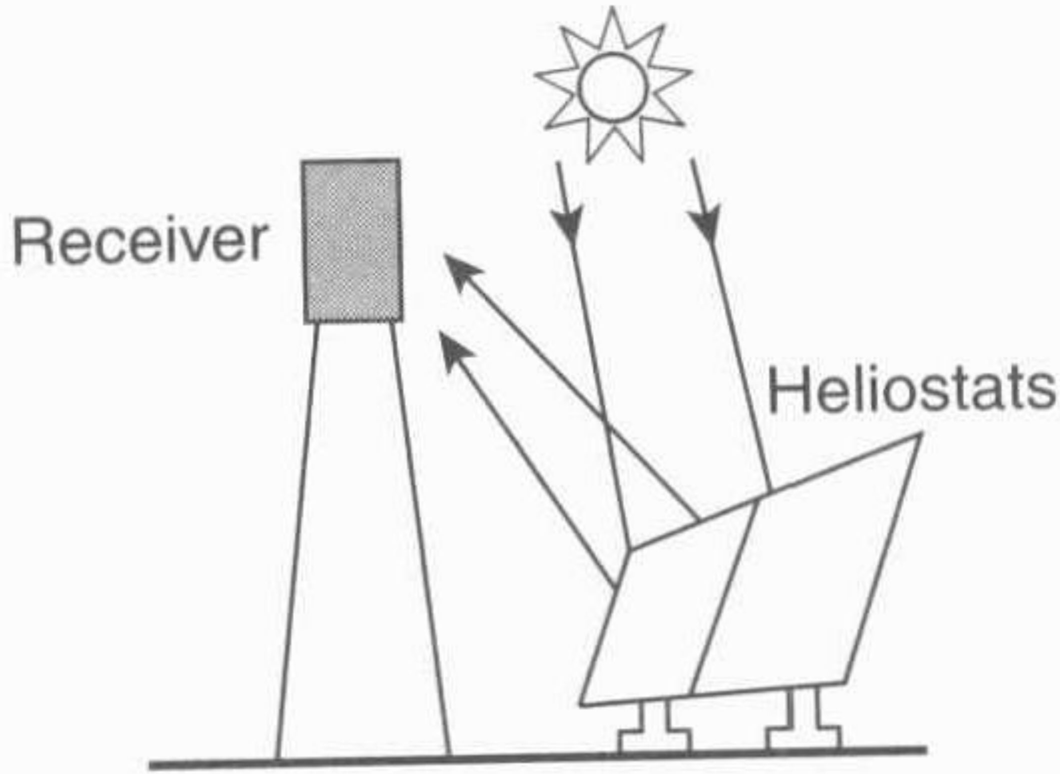
Solar Thermal Electric Systems

- **Three types of technologies are currently available:**
  - **Power towers**
  - **Trough systems**
  - **Dish-engine systems**
- **Current systems are primarily used for commercial power production.**
- **High-quality CSP systems are limited to arid desert or semi-arid regions at lower latitudes near the equator.**
  - **Low cloud cover**
  - **Low atmospheric moisture levels**
  - **Year-round insolation level is high**

Solar Thermal…continued

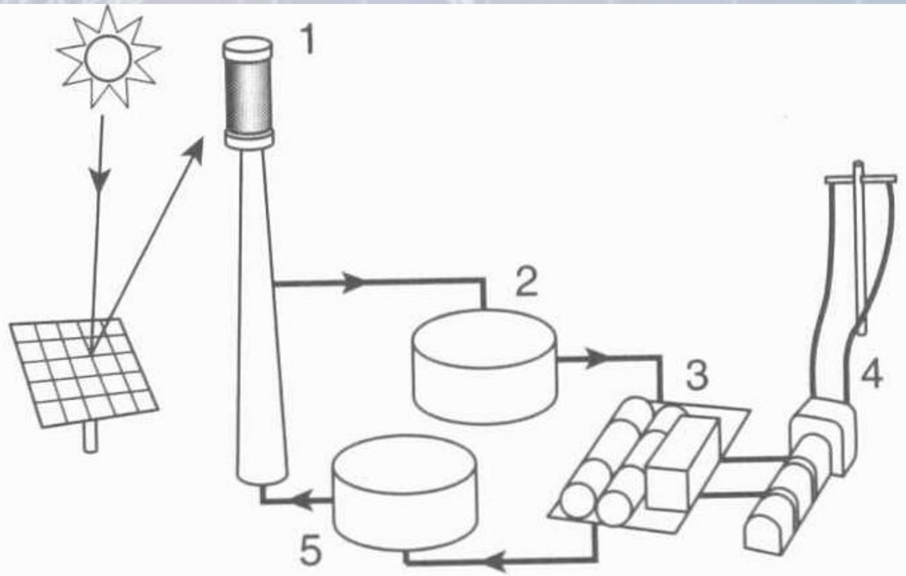
- Power Tower systems
  - Mirrors or heliostats focus the sun’s energy on a centrally located receiver.
  - Energy is absorbed using a high-temperature working fluid (often a molten salt).
  - A Rankine cycle steam turbine is used for electric production.
  - Estimated commercial power costs for towers is about 8 cents/kWh; capital investments of $3000-4,000/kW is projected.
  - These costs will require substantial public support to be competitive.
- Parabolic Troughs
  - Trough concentrators reflect sunlight off a linear, parabolic mirror surface and focus it onto an absorber tube.
  - A working fluid is used to absorb the heat (water or oil).
  - Conventional Rankine cycle stream is used to produce electricity.
  - Overall efficiencies are about 12% with these systems.
  - These systems require considerable area; a 100 MW plant would have to be 0.5 square km.
  - Cooling water demands are high; 1.5 million cubic meters/year; a major issue in desert locales.

Power Tower System



Large sun-tracking mirrors, called heliostats, focus the sun's energy on a receiver located atop a tall tower.

Power generation/power tower



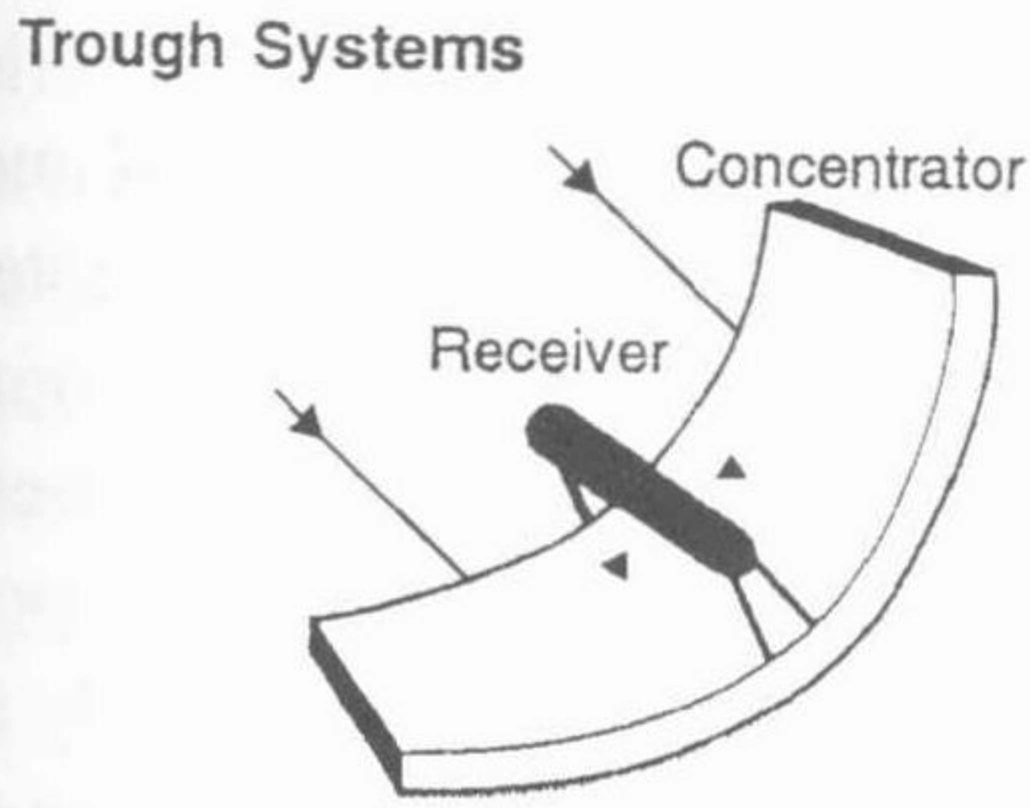
Schematic of electricity generation using molten-salt storage:

1) sun heats salt in receiver;
2) salt stored in hot storage tank;
3) hot salt pumped through steam generator;
4) steam drives turbine/generator to produce electricity;
5) salt returns to cold storage tank to be reheated in the receiver.

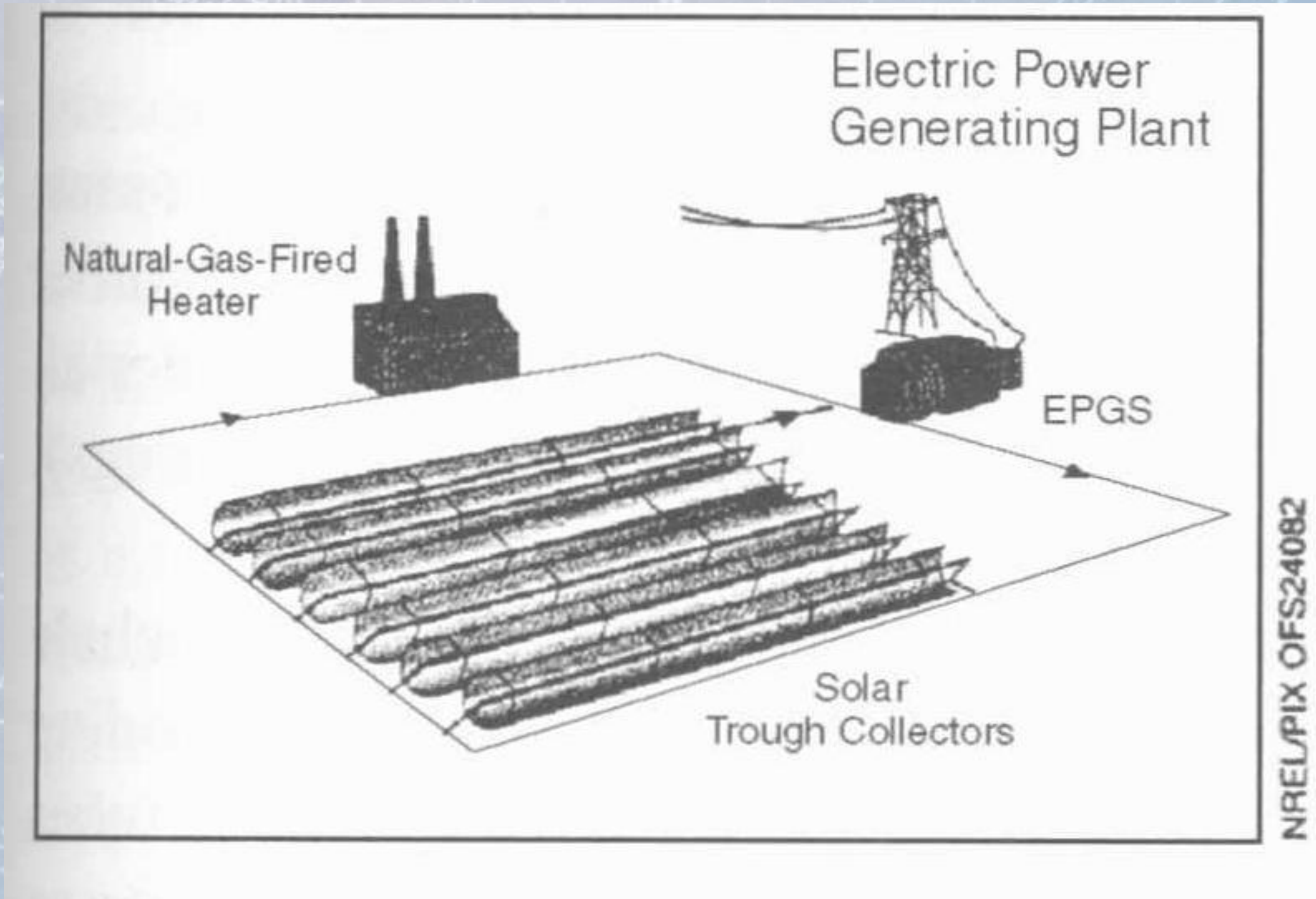
Trough systems continued

- **Commercial trough systems are operating:**
  - **Luz solar electric generating system plants (SEGS) are from 14-80 MW (9 plants).**
  - **Original Luz plants cost $6000/kW; today's costs are estimated at $3000/kW or less.**
  - **Luz went bankrupt in 1991 but the SEGS plants continue to operate under new ownership.**
- **Dish engine systems**
  - **Parabolic dish receiver-heat engine generator.**
  - **The systems have high concentration ratios and absorber temperatures tend to be higher than troughs or towers (600-1500 C).**
  - **Sterling cycle engines can be mounted at the focal point that use air as the working fluid.**
  - **Efficiencies approach 30% on these systems....higher than the other technologies discussed so far.**
  - **Gas-fired backup systems can be used to provide heat for the Stirling engine when solar energy is not available.**
  - **Size of these systems is from 5-50 kW**

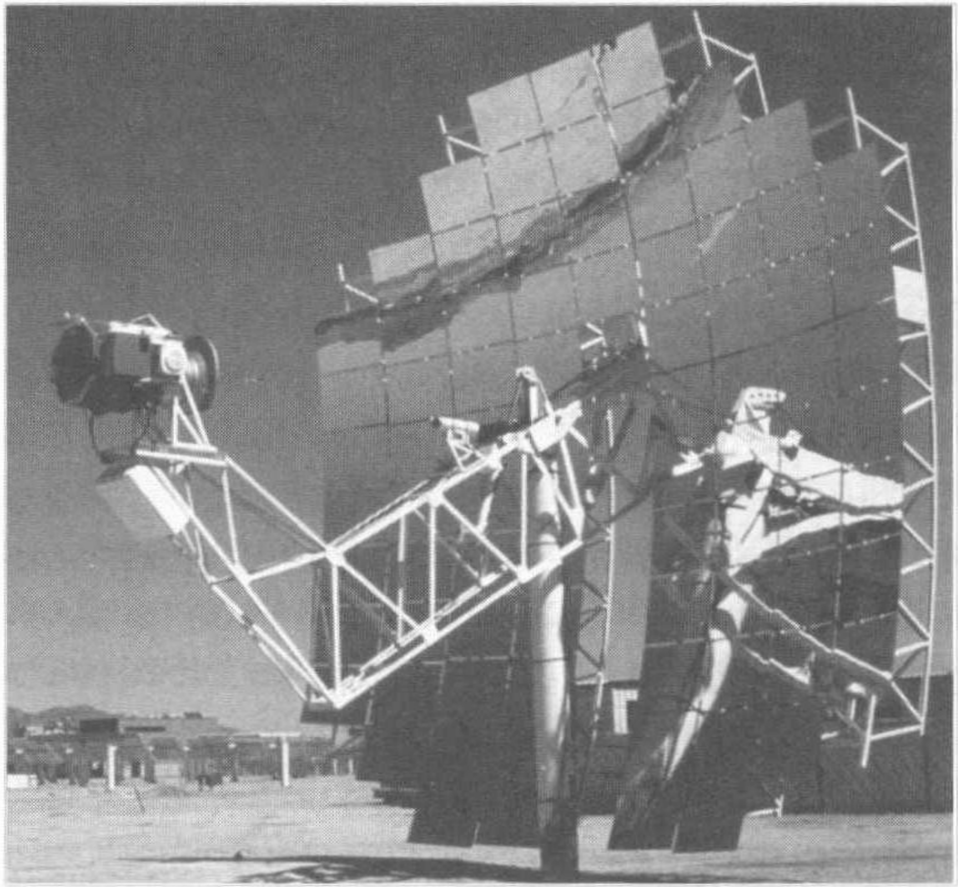
Trough System



(a) Schematic of trough concentrator


Electric Power
Generating Plant
Natural-Gas-Fired
Heater
EPGS
Solar
Trough Collectors
NREL/PIX OFS24082

Parabolic Dish Engine



(b) Boeing/Stirling Engine Systems 25 kW parabolic dish engine prototype (ca. 2002).

Solar Power Characteristics

Table 13.2. Summary of Operating Characteristics and Estimated Costs for Concentrating Solar Power Technologies

			Operating Characteristics			
CSP technology	Concentration ratio	Tracking requirement	Operating temperatures	Average solar to electric efficiency	Unit size range	Status
Power Towers	500–1,000	2-axis heliostats	400– 600°C	12–18%	30–200 MWe	Demonstration and testing at 10 MWe scale
Parabolic Troughs	10–100	1-axis reflector	100– 400+ °C	8–12%	30–100 MWe	20 years operating in California
Dish-Engines	600–3,000	2-axis	600–1,500°C	15–30%	5–50 kWe	Prototypes tested at 25 kWe or less for limited periods

Solar Power Costs

Estimated Costs[a]

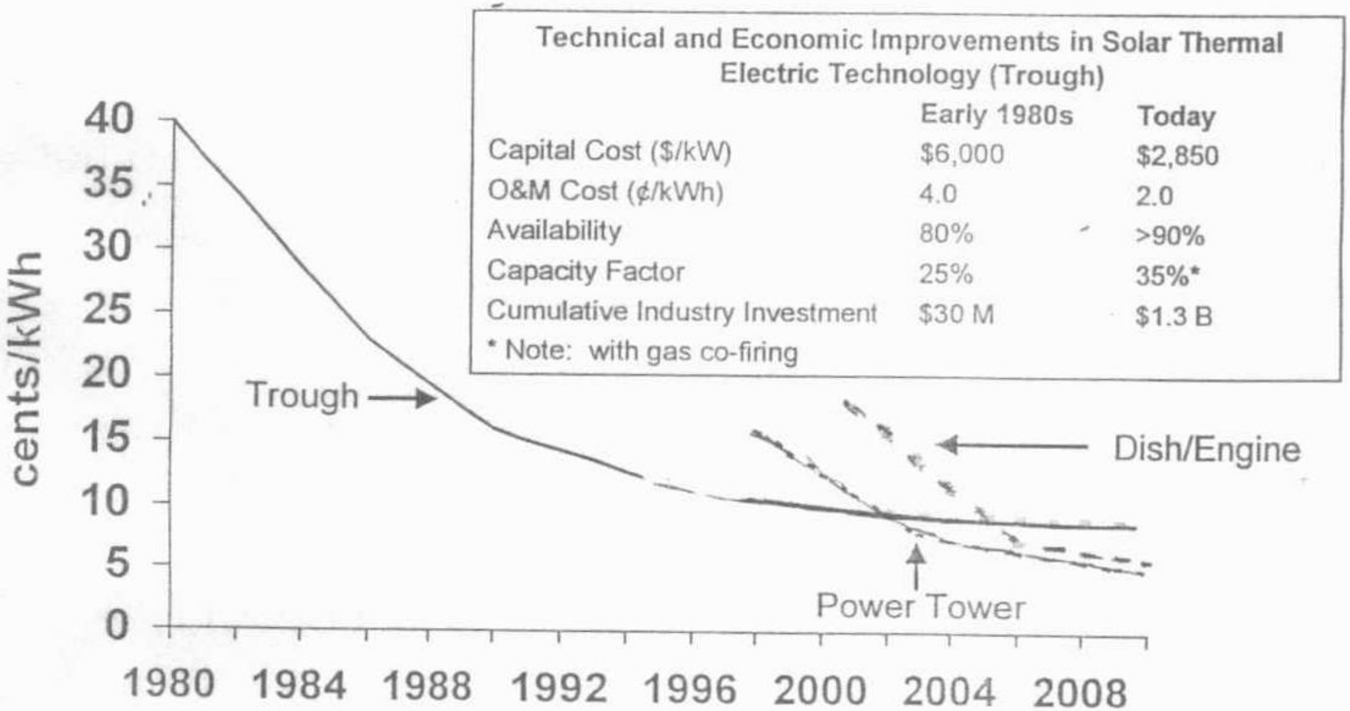
CSP technology	2002 capital costs $/kW	2010+ capital costs $/kW	O&M costs ¢/kWh	2002 levelized electricity cost ¢/kWh	2010+ levelized electricity cost ¢/kWh	Uncertainty
Power Towers	4,000	2,500	0.7	5–9	3.5–5[b]	moderate
Parabolic Troughs	4,000	2,500	1.0	7–11	6–9	low
Dish-Engines	3,500	1,500	2.0	9–13	4–6	moderate

(a) in 2002 US$; see www.eere.energy.gov/solar/ for current updates

(b) low estimate assumes municipal investment and high assumes private investment

Sources: SunLab (1998), US DOE (1996), Butler (1997, 2002), DeLaquil et al. (1993).

Solar Power Cost Projections



Technical and Economic Improvements in Solar Thermal Electric Technology (Trough)

	Early 1980s	Today
Capital Cost ($/kW)	$6,000	$2,850
O&M Cost (¢/kWh)	4.0	2.0
Availability	80%	>90%
Capacity Factor	25%	35%*
Cumulative Industry Investment	$30 M	$1.3 B

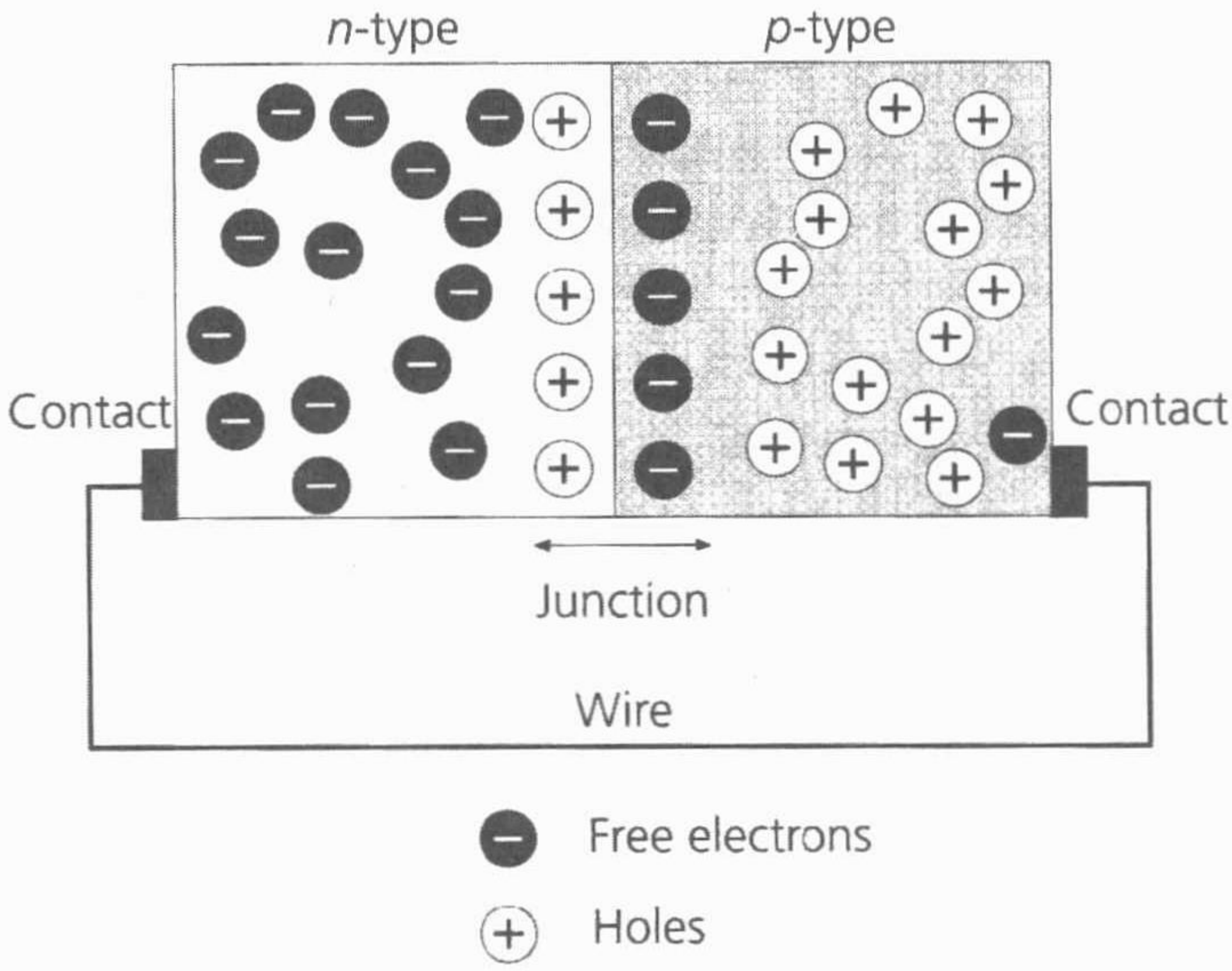
* Note: with gas co-firing

Figure 13.17. Actual and projected levelized electricity costs for concentrating solar power technologies in 2000 US$. Sources: SunLab (1998) and US DOE (1996).

Solar Photovoltaic Systems

- There are several types of PV cell systems:
  - Silica based systems
    - Polycrystalline modules
    - Non-crystalline amorphous silicon
  - Copper indium diselenide (CIS)
  - Cadmium telluride (CdTe)
- Since the mid-1970's installed costs for rooftop flat plate PV systems have dropped from $30,000/kW to less than $7000/kW.
- Costs today are being lowered and solar PV panels are being used in more commercial buildings and residential applications.

Photovoltaic Cell Design



PV Cell Efficiencies

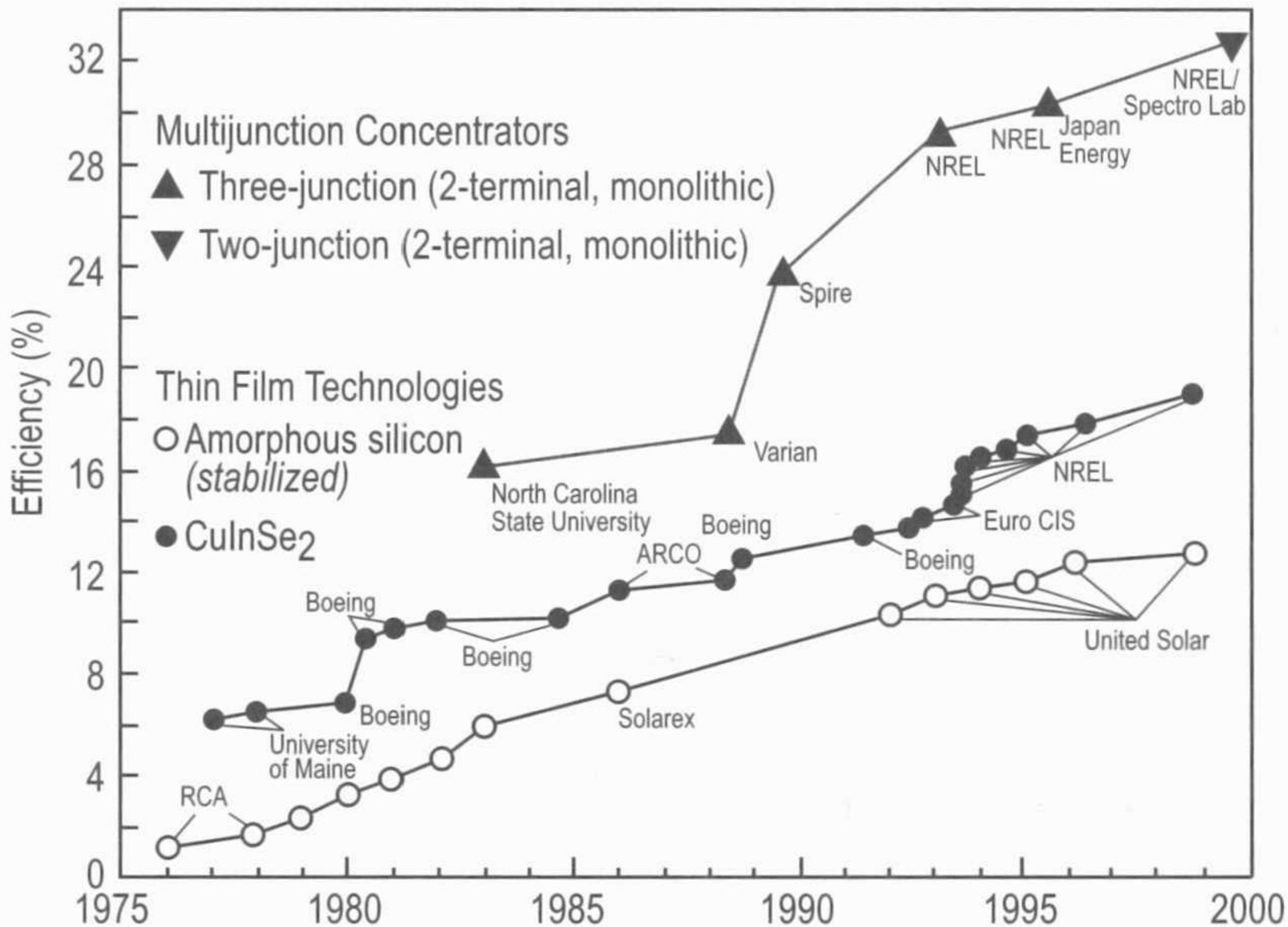


Figure 13.20. Thin film and multi-junction photovoltaic cell efficiencies. Source: NCPV (2002).

Sustainability Attributes

- Solar power is flexible and offers a range of scale for many applications….from home use to commercial power generation.
- PV cell manufacture uses toxic metals that have considerable negative environmental impacts from mining, refining, and processing.
- Thin film PV technologies have reduced the amount of materials used in the manufacture of the cells.
- Land use for large-scale solar electric installations is significant. A CSP plant would need 20 square miles to produce as much power as the Hoover Dam.
- Capital costs of solar systems is high compared to fossil fuel plants.
- Solar systems have a small carbon footprint.
- CSP methods could be used to provide carbon-free power at reasonable prices on a large enough scale to make a difference. This might be important in desert areas of the US and other countries.