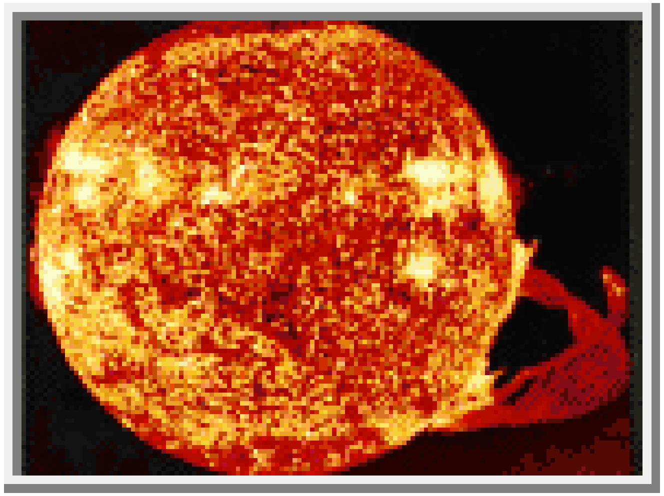
SOLAR ENERGY



- **Sun** - largest object in our solar system; outer visible layer called photosphere has temperature of 6,000 C

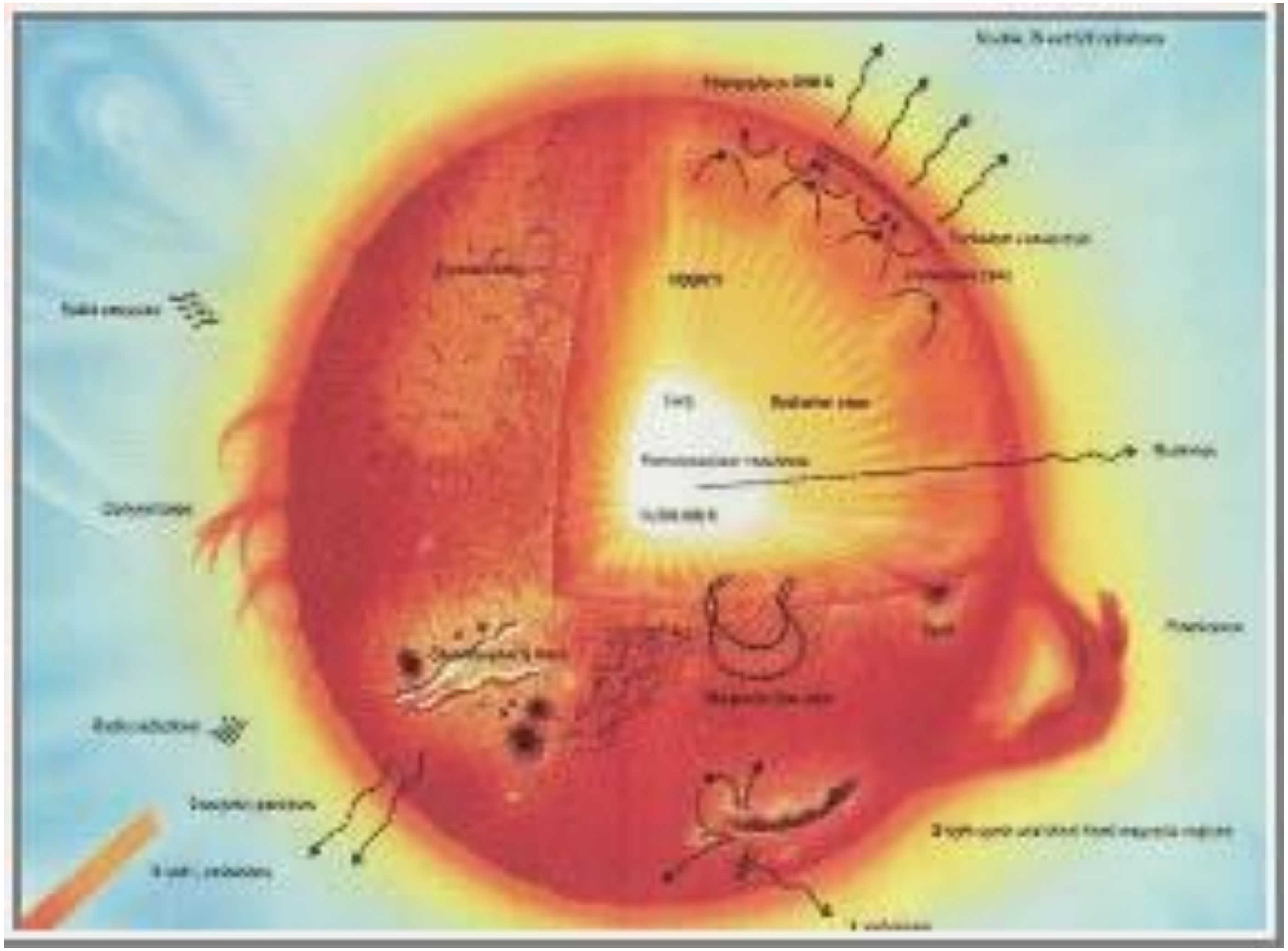
- Sunlight or solar energy - main source of energy for **wind**, **hydro, ocean** and **biomass.**

Solar energy has potential of supplying all our energy needs for: electric, thermal, process, chemical and even transportation; however, it is very diffuse, cyclic and often undependable because of varying weather conditions.

Topics - Solar Energy

- Solar Energy, Its Uses, Origin and History
- Solar Radiation Maps and Land Area
- Solar-Electric Technologies (Types, Principle)
- Theoretical Efficiency of PVs
- Other Solar-Heat Technologies (Passive, Active)
- Cost of Solar PVs and Solar-Thermal Power
- Applicability, Advantages, Disadvantages
- Environmental Impact & Risks

Cross-Section of Sun



Origin of Solar Energy

- Solar energy is created deep within the core of the Sun, where nuclear reactions cause four protons or hydrogen nuclei to fuse together to form one alpha particle or helium nucleus. The alpha particle is about 0.7% less massive than the original four protons.
- Difference in mass is expelled as energy and carried to the surface of Sun where it is released as light and heat.
- Energy generated in the Sun’s core takes a million years to reach its surface.
- Every second, 700 million tons of hydrogen are converted to helium ashes, releasing 5 million tons of pure energy; the Sun becomes lighter as time goes by.

How Long Will the Sun Last?

- Sun appears to have been active for 4.6 billion years and has enough fuel for another 5 billion years or so.
- At the end of its life, the Sun will start to fuse helium into heavier elements and begin to swell up, ultimately growing so large that it will shallow the Earth.
- After a billion years as a red giant, it will suddenly collapse into a white dwarf – the final end product of a star like the Earth.
- It may take a trillion years to cool off the spent Sun completely to Earthly levels.

History of Solar Energy

- **Solar energy -** used for millenia for passive heating of dwellings as shown by archaeological sites around the world.
- ***1874*, solar distilling plant -** installed in a desert in northern Chile to produce 25 m^3/day of fresh water for a nitrate mine for about 40 years.
- ***1878*, solar-to-mechanical conversion -** first demonstrated in Paris when sunlight was concentrated by a focusing collector on a steam boiler that powered a small steam engine that ran a small printing press.

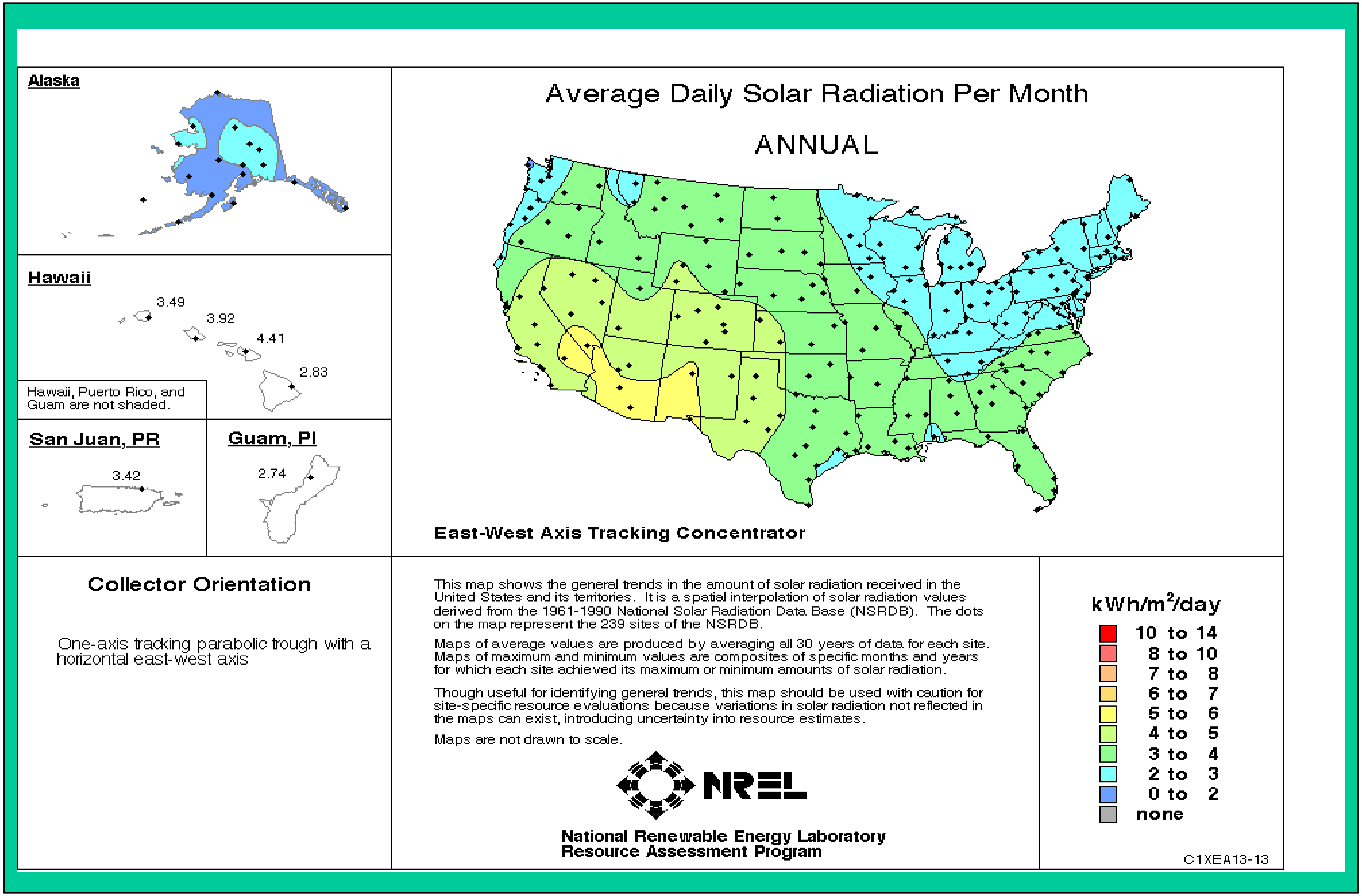
History of Solar Energy (2)

- ***1913*, F. Shuman -** built a 50-hp solar steam engine using a *long parabolic collector* that focused solar radiation onto a central pipe to irrigate water from the Nile.
- ***1915*, J. A. Harrington –** made a solar-electric conversion and energy storage system by by focusing sunlight on a boiler that ran a steam engine that *pumped water* into a 19 m^3 tank 6m above; water stored was released to a *water turbine* that powered an *electric generator* that lighted a small mine.
- ***1958*, photovoltaic electricity -** was first generated to power a radio transmitter on the Vanguard space satellite.

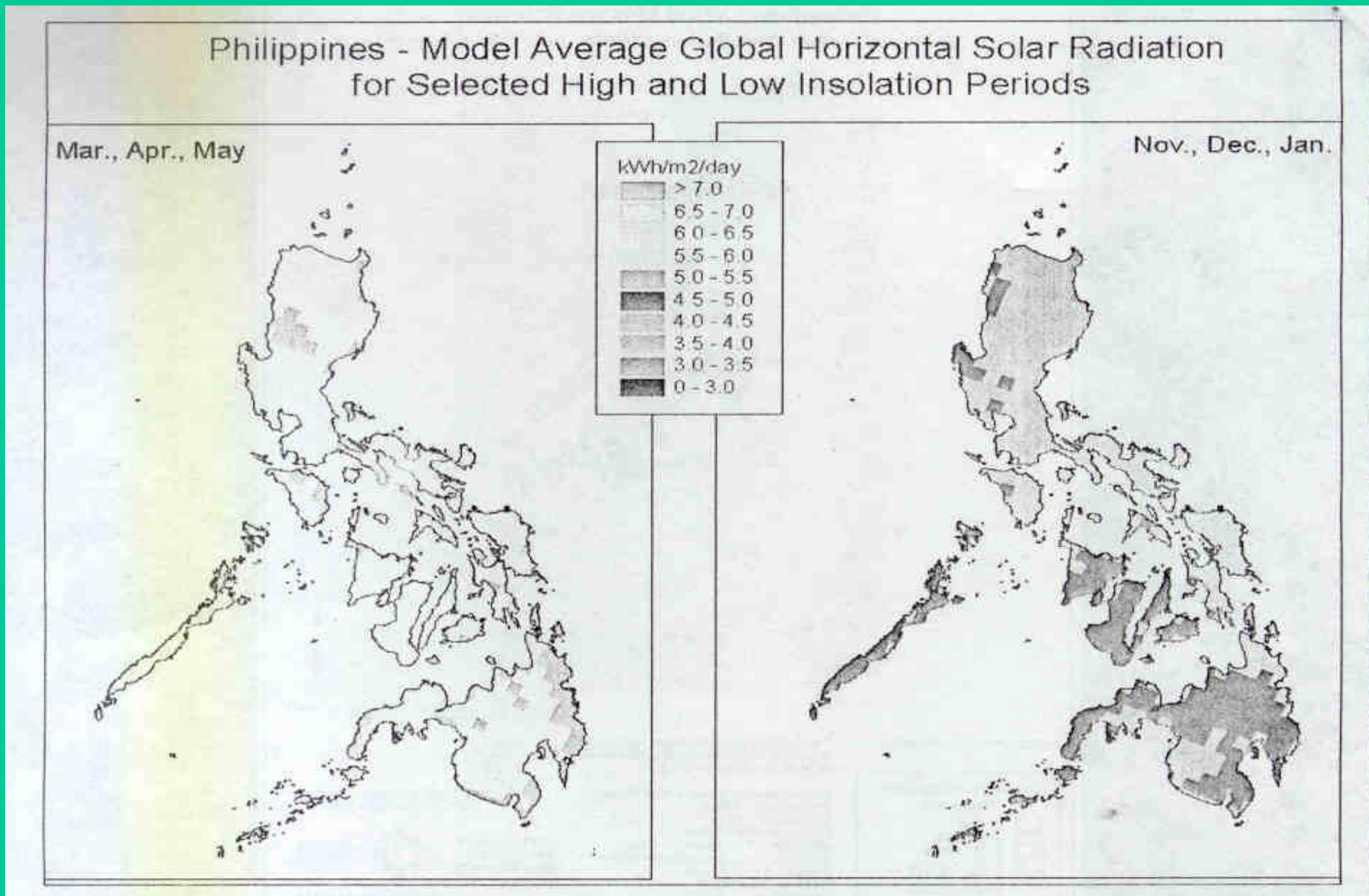
History of Solar Energy (3)

- ***1985*, Solar Electric Generating Systems -** 9 solar trough power plants in the Mojave Desert operated with a total capacity of 354 MW and efficiency of 16-18%.
- ***1982-1988*, Solar One -** 10 MW demonstration plant in Barstow, California used water as fluid to generate steam in driving a turbo-generator
- ***1996*, Solar Two -** cannibalized from *Solar One;* used molten salt as fluid which could be stored and used later to boil water into steam when power was needed; plant could store 30,000 kWh at 10 MW capacity.
- ***1981*, P-40 Stirling Cycle engine -** fluid air heated up to 816 C and equipped with fossil burners produced 25 kWe at conversion efficiency of 24-35%.

Resource Potential – Radiation Maps



Philippine Solar Radiation Map



Terrestrial Solar Radiation

- Solar energy falling on the Earth's surface is called ***terrestrial radiation*** **S = 1.353 kW/m**^{2}**.**
- Solar energy is 7% ultraviolet light, 47% visible light and 46% infrared.
- Varies significantly, both **daily** because of the Earth's rotation and **seasonally** because of the change in the Sun's declination angle.
- Radiation is further reduced due to presence of gases, vapors and particulate matter in the Earth's atmosphere

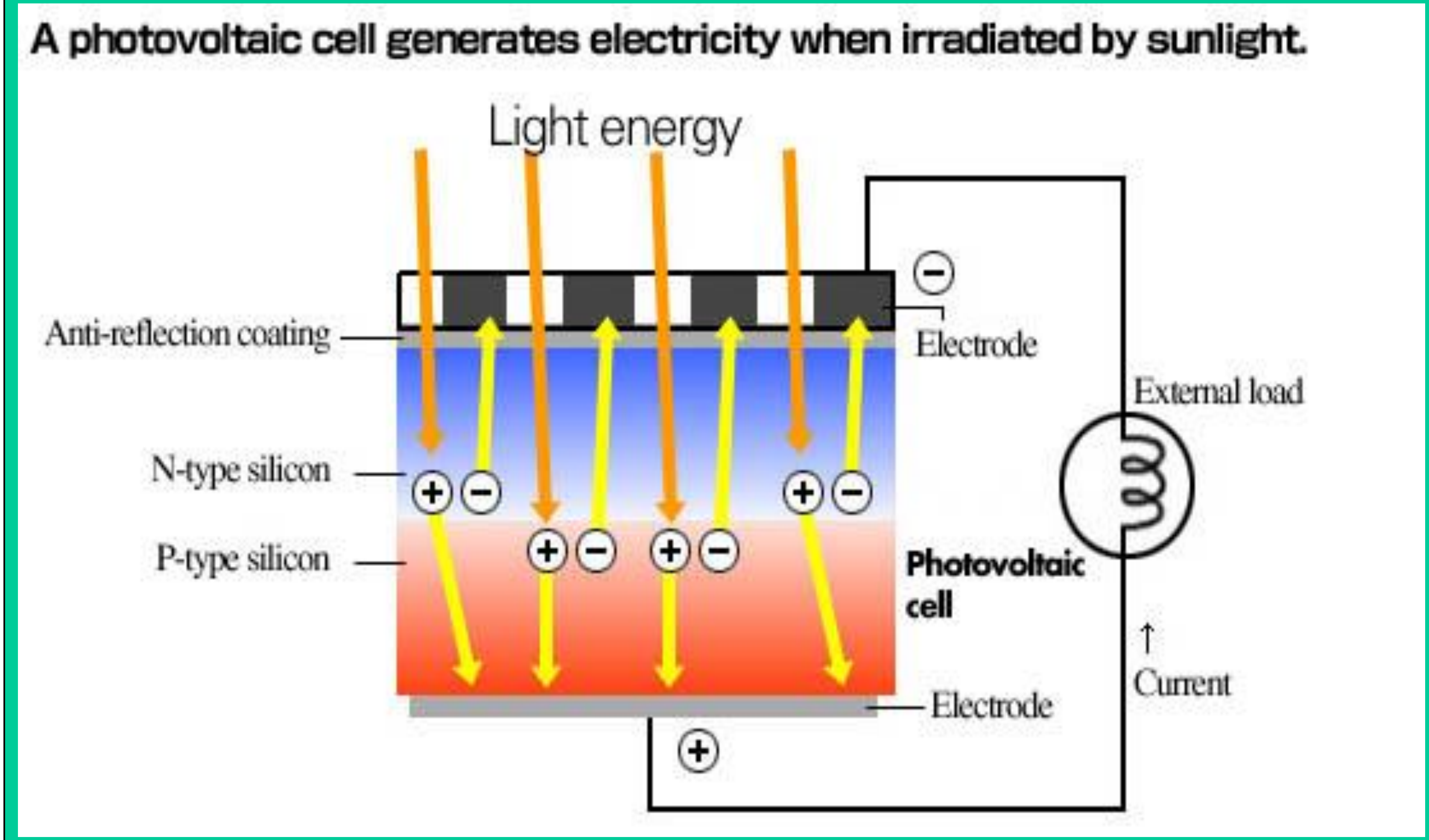
Land Area Requirements

- Amount of energy received from the Sun by the Earth each year is 15,000 times the world's annual power consumption.
- Less than 1% of the world's land area would provide sufficient energy to meet global electricity demand.
- Based on expected solar energy input of 2,725 $kWh/m^2/year$ and assuming 10% conversion efficiency, around 10 million ha of land would generate enough electricity to supply the entire US for a year.
- Solar electricity generation takes up less land than most hydropower projects when we include the reservoirs.
- Land requirements of some hydro schemes can be as much as 50 times a typical solar project yielding the same output (WB).

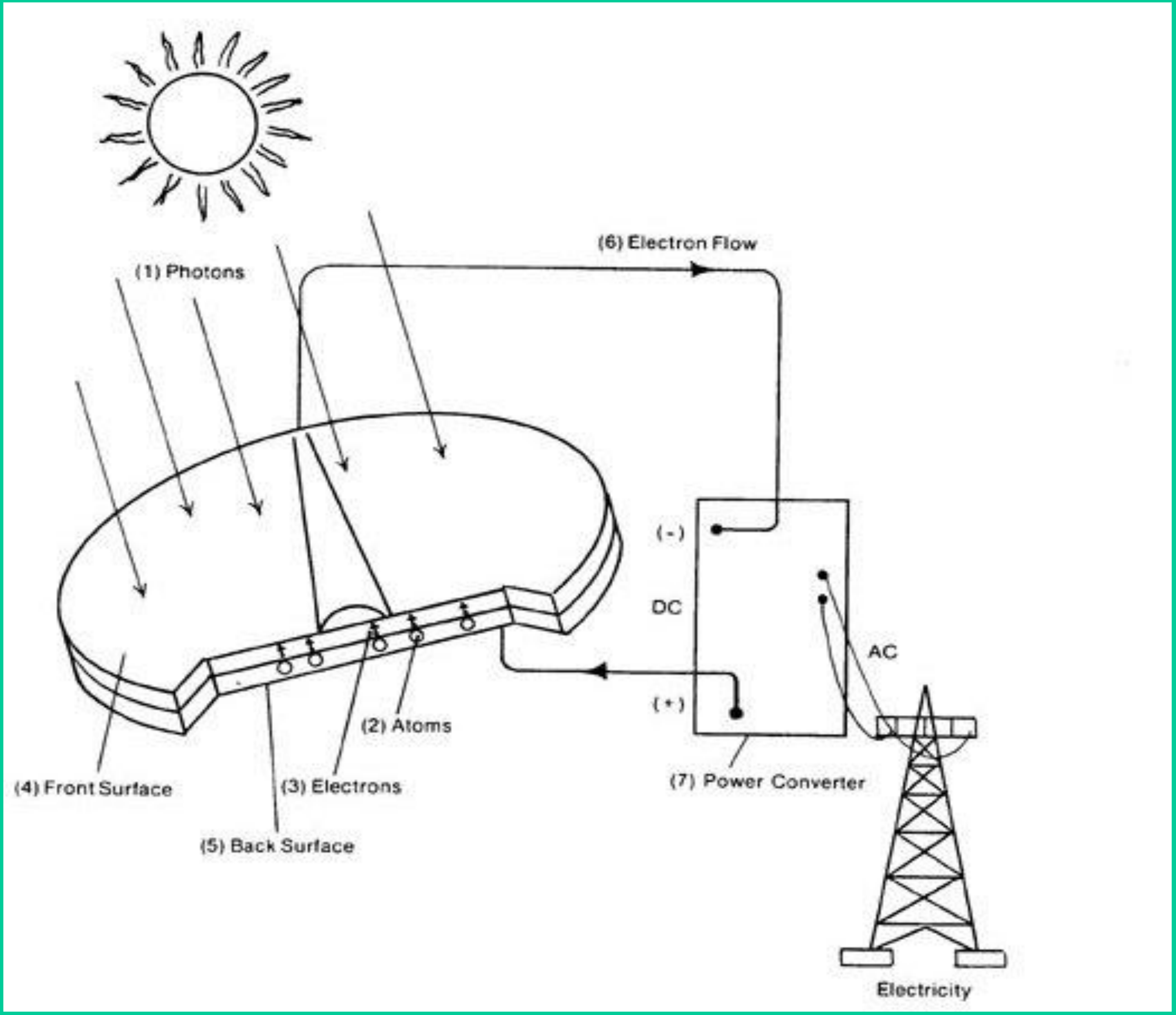
Solar PV Technologies

- **Solar cells -** microchips and transistors fabricated from silicon crystals
- Directly convert sunlight into electricity by means of semi-conducting materials without the benefit of a thermodynamic cycle or working fluid
- Cells produce low currents and voltages and are combined into modules, panels and arrays to meet power demand.

Photovoltaic Principle



Photovoltaic Power Plant Diagram

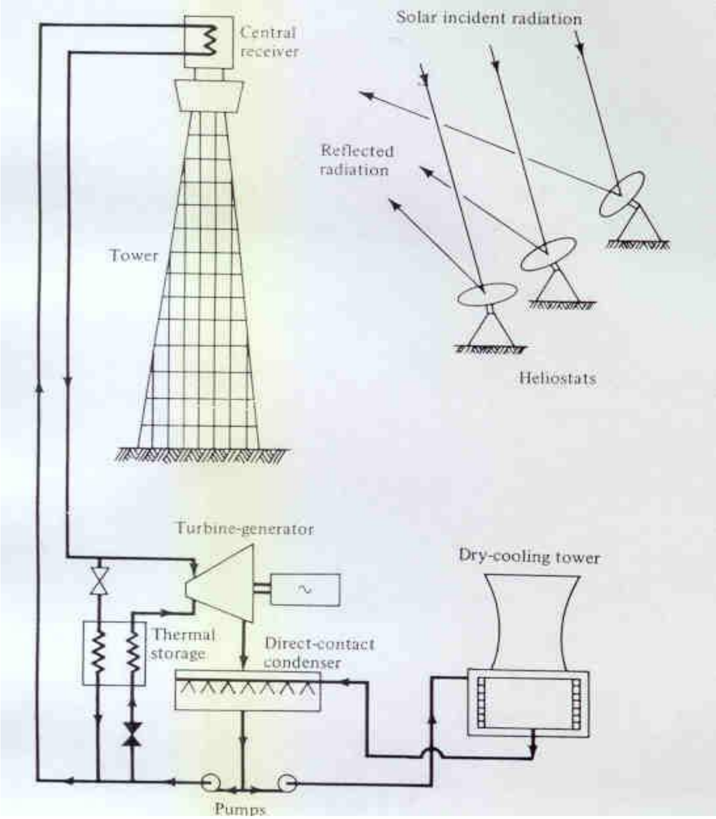


Solar-Thermal Technologies

- **Reflective materials -** such as mirrors collect and concentrate the Sun's energy onto a central receiver that contains a working fluid of a thermodynamic cycle such as the Rankine or Brayton cycles and hybrid systems
- **Types of receivers -** central receivers, dispersed or distributed receivers (point and line focus) and salt ponds
- **Main types -** solar trough, solar tower, solar dish and solar salt pond

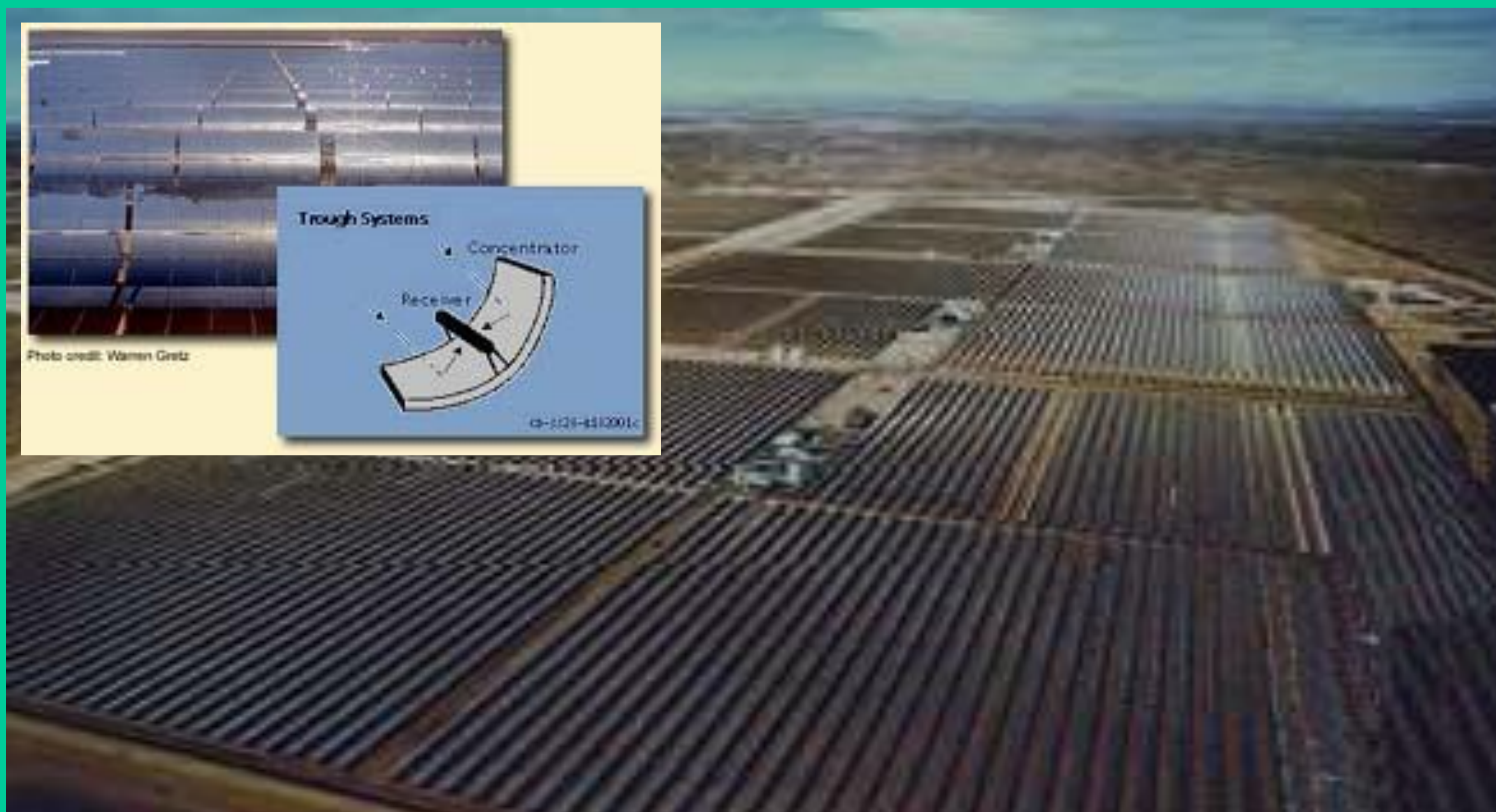
Examples of Solar Technologies

Photovoltaic (PV) Solar Cells



Solar-Thermal Central Receiver (Solar Tower)

Solar Trough



354-MW nine Solar Electric Generating System (SEGS)

Solar Tower

10-MW Solar One Power Plant, Barstow, California

Solar Dish

25-kW Dish-Stirling System (Boeing)- Hydrogen/Helium

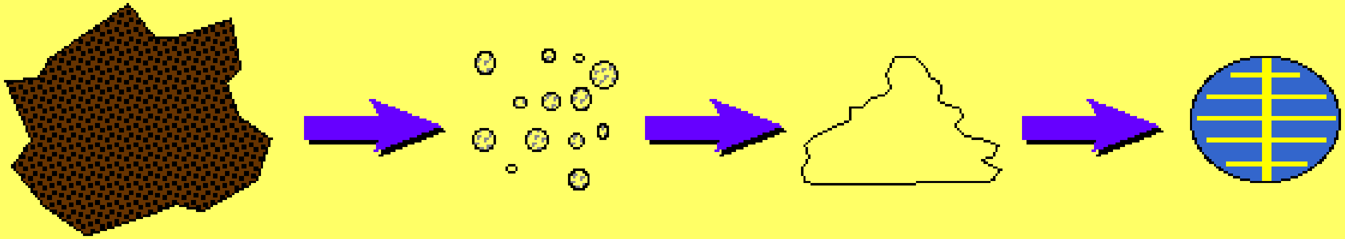
10-kW Solar Dish Water Pumping System (WG Ass.)

Solar Salt Pond

Salinity Gradient Solar Pond (SGSP), El Paso, Texas; the bottom temperature could go as high as 100 C to heat a working fluid to generate power and desalinate water; top layer serves as condenser. It generates 300 kW plus 16,000 liters/day of desalinated water.

Types of Solar Cells (PVs)

- **Single crystal silicon**: the first PV used were of this type; gross conversion efficiency of 24%; very expensive



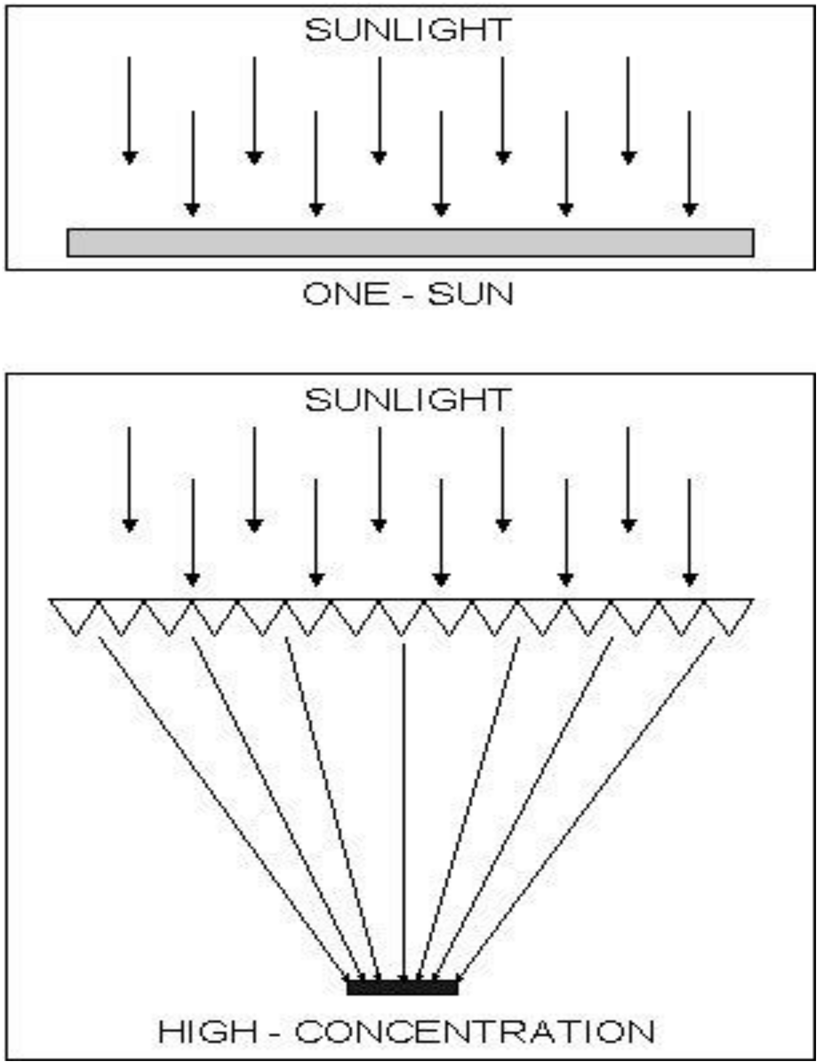
- **Possible cheaper alternative materials:**
  1. polycrystalline silicon - 18% gross efficiency
  2. amorphous silicon - 12% gross efficiency
  3. thin films, e.g. copper indium diselenide (18% gross efficiency)

Integrated High-Concentration Photovoltaic (IHCPV) Systems

A 25-kW IHCPV System

Utility-scale solar generating systems have to be competitive. Key is in reducing the cost of the silicon solar cell by concentrating the Sun's rays thru cheap plastic *Fresnel* lenses to focus in a smaller PV cell. Energy captured is 30% more, efficiency is 18% to 26.5% higher and cell area reduced by over 250 times.

Principle of IHCPV System



Solar cells become very inefficient when exposed to concentrated sunlight. EPRI thru Amonix solved the solar cell stabilization problem by developing **back-junction point-contact** silicon solar cell in 1989. Inexpensive flat plastic *Fresnel* magnifying lenses focus and concentrate sunlight 250 times onto a small expensive silicon cell. With tracking, 30% more energy is captured. Has possibly the lowest levellized cost ($/kWh) of solar PVs.

Theoretical Efficiency of PVs

Ideal spectral solar energy utilized by silicon cells.

Wavelength range micrometer	Solar energy %	Converted by cell, %	Solar energy Converted, %
< 0.3	0	0	0
0.3 - 0.5	17	36	5
0.5 - 0.7	28	55	15
0.7 - 0.9	20	73	15
0.9 - 1.1	13	91	12
> 1.1	22	0	0
Total			48

Other Solar-Heat Technologies

- **Passive solar heating, cooling and daylighting –** buildings incorporate design features such as large south-facing windows and building materials that absorb and slowly releases the Sun's heat to reduce heating and lighting costs; design also includes natural ventilation for cooling
- **Solar hot water, space heating and cooling –** solar water heaters use the Sun to heat either water or a heat-transfer fluid in collectors; high-temperature solar water heaters can provide energy-efficient hot water and heat for large commercial and industrial facilities.

Solar Photovoltaic Costs

- Average annual solar radiation in the US is 1,800 kWh/m^2 or 4.9 kWh/m^2/day.
- Solar cell module at 10% conversion efficiency would generate 180 kWh/m^2/year.
- Assuming a 30-year lifetime, total output is 5,400 kWh.
- At 10% internal rate of return, this photovoltaic system would become commercially attractive if the solar converter costs less than \$150/m^2.
- Current costs in the US for installed solar cell based systems are more likely at \$600/m^2.
- Its applicability to remote sites make it the next cost-effective alternative of providing electric power.

Balance of Plant Equipment

- DC-to-AC converters and step-up transformers are needed to connect the PV system to the grid which requires high voltage and alternating current.
- Solar cells and solar thermal plants must be kept clean since dust will reduce performance, so facilities for cleaning must be included.
- Aside from PV modules, other components are: mounting structures, sun tracking devices, batteries, power electronics (inverter, charge controller) and grid interconnection.
- NREL (1997) puts the cost of solar modules at $\$440/m^2$ or \$4,000/kW plus balance of plant equipment at $\$250/m^2$ or \$2,500/kW.

Cost of Solar-Electric Power

- The EIA estimates the cost of solar photovoltaic (1996):

Resource type	Intermittent, predictable
Capacity factor	16 – 30 %
Real levelized cost (1998 $)	17 – 21 cents / kWh
Overnight capital cost	$3,135 / kW
Fixed O&M costs	$0.097 / kW / year
Variable O&M, $/kWh	nil
Efficiency, %	12 - 24

- For solar thermal systems:

Construction lead time	0 – 2 years
Real levelized cost (1998 $)	2 - 13 cents / kWh
Overnight capital cost	$2,060 / kW
Fixed O&M costs	$0.046 / kW / year
Variable O&M, $/kWh	nil

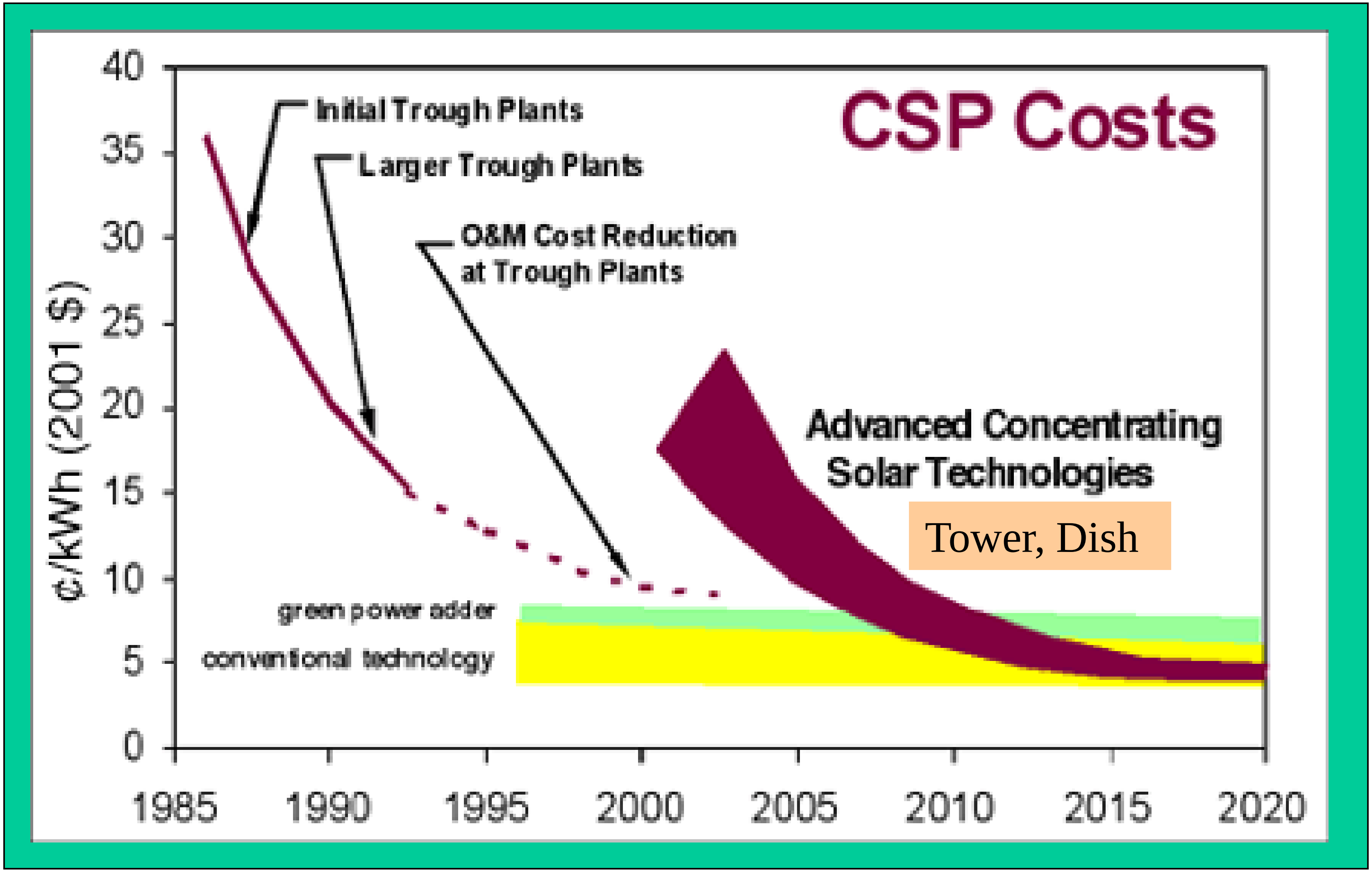
Cost of Solar-Thermal Power

The National Renewable Energy Laboratory (NREL) of the US DOE lists the overnight capital cost, fixed O&M and levelized energy cost (LEC) and efficiency of 3 solar thermal technologies as follows (1996):

	Capital $/kW	Fixed O&M $/kW/year	LEC $/kWh	Efficiency %
Solar trough	2,900	1.0	0.11	16-18
Solar tower	2,400-2,900	0.7	0.09	
Solar dish	2,900	2.0	0.13	24-35
Solar pond				

Around 9 solar troughs totaling 354 MW are operating commercially in California since the 1980s. The other two (tower & dish) are still at an early stage of development.

Concentrating Solar Power (CSP) Levelized Cost vs Others



Applicability of Solar Power

- **Concentrating PV collectors (IHCPV) -** lenses, mirrors or dish concentrate sunlight onto a smaller solar cell that can efficiently convert concentrated solar energy to electricity
- **Building-integrated PVs (BIPV) -** double purpose for producing electricity and serving as construction materials to replace building components like walls, skylights, roofs
- **Stand-alone PVs -** produce power independently of the grid; good for remote areas like national parks, homes, rural villages: lighting, battery charging (night) and water pumps
- **Hybrid systems -** combine solar, wind, battery and diesel for renewable and reliable back-up power.
- **Grid-connected PVs -** supply surplus power to the grid and takes from the grid when power is low; does not need battery for storage but needs "net metering" device

Advantages of Solar Energy

- **Can be generated anywhere** - main alternative in remote sites; the greater the sunlight, the greater the output; it does not consume expensive fossil fuel
- **Do not take up enormous amounts of land** - compared to hydro and dendro thermal plants, but require more space than similarly sized fossil power plants.
- **Do not require large contiguous areas of land** - solar panels can be made in small modular units and built into buildings
- **Distributed generation** - generating power close to site of consumption improves the stability of the electrical grid
- **Could be stored for nighttime use** - through storage batteries or hybrid with other systems like wind and other generators.

Disadvantages of Solar Energy

- **Not steady or reliable** – like wind power, and its production at daytime does not coincide with night-time demand; needs storage or hybrid with diesel generators to be reliable
- **May compete in the peak power market only -** although the US DOE predicts that by 2010 solar towers, dishes and troughs will cost lower at $0.05, $ 0.06 and $0.09 per kWh
- **Difficult to compete in the bulk power market -** with the current low cost of conventional power, unless users are prepared to pay a premium for clean and green power.
- **Outside the US, solar power will cost more -** because of the lack of domestic capability to manufacture the system components owing to complexity of solar technology.
- **Operators in developing countries need special training -** to maintain such plants, otherwise, the facilities will rapidly fall into disrepair as was experienced in India.

Environmental Impact

- **Green power and global warming–** solar, wind, geothermal, biomass and small-scale hydro power are what consumers demand today; solar energy plants produce no SO_2 and CO_2
- **Aesthetics and visual impacts –** solar panels, collectors and concentrators would require large areas of land; plant must be sited in remote areas and designed to enhance its aesthetics
- **Birds and other living resources –** affected, especially for solar-thermal systems along migration routes; flying birds may get fried when they cross the path of concentrated sunlight from heliostats to central receiver
- **Mining of large quantities of mineral ores -** into silicon have their own pollution, health and occupational safety risks.
- **Low efficiency of solar-electric plants -** results in large heat rejection rates in a concentrated manner, even though the energy input is diffuse

Risks associated with Solar Power

- Primarily the risks associated with **new technologies**: *reliability*, *plant lifetime*, *long-term O&M costs*.
- Risks are being addressed by **current research projects**, particularly in the US where major test and pilot schemes are demonstrating the long-term viability of both systems.
- Solar energy as a **resource is well understood** and solar insolation records exits just about everywhere so there should be no problem establishing the expected solar input at any site on the Earth.
- **Unforeseen effects** such as on Kramer Junction, California whose output dropped during 1991-1992 due to the eruption of Mt. Pinatubo.
- **Diurnal nature** of solar power generation means it could replace conventional power only during daylight ours only or needs energy storage or hybrid system which adds costs.