Concentrating Collectors

Collectors are oriented to track the sun so that the beam radiation will be directed onto the absorbing surface

Collector: Receiver and the concentrator

Receiver: Radiation is absorbed and converted to some other energy form (e.g. heat).

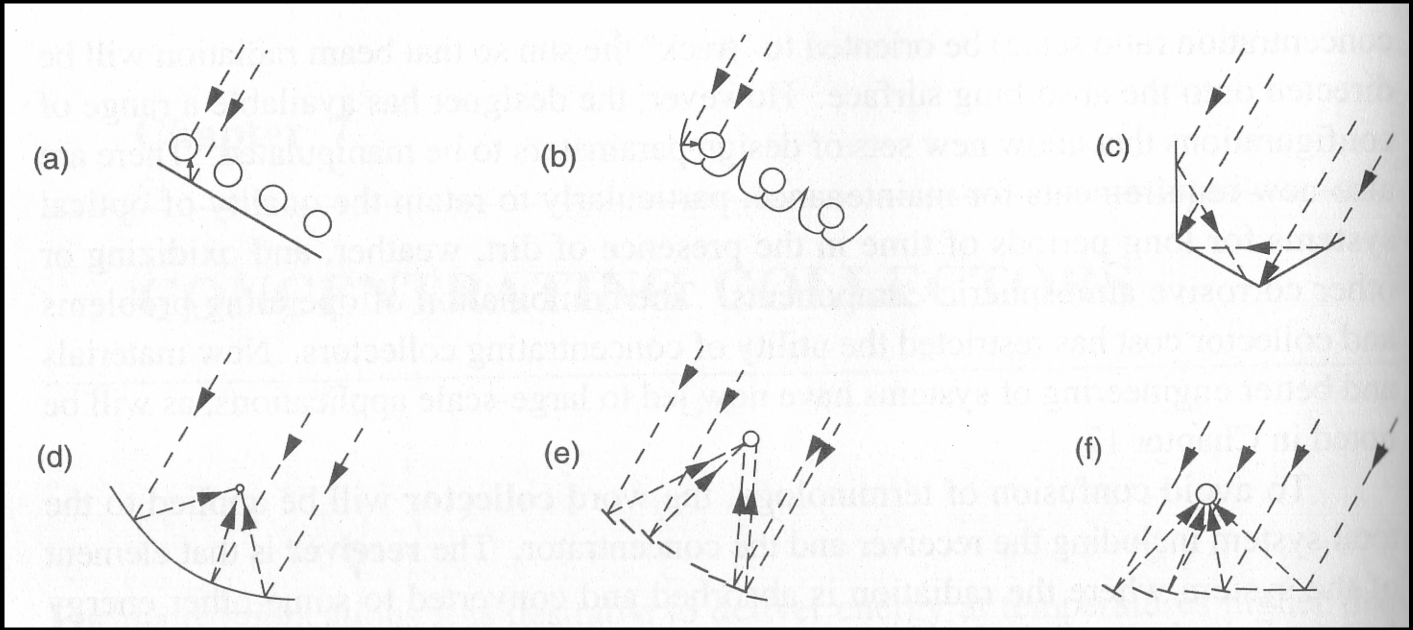
Concentrator: Collector that directs radiation onto the receiver. The aperture of the concentrator is the opening through which the solar radiation enters the concentrator

Source: Chapter 7 of Solar Engineering of thermal processes by Duffie & Beckman, Wiley, 1991

Reference: http://www.powerfromthesun.net/book.htm

Collector Configurations

Goal: Increasing the radiation flux on receivers



a) Tubular absorbers with diffusive back reflector; b) Tubular absorbers with specular cusp reflector; c) Plane receiver with plane reflector; d) parabolic concentrator; e) Fresnel reflector f) Array of heliostats with central receiver

Concentrating Collectors

Fresnel Lens: An optical device for concentrating light that is made of concentric rings that are faced at different angles so that light falling on any ring is focused to the same point.

Parabolic trough collector: A high-temperature (above 360K) solar thermal concentrator with the capacity for tracking the sun using one axis of rotation. It uses a trough covered with a highly reflective surface to focus sunlight onto a linear absorber containing a working fluid that can be used for medium temperature space or process heat or to operate a steam turbine for power or electricity generation.

Central Receiver: Also known as a *power tower*, a solar power facility that uses a field of two-axis tracking mirrors known as heliostat (A device that tracks the movement of the sun). Each heliostat is individually positioned by a computer control system to reflect the sun's rays to a tower-mounted thermal receiver. The effect of many heliostats reflecting to a common point creates the combined energy of thousands of suns, which produces high-temperature thermal energy. In the receiver, molten nitrate salts absorb the heat energy. The hot salt is then used to boil water to steam, which is sent to a conventional steam turbine-generator to produce electricity.

Concentration Types

Planar and non-concentrating type which provides concentration ratios of up to four and are of the flat plate type.

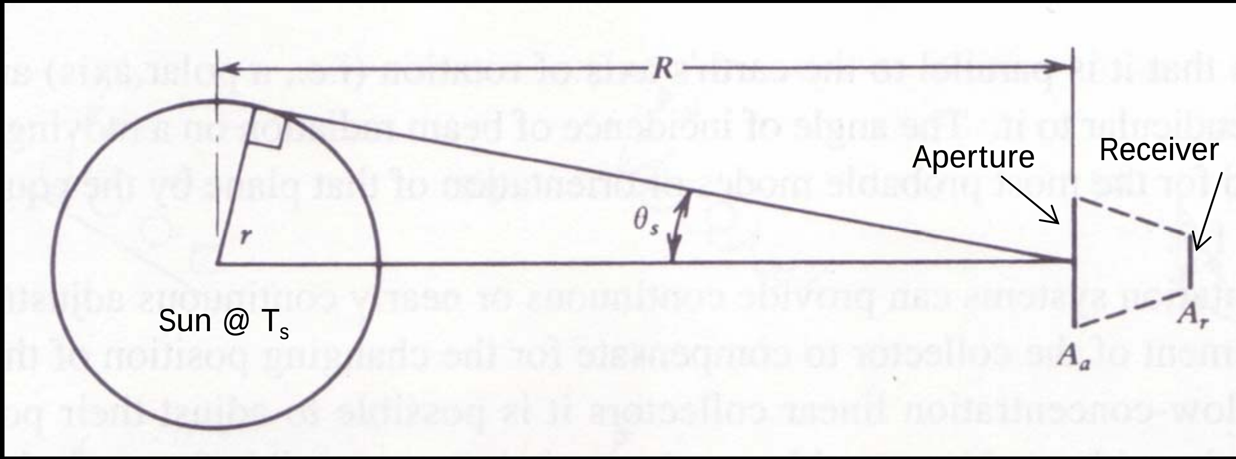
Line focusing type produces a high density of radiation on a line at the focus. Cylindrical parabolic concentrators are of this type and they could produce concentration ratios of up to ten.

Point focusing type generally produce much higher density of radiation in the vicinity of a point. Paraboloids are examples of point focus concentrators.

Concentration Ratio

Area concentration ratio (geometric):

$$C = \frac{A_a}{A_r}$$



Optical concentration ratio:

$$C_O = \frac{\frac{1}{A_r}\int I_r dA_r}{I_a}$$

I_r is the averaged irradiance

I_a is the insolation incident on the collector aperture

Radiative Heat Exchange Between the Sun and the Receiver

The sun is assumed to be a blackbody at T_s and the radiation from the sun on the aperture/receiver is the fraction of the radiation emitted by the sun which is intercepted by the aperture.

$$Q_{s\to r} = A_a \frac{r^2}{R^2}\sigma T_s^4$$

$\sigma = 5.6697\mathrm{x}10^{-8}\ \mathrm{W/m^2K^4}$

A perfect receiver, such as a blackbody, radiates energy equal to $A_r T_r^4$ and a fraction of this reaches the sun

$$Q_{r\to s} = A_r \sigma T_r^4 E_{r\to s}$$

Exchange (view) factor

Maximum Concentration Ratio

When $T_r = T_s$, the second law requires that

$$Q_{s\to r} = Q_{r\to s}$$

$$\frac{A_a}{A_r} = \frac{R^2}{r^2} E_{r\to s}$$

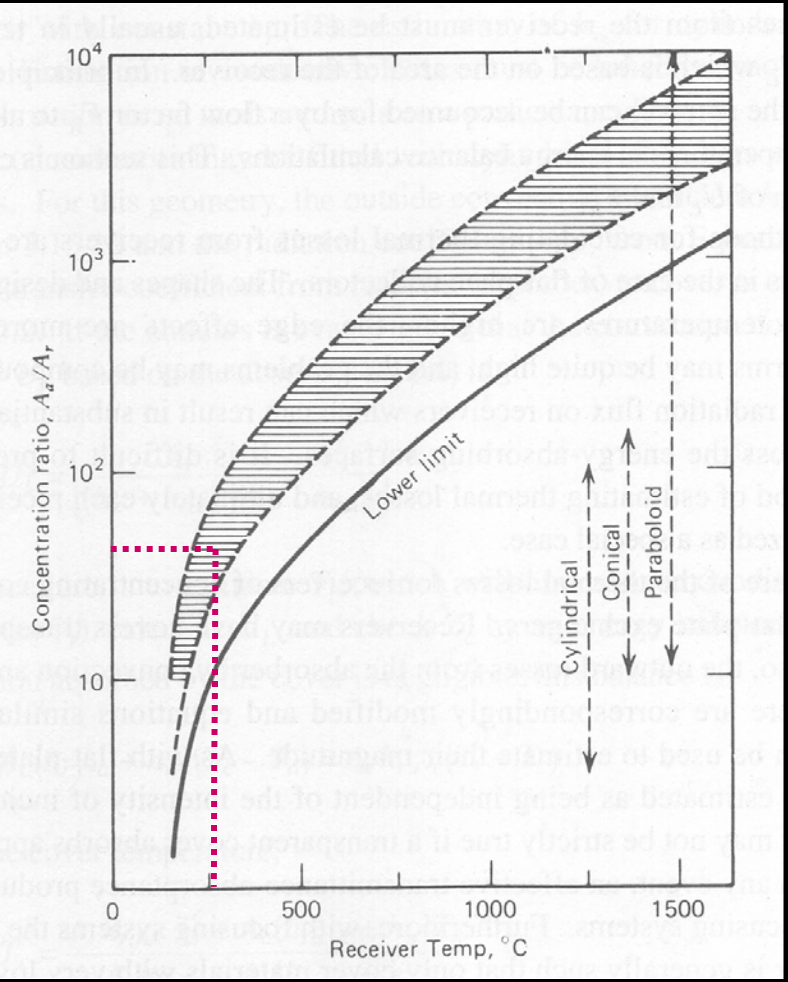
$$\left(E_{r\to s}\right)_{\max imum} = 1$$

$$\left(\frac{A_a}{A_r}\right)_{circular,\max} = \frac{R^2}{r^2} = \frac{1}{\sin^2\theta_s}$$

$$\left(\frac{A_a}{A_r}\right)_{linear,\max} = \frac{1}{\sin\theta_s}$$

With $\theta_s = 0.27^o$, the maximum possible concentration ratio for circular concentrators is 45,000 and for linear concentrators, it is 212.

Concentration Ratio vs. Receiver Temperature



Lower limit:

thermal losses = absorbed energy

SESEC Concentrator

Thermal Performance

$$\dot{Q}_{out} = \dot{Q}_{opt} - \dot{Q}_{loss}$$

The generalized thermal analysis of a concentrating collector is similar to that of a flat-plate collector. The expressions for collector efficiency factor $F`$, the loss coefficient U_L, and the collector heat removal factor F_R need to derived for a specific configuration. With F_R and U_L known, the collector useful gain can be calculated from an expression that is similar to that of a flat-plate collector.

For a linear concentrator, with no temperature gradients around the receiver tube, the thermal loss coefficient is

$$U_L = h_w + h_r + U_{cond}$$

$$h_r = 4\sigma\varepsilon\bar{T}^3$$

$$h_w = \frac{8.6V^{0.6}}{L^{0.4}}$$

where T is the mean radiation temperature ε is the remittance of the absorbing surface, V is the wind speed and L is the characteristic length.

Thermal Performance

We will use the same terminology used in flat plate collector analysis and consider a cylindrical absorbing tube with a linear concentrator.

The thermal loss coefficient U_L is given by:

$$U_L = \left[\frac{A_r}{(h_w + h_{r,c-a})A_c} + \frac{1}{h_{r,r-c}} \right]^{-1}$$

Convection heat transfer coefficient *Radiation heat transfer coefficient*

Thermal Performance

The overall heat transfer coefficient from the surroundings to the fluid in the tube is

$$U_o = \left[\frac{1}{U_L} + \frac{D_o}{h_{fi} D_i} + \frac{D_o \ln\left(\frac{D_o}{D_i}\right)}{2k} \right]^{-1}$$

Where D_o and D_i are the outside and inside tube diameters, h_{fi} is the heat transfer coefficient inside the tube and k is the thermal conductivity of the tube.

Thermal Performance

The useful energy gain per unit of collector length:

$$q'_u = F' \frac{A_a}{L}\left[S - \frac{A_r}{A_a} U_L \left(T_f - T_a\right)\right]$$

Where A_a is the unshaded area of the concentrator aperture and A_r is the area of the receiver ($\pi D_o L$ for a cylindrical absorber), S is the absorbed solar radiation per unit of aperture area, T_f is the local fluid temperature and F' is the collector efficiency factor given by U_o/U_L.

Thermal Performance

The actual useful energy gain:

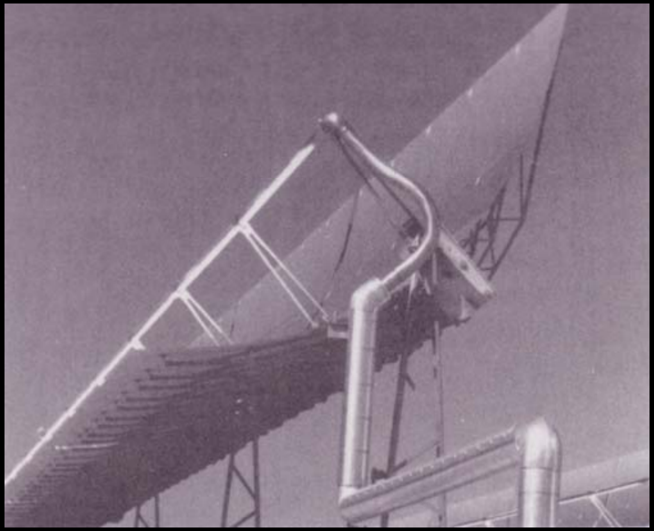
$$Q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L \left(T_i - T_a \right) \right]$$

Where A_a is the unshaded area of the concentrator aperture and A_r is the area of the receiver, S is the absorbed solar radiation per unit of aperture area, T_i is the inlet fluid temperature and F_R is the collector heat removal factor.

$$F_R = \frac{\overset{*}{m} C_p}{A_c U_L} \left[1 - \exp\left(- \frac{A_C U_L F'}{\overset{*}{m} C_p} \right) \right]$$

Linear Concentrator

Linear concentrators with parabolic cross section:



Used in power generation systems in California and elsewhere. Fluid temperatures can reach up to about 700K.

The optical design of the concentrator is done to obtain desirable distribution of solar radiation flux across the focus.

Linear Concentrator

The absorbed radiation per unit area of unshaded aperture is given by:

$$S = I_b \rho (\gamma \tau \alpha)_n K_{\gamma\tau\alpha}$$

Where I_b is effective incident beam radiation on the plane of the aperture, ρ is the specular reflectance of the concentrator, γ (the intercept factor), τ (the transmittance), and α (the absorptance) are functions of the angle of incidence of radiation on the aperture. $K_{\gamma\tau\alpha}$ is an incidence angle modifier that can be used to account for deviations from the normal of the angle of incidence of the radiation on the aperture.

The intercept factor is defined as the fraction of the reflected radiation that is incident on the absorbing surface of the receiver.

$$\gamma = \frac{\int_A^B I(y)dy}{\int_{-\infty}^{\infty} I(y)dy}$$

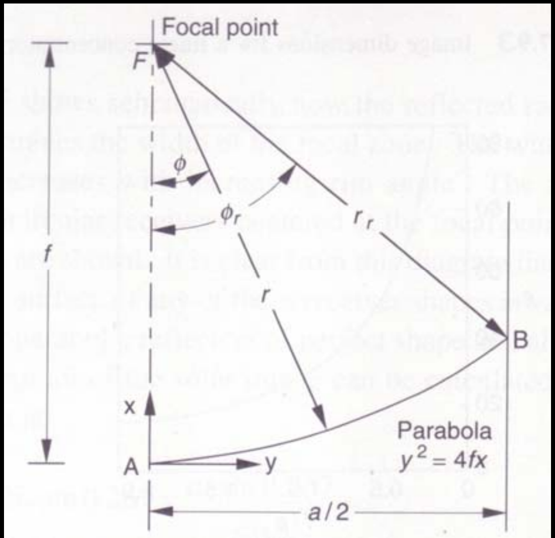
Receiver extends from *A* to *B*

Linear Concentrator Geometry

A beam of solar radiation is incident on the reflector, with parabolic cross section, at pint B on the rim where the mirror radius is a maximum r_r. The rim angle ϕ_r is described by AFB and the local mirror radius is r.

$$\phi_r = \tan^{-1}\left[\frac{8\left(\frac{f}{a}\right)}{16\left(\frac{f}{a}\right)^2 - 1}\right] = \sin^{-1}\frac{a}{2r_r}$$

$$r = \frac{2f}{1+\cos\phi}$$



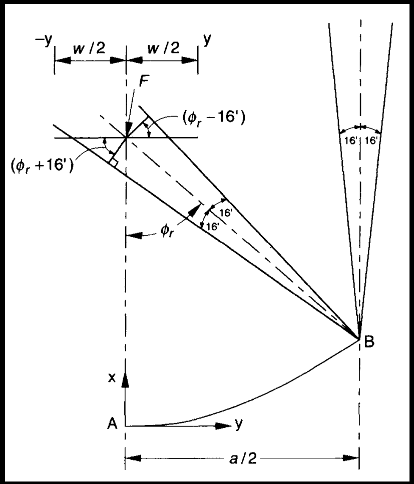
The aperture is a and the focal length is f.

An incident beam of solar radiation is a cone with an angular width of 0.53° (a half angle θ_s = 0.267°)

Linear Concentrator Geometry

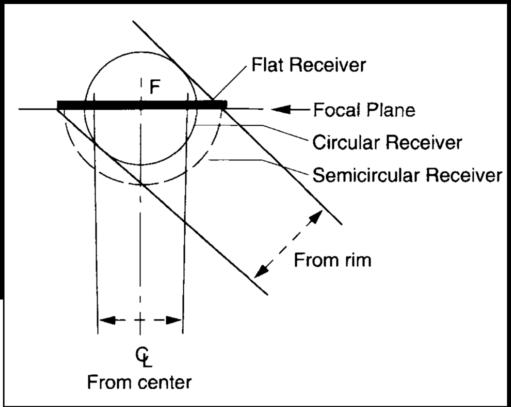
For specular parabolic reflectors of perfect shape and alignment, the size of the cylindrical receiver of diameter *D*, to intercept all of the solar image is

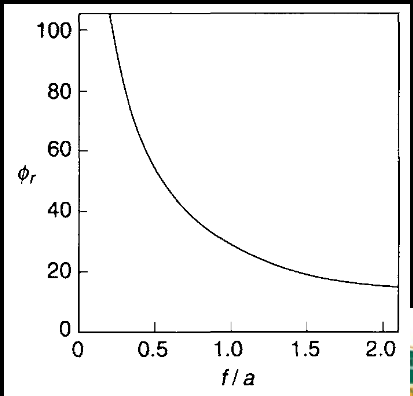
$$D = 2r_r \sin 0.267 = \frac{a \sin 0.267}{\sin \phi_r}$$



For a flat plate receiver in the focal plane of the parabola, the width *w* (also the diameter of the semicircular receiver) is

$$w = \frac{a \sin 0.267}{\sin \phi_r \cos(\phi_r + 0.267)}$$





3-D Parabolic Reflectors

For spherical receivers with minimum shading by the receiver:

$$C_{\max} = \frac{\sin^2 \phi_r}{4\sin^2\left(0.267 + \frac{\delta}{2}\right)} - 1$$

δ is the a measure of the limits of the angular errors of the reflector surface - dispersion angle

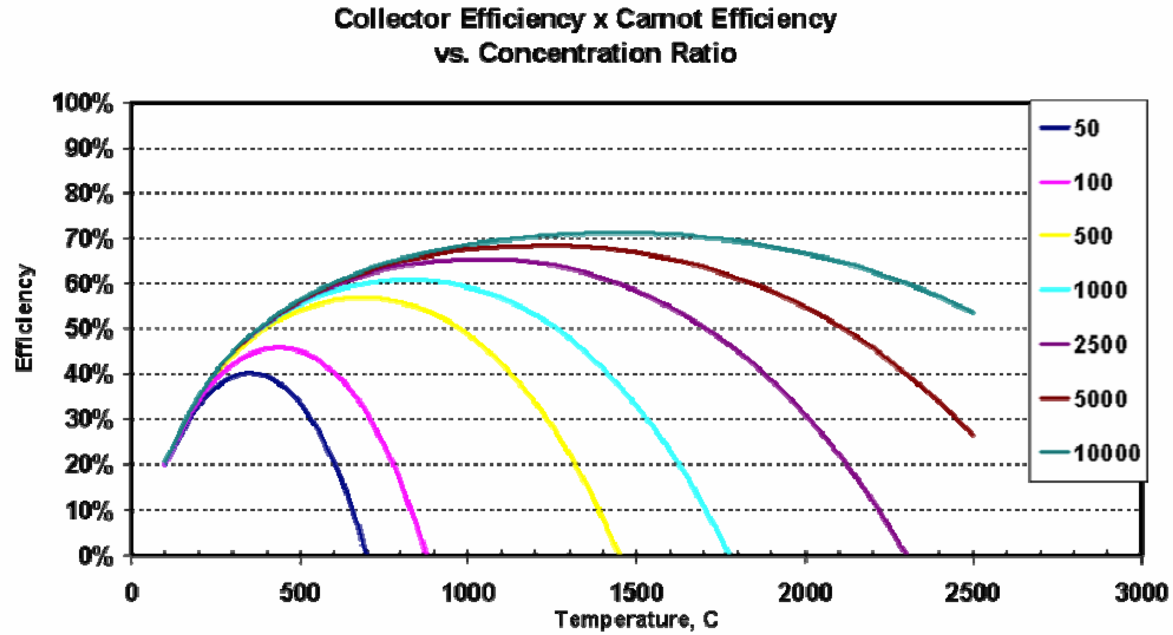
For flat receivers:

$$C_{\max} = \frac{\sin^2 \phi_r \cos^2\left(\phi_r + 0.267 + \frac{\delta}{2}\right)}{4\sin^2\left(0.267 + \frac{\delta}{2}\right)} - 1$$

C_{max} is defined as the maximum concentration that can be obtained based on interception of all of the specular reflected radiation which is within the cone of of angular width (0.53+δ)

System Efficiency

$$\eta_{system} = \eta_{collector} * \eta_{process}$$



Central Receiver Collectors

A Fresnel-type concentrator, a parabolic reflector broken up into small segments. If all the reflected beam radiation is to be intercepted by a spherical receiver, the maximum concentration ratio is given by

$$C_{\max} = \frac{\psi \sin^2 \phi_r}{4\sin^2\left(0.267 + \frac{\delta}{2}\right)} - 1$$

A fraction of the ground area ψ is covered by mirrors ~ 0.3-0.5

$$C_{\max} = \psi \left[\frac{\sin \phi_r \cos(\phi_r + 0.267 + \frac{\delta}{2}}{\sin(0.267 + \frac{\delta}{2}} \right]^2 - 1$$

For Flat receiver and d is the dispersion angle

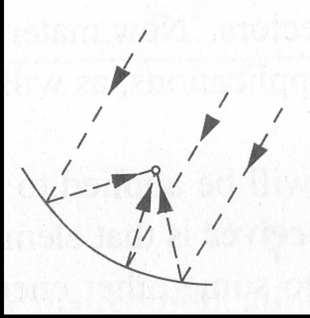
Concentrating Collectors and PV

Photovoltaics under concentrated sunlight:

Motivation: reduced cost due to small area of the PV array

Concentrators only use the direct beam light.

They are always pointed towards the sun - sun tracker



The important parameter is the concentration ratio: the ratio of the collector aperture (the opening through which the solar radiation enters the concentrator) area to absorber area; increasing ratio means increasing temperature at which energy can be delivered.

PV-Trough system at ANU

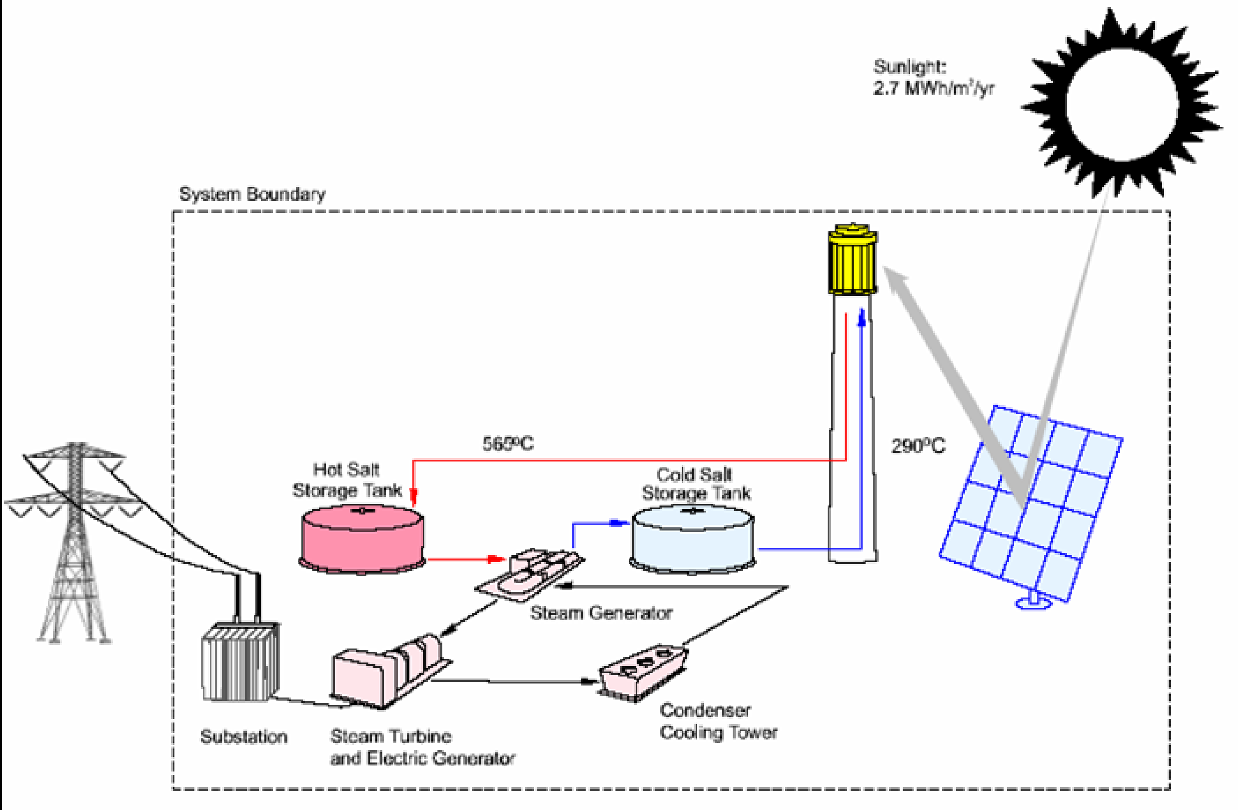
A photovoltaic/trough concentrator system for the production of electricity in remote areas has been developed, in conjunction with Solahart Industries Pty Ltd. The system is based on sun-tracking mirrors that reflect light onto a receiver lined with solar cells. The solar cells are illuminated with approximately 25 times normal solar concentration, and convert about 20% of the sunlight into electricity. The balance of the solar energy is converted into heat, which is removed via a finned aluminium heat exchanger. A 20 kW demonstration system was constructed in Rockingham, near Perth (Western Australia).

PV Concentrator - EUCLIDES

ITER, IES and BP Solarex have carried out the project for the installation of the world largest PV concentration grid connected power plant, the EUCLIDESTM-THERMI plant. This plant is rated 480 kWp and is composed of 14 parallel arrays, each 84 meters long. The arrays are North/South oriented and close to the ground. Each array carries 138 modules and 140 mirrors. The modules are series connected in each array. The geometric concentration ratio is x38.2, 1.2 times the one in the prototype. The mirror technology is based on metallic reflective sheets shaped with ribs to the parabolic profile. Three different materials have been tested to be used as reflective material. The fully encapsulated receiving modules are made of 10 concentration LGBG BP Solarex cells, series connected. The modules are cooled with a passive heat sink. Every two contiguous arrays are connected, in parallel, to one inverter sized 60 kVA. The output voltage at standard operating conditions is 750 Volts. The inverter, without intermediate transformer, was designed and manufactured by ITER. The concentrating optics are mirrors instead of Fresnel lenses used previously in all PV concentration developments. The tracking system is one axis, horizontal, as it is thought that the one-axis solutions are cheaper than the two-axes tracking ones. The concentrating schemes present a more constant output than the flat panels, so they might present some advantage in the value of the electricity produced.

Solar Power Tower

Molten-salt power tower system



Electric power from sunlight by focusing concentrated solar radiation on a tower-mounted heat exchanger. Best suited for large scale applications: 30-400 MW

Liquid salt at 290ºC is pumped from a storage tank through the receiver where it is at 565ºC and then to a hot storage tank.

The hot salt is pumped to a steam generating system that produces superheated steam for a conventional Rankine cycle turbine generator system.

Source: Sandia National Laboratories

Solar Power Tower

Electricity dispatchability

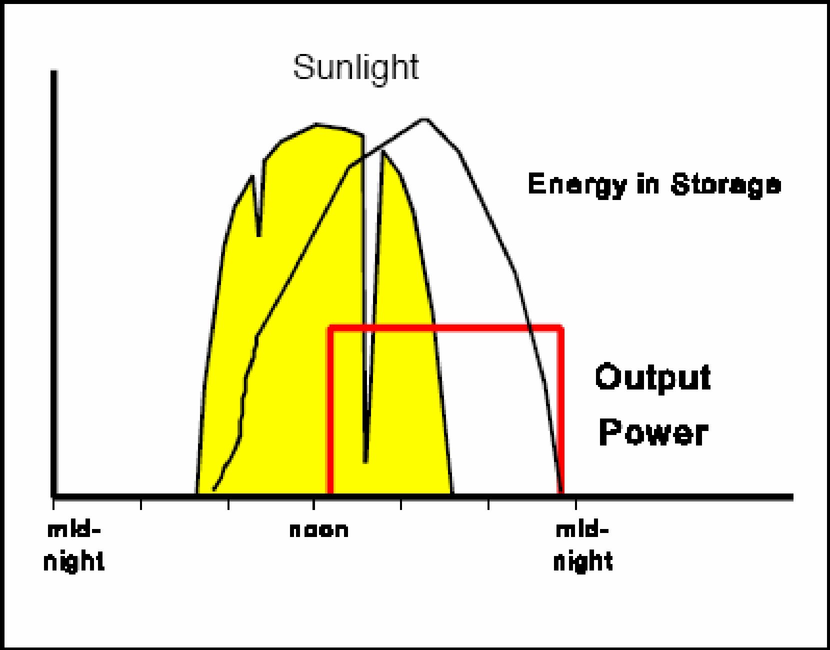


Table 1. Experimental power towers.

Project	Country	Power Output (MWe)	Heat Transfer Fluid	Storage Medium	Operation Began
SSPS	Spain	0.5	Liquid Sodium	Sodium	1981
EURELIOS	Italy	1	Steam	Nitrate Salt/Water	1981
SUNSHINE	Japan	1	Steam	Nitrate Salt/Water	1981
Solar One	USA	10	Steam	Oil/Rock	1982
CESA-1	Spain	1	Steam	Nitrate Salt	1983
MSEE/Cat B	USA	1	Molten Nitrate	Nitrate Salt	1984
THEMIS	France	2.5	Hi-Tec Salt	Hi-Tec Salt	1984
SPP-5	Russia	5	Steam	Water/ Steam	1986
TSA	Spain	1	Air	Ceramic	1993
Solar Two	USA	10	Molten Nitrate Salt	Nitrate Salt	1996

Table 2. Comparison of solar-energy storage systems.

	Installed cost of energy storage for a 200 MW plant ($/kWhr$_e$)	Lifetime of storage system (years)	Round-trip storage efficiency (%)	Maximum operating temperature (°C/°F)
Molten-Salt Power Tower	30	30	99	567/1,053
Synthetic-Oil Parabolic Trough	200	30	95	390/734
Battery Storage Grid Connected	500 to 800	5 to 10	76	N/A

Solar Power Tower

Thermal Loss

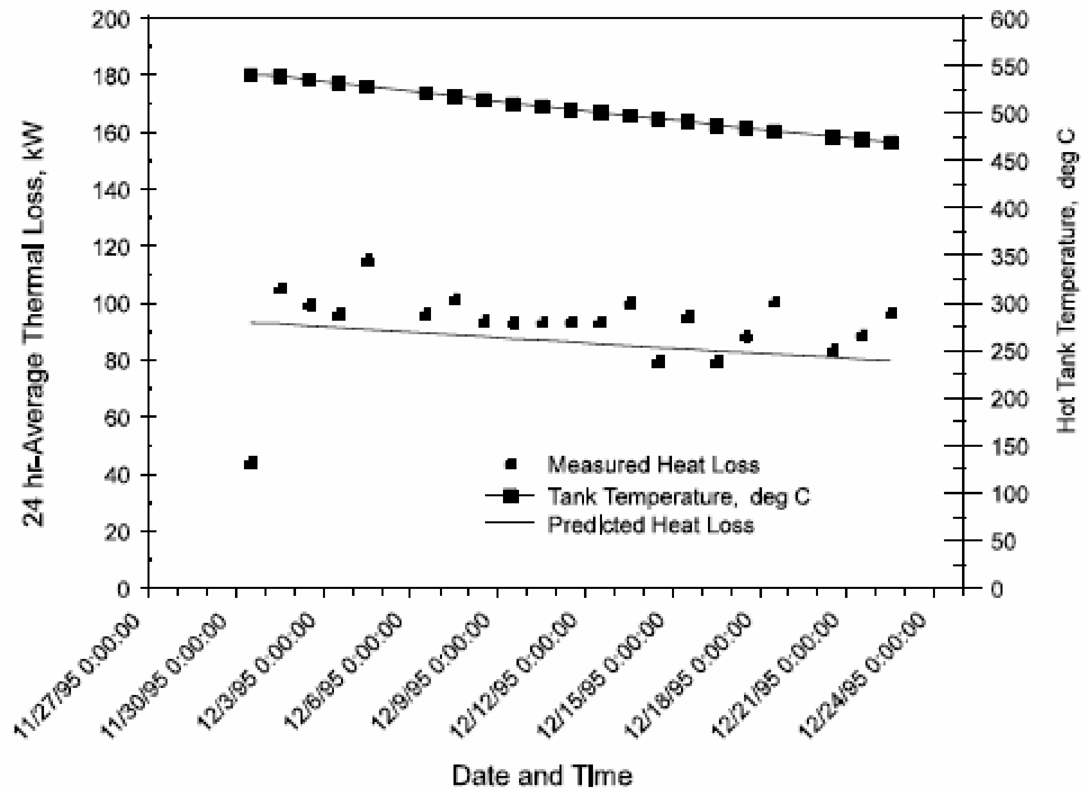


Figure 3. Cool down of hot storage tank at Solar Two.

Solar Power Tower

Variable Load

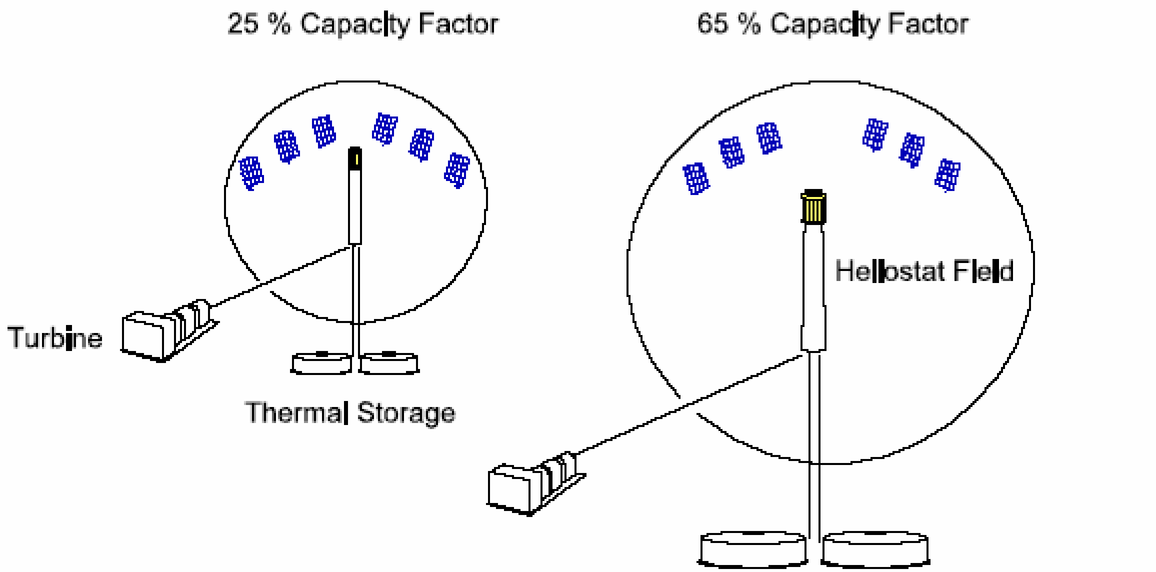
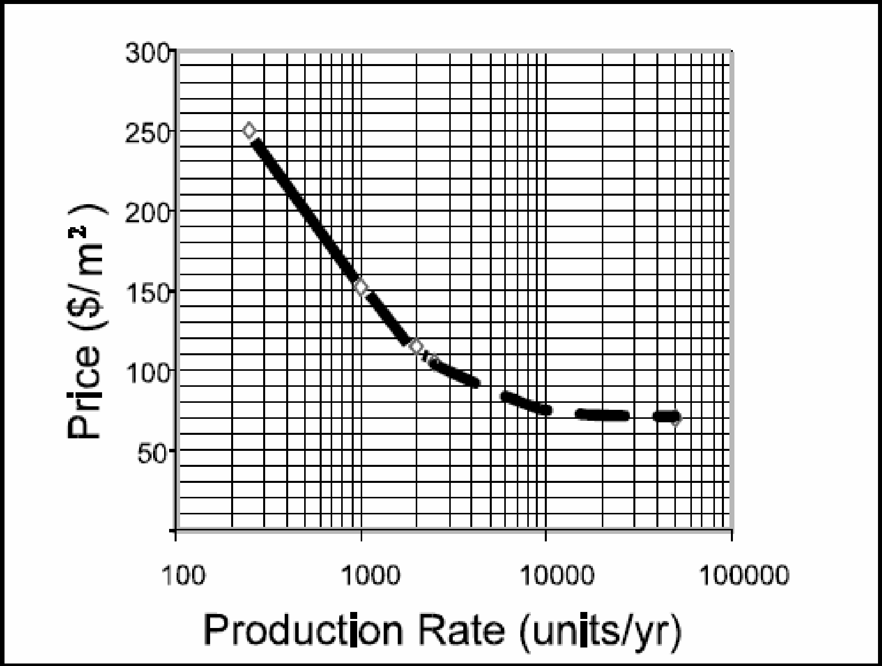


Figure 6. In a solar power tower, plant design can be altered to achieve different capacity factors. To increase capacity factor for a given turbine size, the designer would (1) increase the number of heliostats, (2) enlarge the thermal storage tanks, (3) raise the tower, and (4) increase the receiver dimensions.

Heliostats

Relatively few heliostats have been manufactured to date at a cost of about $250/m^2.



Low cost manufacturing methods are needed to make solar power tower viable technology for electricity production. Particularly, a low cost drive systems must be developed.

Surface area: 150 m^2

Solar Power Tower

Receiver:

Smaller and simpler receivers are needed to improve efficiency and reduce maintenance.

Molten salt:

Molten nitrate salt, though an excellent thermal storage medium, it is not an ideal material due to its relatively high freezing point of 220^{o}C.

Solar Power Tower

Table 3. Performance and cost indicators.

INDICATOR NAME	UNITS	Solar Two Prototype 1997	+/-%	Small Hybrid Booster 2000	+/-%	Large Hybrid Booster 2005	+/-%	Solar Only 2010	+/-%	Advanced Solar Only 2020	+/-%	Advanced Solar Only 2030	+/-%
Plant Size	MW	10		30		100		200		200		200	
Receiver Thermal Rating	MW_t	43		145		470		1,400		1,400		1,400	
Heliostat Size	m^2	40		95		150		150		150		150	
Solar Field Area	m^2	81,000		275,000		883,000		2,477,000		2,477,000		2,477,000	
Thermal Storage	Hours	3		7		6		13		13		13	
	MWh_t	114		550		1,600		6,760		6,760		6,760	
Performance													
Capacity Factor	%	20		43		44		65		77		77	
Solar Fraction		1.00		0.22		0.22		1.00		1.00		1.00	
Direct Normal Insolation	$kWh/m^2/yr$	2,700		2,700		2,700		2,700		2,700		2,700	
Annual Solar to Elec. Eff.	%	8.5	+5/-20*	15.0	+5/-20	16.2	+5/-20	17.0	+5/-20	20.0	+5/-20	20.0	+5/-20
Annual Energy Production	GWh/yr	17.5		113.0		385.4		1,138.8		1,349.0		1,349.0	
Capital Cost													
Structures & Improvements	$\$/kW_{nameplate}$			116	15	60	15	50	15	50	15	50	15
Heliostat System		†		1,666	25	870	25	930	25	865	25	865	25
Tower/Receiver System		†		600	25	260	25	250	25	250	25	250	25
Thermal Storage System		370		420	15	240	15	300	15	300	15	300	15
Steam Gen System		276		177	15	110	15	85	15	85	15	85	15
EPGS/Balance of Plant		†		417	15	270	15	400	15	400	15	400	15
Master Control System				33	15	10	15	15	15	15	15	15	15
Directs SubTotal (A)		†		3,429		1,820		2,030		1,965		1,965	
Indirect Engineering/Other	A * 0.1			343		182		203		197		197	
SubTotal (B)				3,772		2,002		2,233		2,162		2,162	
Project/Process Contingency	B * 0.15			566		300		335		325		325	
Total Plant Cost‡				4,338		2,302		2,568		2,487		2,487	
Land (@ $4,942/hectare)				27		27		37		37		37	
Total Capital Requirements	$\$/kW_{nameplate}$			4,365		2,329		2,605		2,523		2,523	
	$\$/kW_{peak}$ #			2,425		1,294		965		934		934	
	$\$/m^2$			476		264		210		204		204	
Operation and Maintenance Cost													
Fixed Labor & Materials	\$/kW-yr												
Total O&M Costs		300		67	25	23	25	30	25	25	25	25	25

Notes:

1. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
2. The construction period is assumed to be 2 years.

* Design specification for Solar Two. This efficiency is predicted for a mature operating year.

† Cost of these items at Solar Two are not characteristic of a commercial plant and have, therefore, not been listed.

‡ Total plant cost for Solar Two are the actuals incurred to convert the plant from Solar One to Solar Two. The indirect factors listed do not apply to Solar Two.

\# To convert to peak values, the effect of thermal storage must be removed. A first-order estimate can be obtained by dividing installed costs by the solar multiple (i.e., SM = {peak collected solar thermal power} ÷ {power block thermal power}). For example, as discussed in the text, in 2010 the peak receiver absorbed power is 1400 MW_t. If this is attached to a 220 MW_e turbine (gross) with a gross efficiency of 42%, thermal demand of the turbine is 520 MW_t. Thus, SM is 2.7 (i.e., 1400/520) and peak installed cost is 2605/2.7 = $965/$kW_{peak}$. Solar multiples for years 1997, 2000, and 2005 are 1.2, 1.8, and 1.8, respectively.

Parabolic-Trough Technology

Solar Electric Generating Station (SEGS)

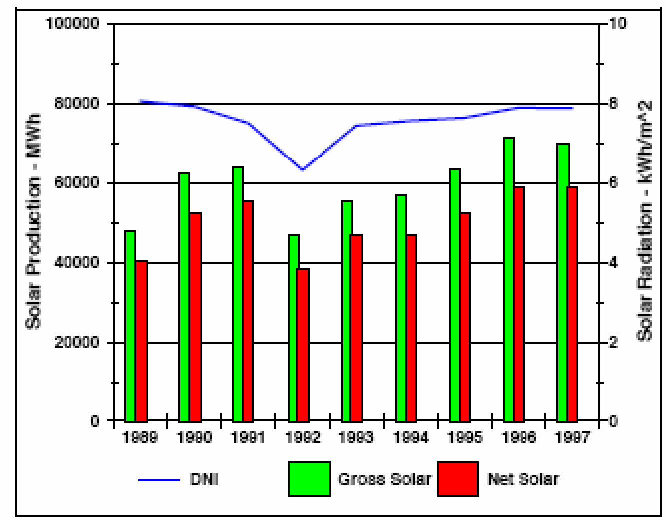


Figure 3. SEGS VI historical performance

Table 1. Parabolic-Trough Project Status (as of December 1998)

Country/State	Plant Configuration	Status
India	135 MW_e ISCCS	GEF approved, waiting for RFP**
Egypt	Open	GEF PDF*** B Grant approved
Morocco	Open	GEF government request
Mexico	ISCCS	GEF government request
Greece	50 MW_e SEGS*	IPP development, EU****Thermie Grant
Jordan	ISCCS or SEGS	On hold pending conventional IPP
Spain	50 MW_e SEGS	Waiting outcome of solar tariff
Arizona	15–30 MW_e ISCCS	Waiting outcome of solar portfolio standard

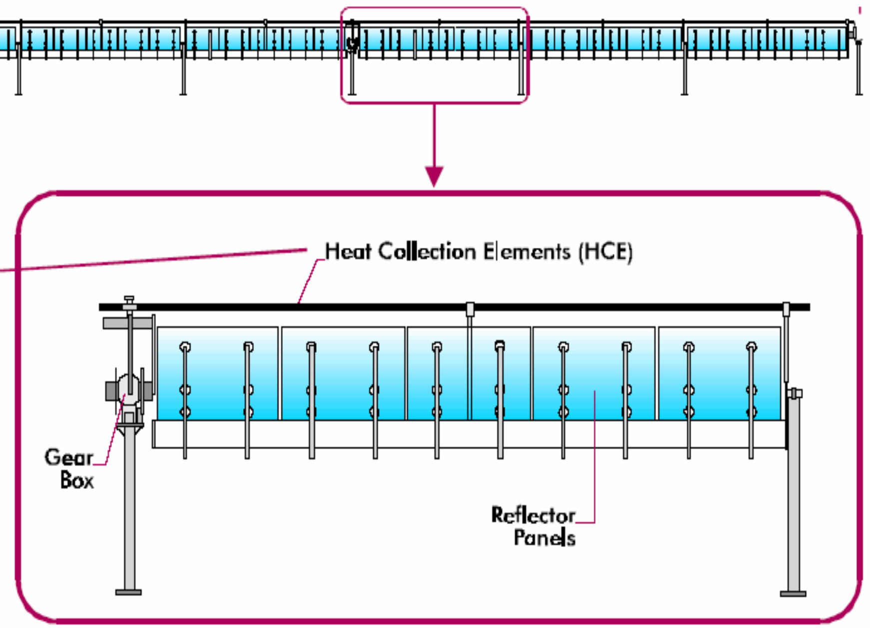
*solar electric generating systems
**request for proposals
***project development funding
****European Union

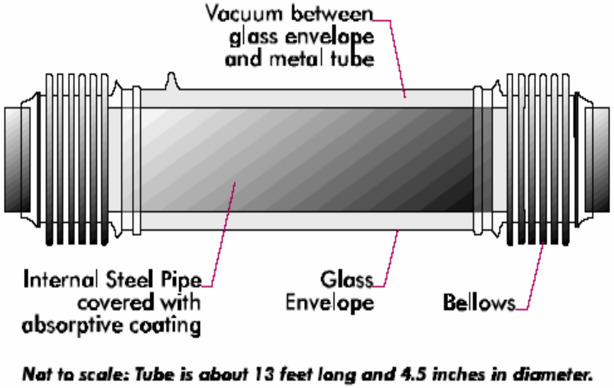
Solar-electric efficiency : 10%

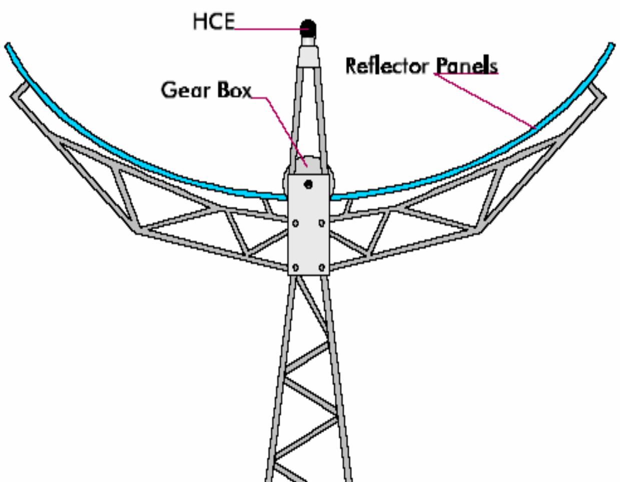
Levelized energy cost: \$0.04-0.05/kWh

Parabolic-Trough Technology

Components







KRAMER JUNCTION - SOLAR FIELDS' CHARACTERISTICS
SOLAR ELECTRIC GENERATING SYSTEMS III-VII

SEGS	III	IV	V	VI	VII	TOTALS
LS-2	980	980	992	800	400	4,152
LS-3	---	---	32	---	184	216
# OF PANELS	117,600	117,600	126,208	96,000	89,216	546,624
# OF HCE	11,760	11,760	12,672	9,600	9,216	55,008
OUTLET TEMP °F	660	660	660	735	735	---

High Temperature Fluids

Fluid	Application T (ºC)	Properties
Synthetic oils e.g. Therminol VP-1 (aromatic HC's)	13 - 395	Flammable
Mineral oils e.g. Caloria (paraffinic HC's)	-10 - 300	Flammable
Silicone oils	-40 - 400	Expensive Flammable
Nitrate salts e.g. HITEC-XL	220 - 500	Freezing point ≥ 120 ºC High T stability

Source: Luc Moens. NREL; GCEP Workshop, October, 2004

Heat Transfer Fluid = Heat Storage Fluid

- *Higher operating temperatures: low vapor pressure fluid needed*
- *Improved cost / performance of solar plant*
- *Optimized dispatch of power to meet utility peak loads (up to 12 h of storage)*

Source: Luc Moens. NREL; GCEP Workshop, October, 2004

Desired Properties for 'ideal' heat storage fluid

- High thermal stability (up to 425°C)
- Low freezing point (≤ 0 °C)
- Non-flammable
- Low vapor pressure (@ high T)
- High boiling point
- Relatively inexpensive

Source: Luc Moens. NREL; GCEP Workshop, October, 2004

Parabolic-Trough Technology

US Development Activity

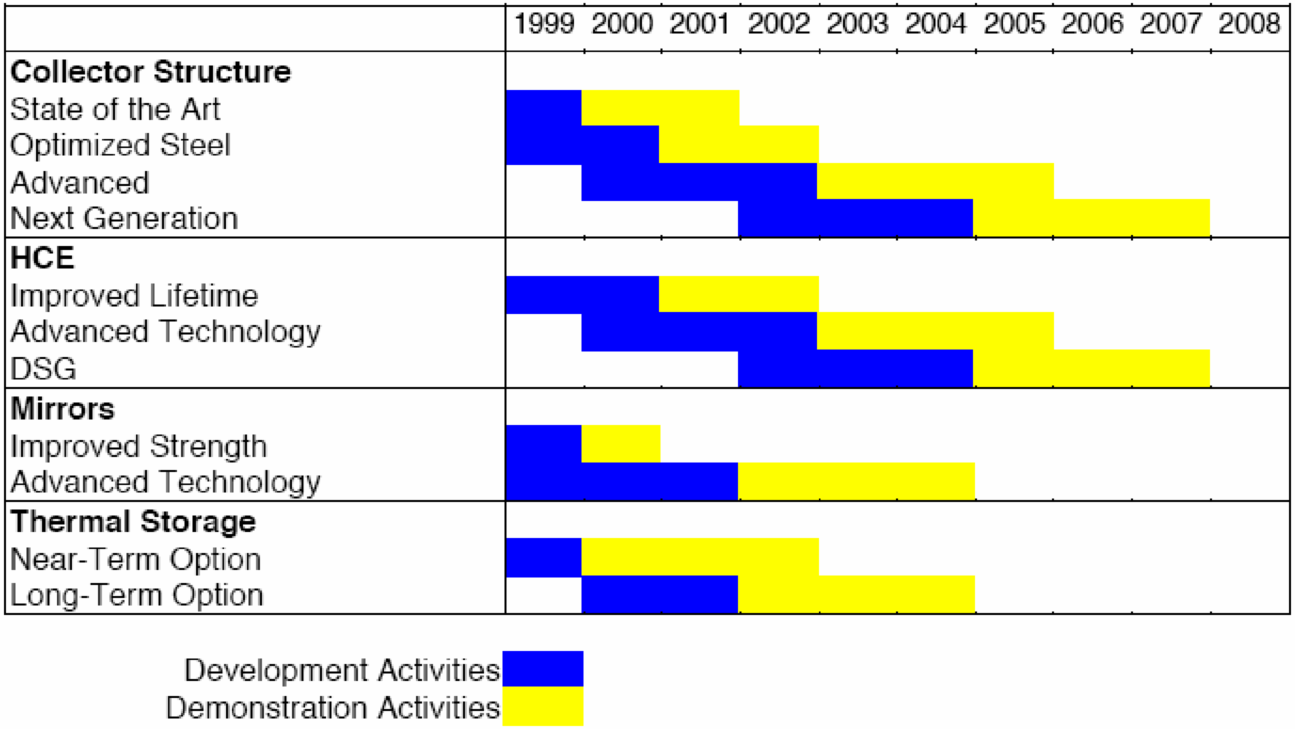


Figure 10. Component development activity time line

Source: National Renewable Energy Laboratory

Solar Dish-Engine System

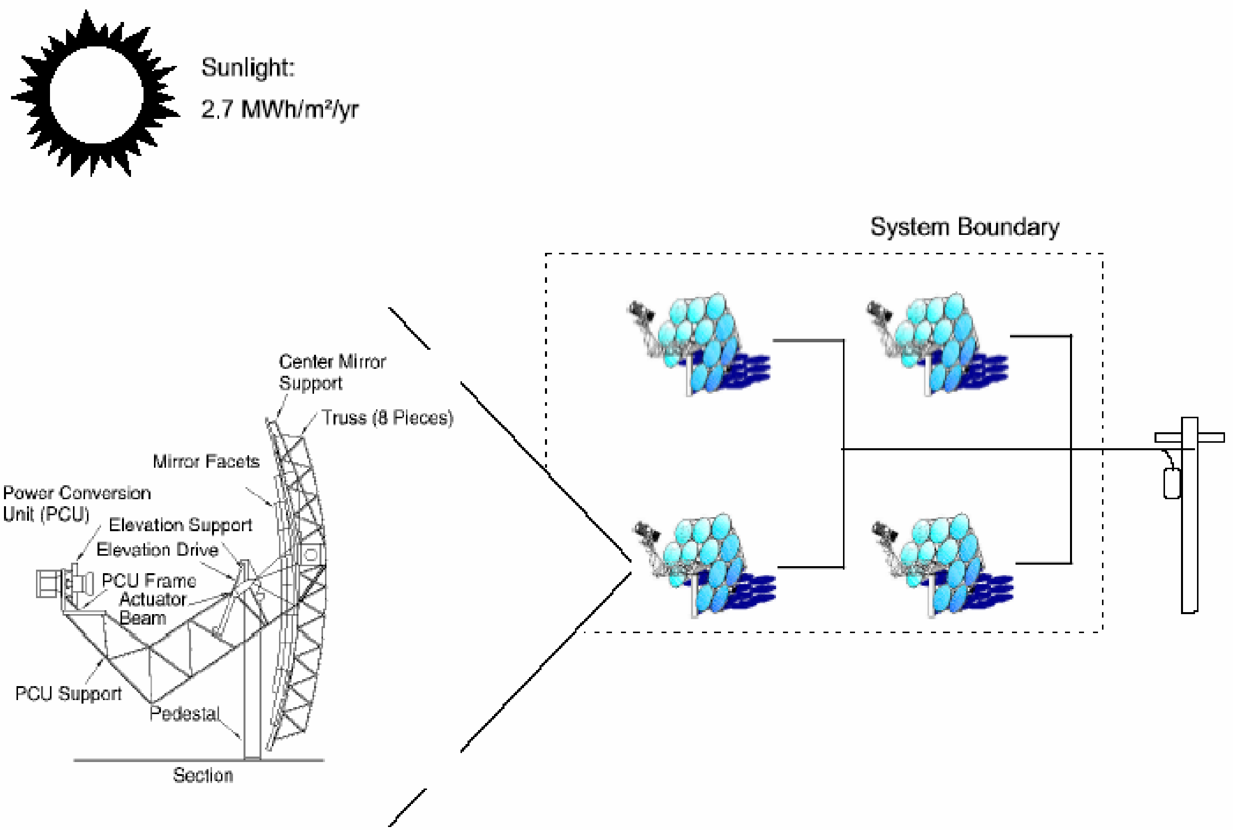
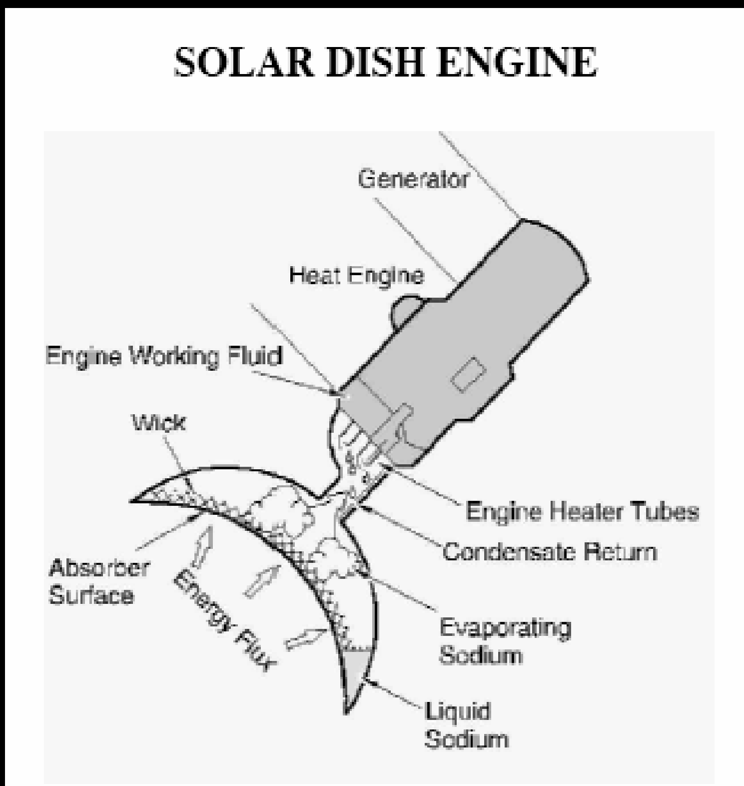


Figure 1. Dish/engine system schematic. The combination of four 25 kW_e units shown here is representative of a village power application

Dish diameter: 10m

Solar Dish-Engine System

Use of Heat pipes



Use of Sterling Engine

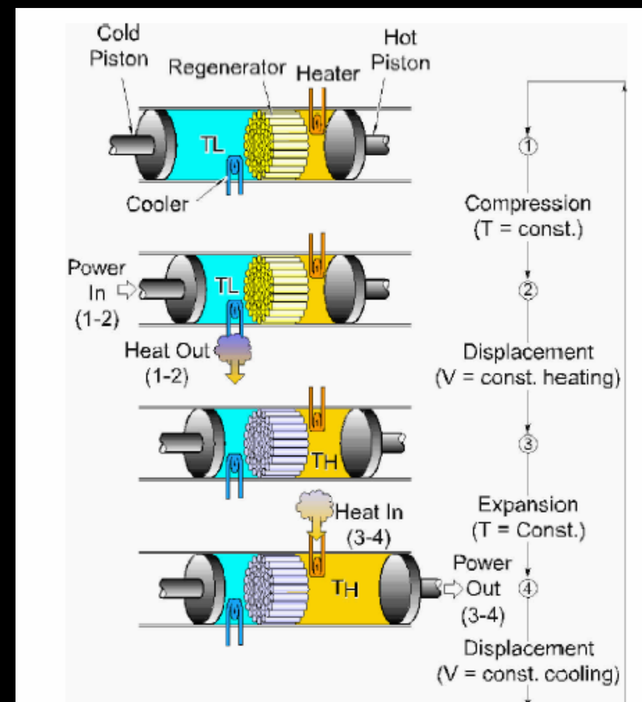


Figure 4. Schematic showing the principle of operation of a Stirling engine.

Solar Dish-Engine System

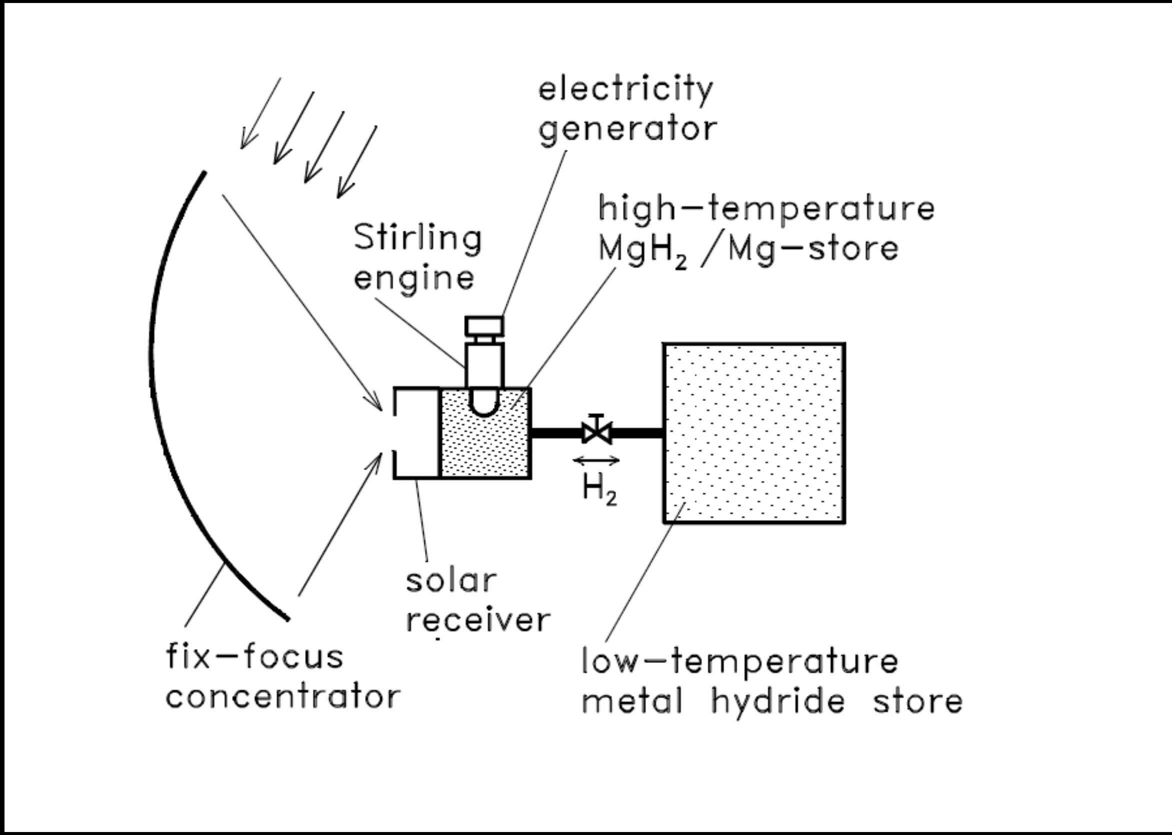
Table 1. Performance and cost indicators.

INDICATOR NAME	UNITS	1980's Prototype 1997	+/-%	Hybrid System 2000	+/-%	Commercial Engine 2005	+/-%	Heat Pipe Receiver 2010	+/-%	Higher Production 2020	+/-%	Higher Production 2030	+/-%
Typical Plant Size, MW	MW	0.025		1	50	30	50	30	50	30	50	30	50
Performance													
Capacity Factor	%	12.4		50.0		50.0		50.0		50.0		50.0	
Solar Fraction	%	100		50		50		50		50		50	
Dish module rating	kW	25.0		25.0		25.0		27.5		27.5		27.5	
Per Dish Power Production	MWh/yr/dish	27.4		109.6		109.6		120.6		120.6		120.6	
Capital Cost													
Concentrator	$/kW	4,200	15	2,800	15	1,550	15	500	15	400	15	300	15
Receiver		200	15	120	15	80	15	90	15	80	15	70	15
Hybrid		----		500	30	400	30	325	30	270	30	250	30
Engine		5,500	15	800	20	260	25	100	25	90	25	90	25
Generator		60	15	50	15	45	15	40	15	40	15	40	15
Cooling System		70	15	65	15	40	15	30	15	30	15	30	15
Electrical		50	15	45	15	35	15	25	15	25	15	25	15
Balance of Plant		500	15	425	15	300	15	250	15	240	15	240	15
Subtotal (A)		10,580		4,805		2,710		1,360		1,175		1,045	
General Plant Facilities (B)		220	15	190	15	150	15	125	15	110	15	110	15
Engineering Fee, 0.1*(A+B)		1,080		500		286		149		128		115	
Project /Process Contingency		0		0		0		0		0		0	
Total Plant Cost		11,880		5,495		3,146		1,634		1,413		1,270	
Prepaid Royalties		0		0		0		0		0		0	
Init Cat & Chem. Inventory		120	15	60	15	12	15	6	15	6	15	6	15
Startup Costs		350	15	70	15	35	15	20	15	18	15	18	15
Other		0		0		0		0		0		0	
Inventory Capital		200	15	40	15	12	15	4	15	4	15	4	15
Land, @$16,250/ha		26		26		26		26		26		26	
Subtotal		696		196		85		56		54		54	
Total Capital Requirement		12,576		5,691		3,231		1,690		1,467		1,324	
Total Capital Req. w/o Hybrid		12,576		5,191		2,831		1,365		1,197		1,074	
Operation and Maintenance Cost													
Labor	¢/kWh	12.00	15	2.10	25	1.20	25	0.60	25	0.55	25	0.55	25
Material	¢/kWh	9.00	15	1.60	25	1.10	25	0.50	25	0.50	25	0.50	25
Total	¢/kWh	21.00		3.70		2.30		1.10		1.05		1.05	

Notes:
1. The columns for "+/-%" refer to the uncertainty associated with a given estimate.
2. The construction period is assumed to be <1year for a MW scale system.

Solar Dish-Engine System

Use of Metal Hydrides



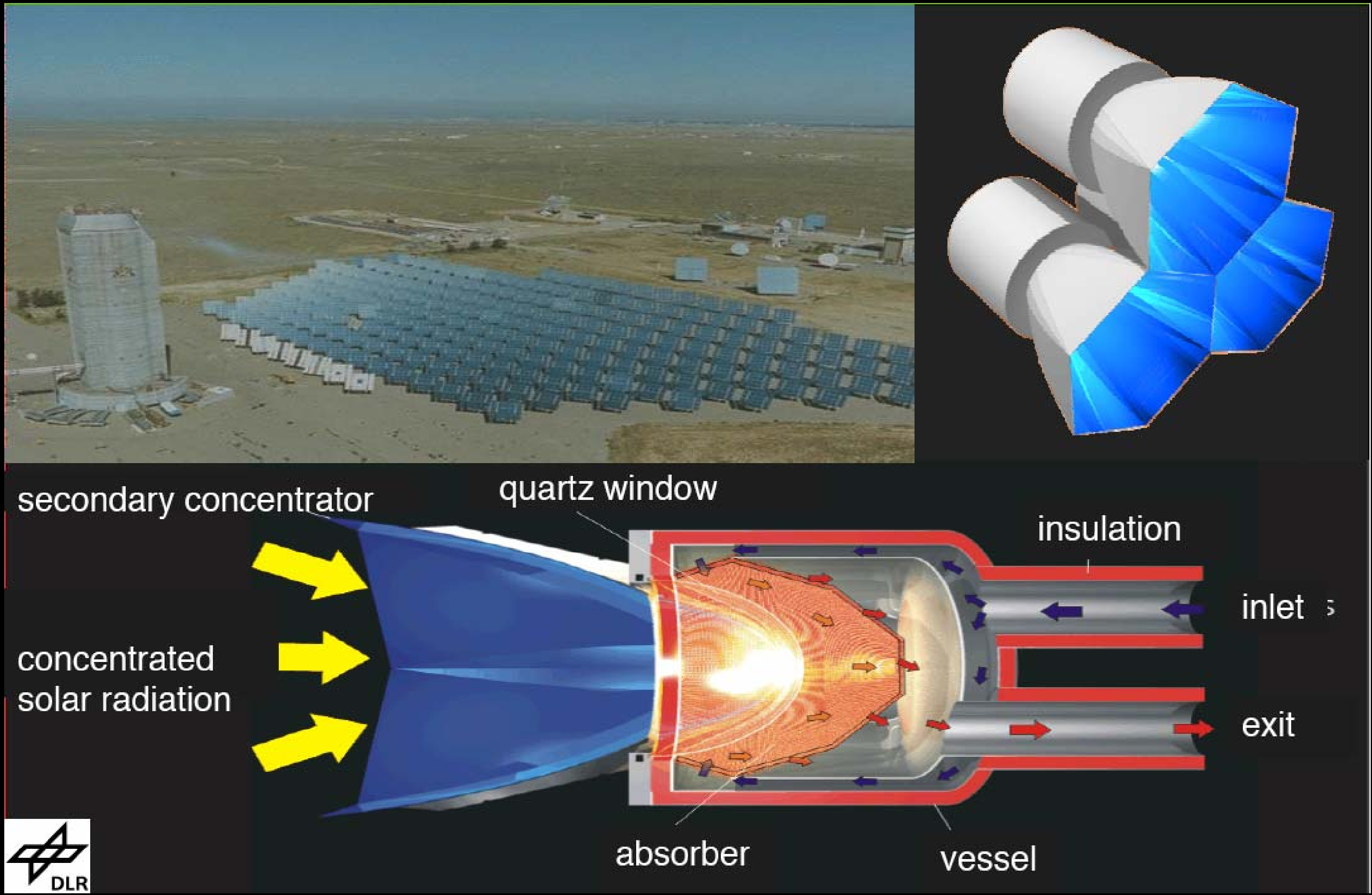
Source: *Institut für Kerntechnik und Energiewandlung e.V. (IKE e.V.), Pfaffenwaldring 31, W-7000 Stuttgart 80 (F.R.G.)*

Solar Dish-Engine System

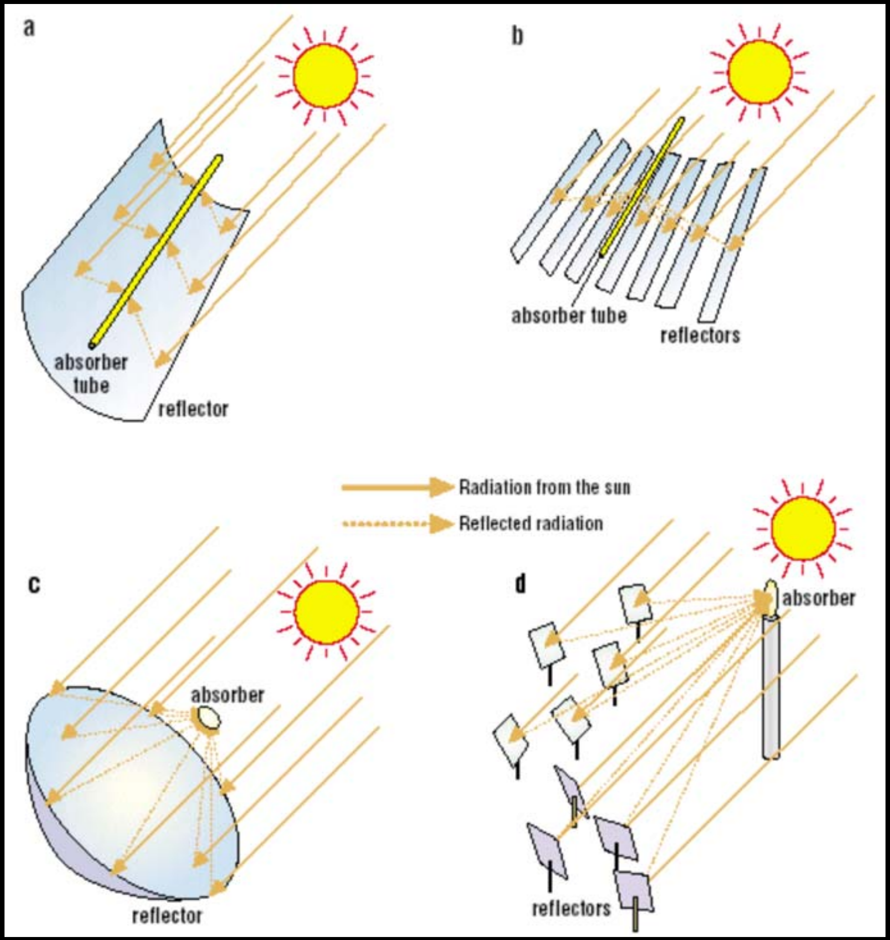
Table 1: Comparison between the operational data of solar-thermal power stations using a MgH_2/Mg-store and a TiH_2/TiH-store, respectively

STORAGE SYSTEM	MgH_2/Mg	TiH_2/TiH
Operating temperatures, °C	300-480	650-750
Operating H_2 pressures, MPa	1.0-10	0.1-1.0
Mass of storage material, kg	24	72
Total system mass, kg	512	655
Energy storage capacity, kWh_{th}	14.4	17.3
Efficiency of the Stirling engine (2nd law)	0.2	0.4
Electric power, kW_e	1	2
System efficiency ($kW_e/kW_{incoming\ solar\ flux}$):		
(a) Without storage	0.12	0.22
(b) Including storage	0.10	0.18

Advanced Tower



Sun Radiation Concentration



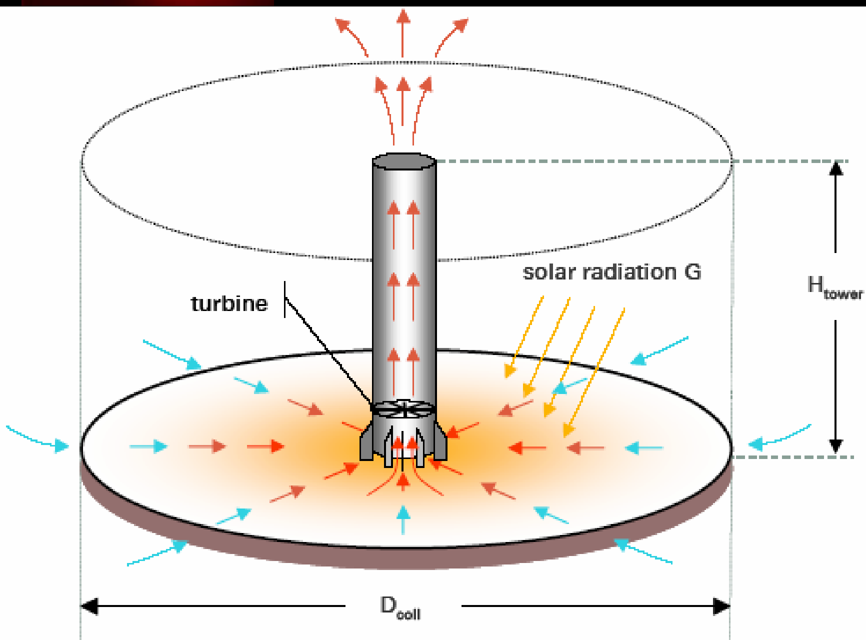
(a) parabolic trough collector

(b) linear Fresnel collector

(c) central receiver system with dish collector and

(d) central receiver system with distributed reflectors

Solar Chimney/Tower



A solar chimney power plant has a high chimney (tower), with a height of up to 1000 m, and this is surrounded by a large collector roof, up to 130 m in diameter, that consists of glass or resistive plastic supported on a framework (see artist's impression). Towards its centre, the roof curves upwards to join the chimney, creating a funnel. The sun heats up the ground and the air underneath the collector roof, and the heated air follows the upward incline of the roof until it reaches the chimney. There, it flows at high speed through the chimney and drives wind generators at its bottom. The ground under the collector roof behaves as a storage medium, and can even heat up the air for a significant time after sunset. The efficiency of the solar chimney power plant is below 2%, and depends mainly on the height of the tower, and so these power plants can only be constructed on land which is very cheap or free. Such areas are usually situated in desert regions. However, the whole power plant is not without other uses, as the outer area under the collector roof can also be utilized as a greenhouse for agricultural purposes. As with trough and tower plants, the minimum economical size of solar chimney power plants is also in the multi-megawatt range.

Source: www.sbp.de

Design of Commercial Solar Updraft Tower Systems – Utilization of Solar Induced Convective Flows for Power Generation

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Solar Chimney/Tower

Power output:

Power output: P

solar input: $\dot{Q}_{solar}$

$$P = \dot{Q}_{solar}\eta_{coll}\eta_{tower}\eta_{turbine} = \dot{Q}_{solar}\eta_{plant}$$

$$\dot{Q}_{solar} = G_h A_{coll}$$

$$\Delta p_{tot} = g\int_{o}^{H_{tower}}(\rho_a - \rho_{tower})dH = \Delta p_{static} + \Delta p_{dynamic}$$

$$P_{tot} = \Delta p_{tot} V_{tower,\max} A_{coll}$$

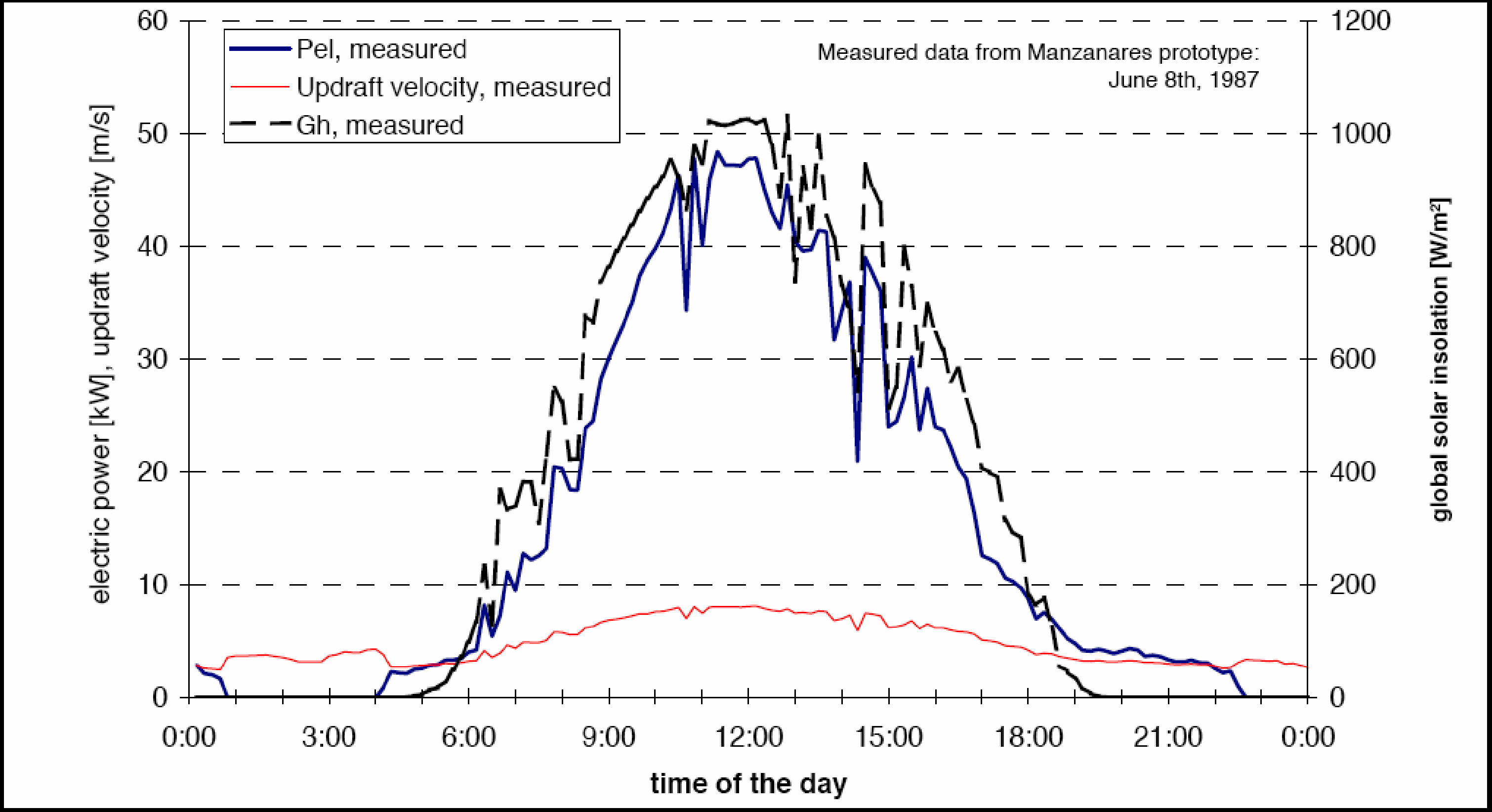
$$\eta_{tower} = \frac{P_{tot}}{\dot{Q}} = \frac{\frac{1}{2}\dot{m}V^2_{tower,\max}}{\dot{Q}}$$

$$V_{tower,\max} = \sqrt{2gH_{tower}\frac{\Delta T}{T_o}}$$

$$\eta_{tower} = \frac{gH}{c_p T_o}$$

The tower converts the heat flow column produced by the collector into kinetic energy and potential energy. The density difference of the air caused by the temperature rise in the collector works as driving force. The lighter of air in the tower is connected with the surrounding atmosphere at the base and at the top of the tower. Hence a pressure difference is produced between tower base and the ambient:

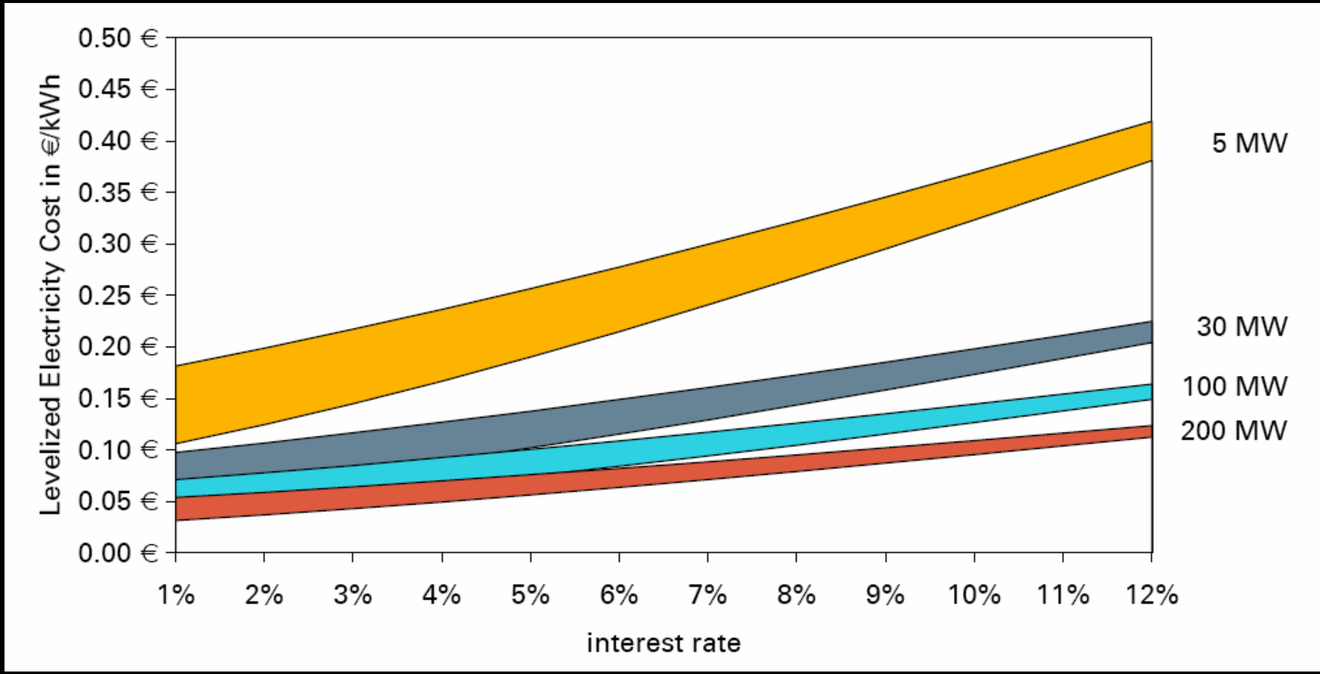
Solar Chimney/Tower



Solar Chimney / Tower

Capacity	MW	5	30	100	200
tower height	m	550	750	1000	1000
tower diameter	m	45	70	110	120
collector diameter	m	1250	2900	4300	7000
electricity output [A]	GWh/a	14	99	320	680

[A] at a site with an annual global solar radiation of 2300 kWh/(m²a)



Levelized Energy Cost

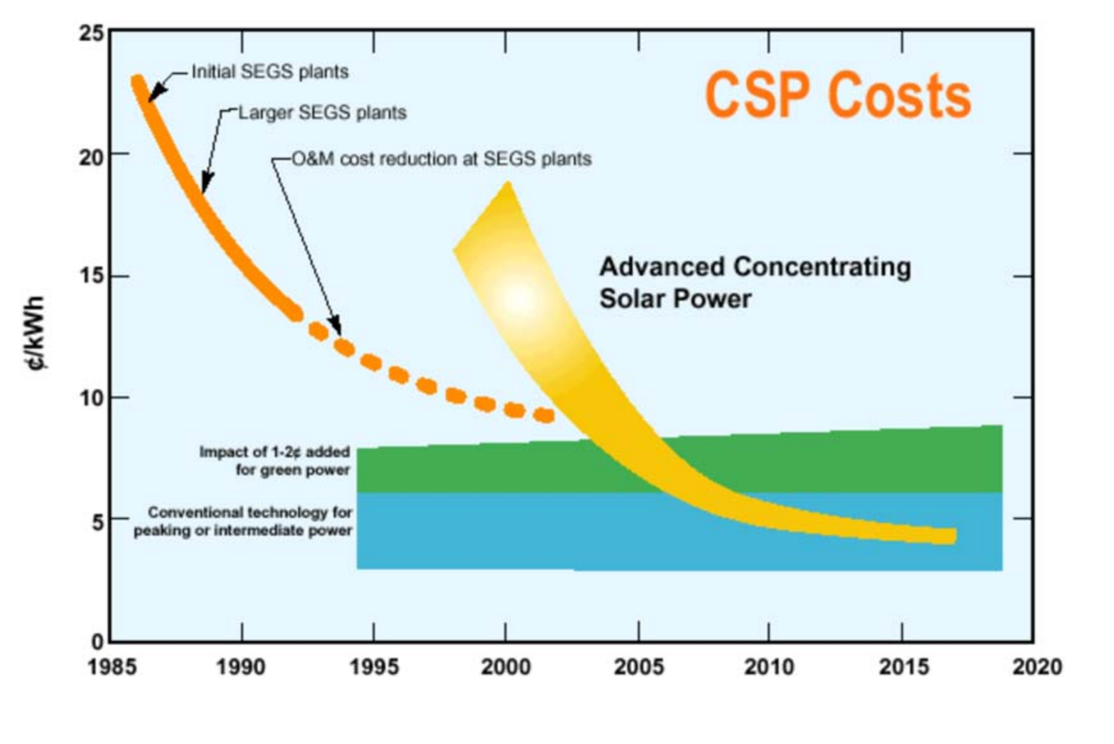
$$\mathrm{LEC} = \frac{\mathrm{CC}(\$) \times \mathrm{FCR} + \mathrm{O\&M}_{\mathrm{fixed}}(\$)}{\mathrm{Annual\,Energy(kWh)}} + \cancelto{0}{\mathrm{O\&M}_{\mathrm{variable/fuel}}}(\$/\mathrm{kWh})$$

- Performance
- Capital Cost
- Financing
- Operating Cost

- Efficiency
- Size
- Capacity Factor
- Risk

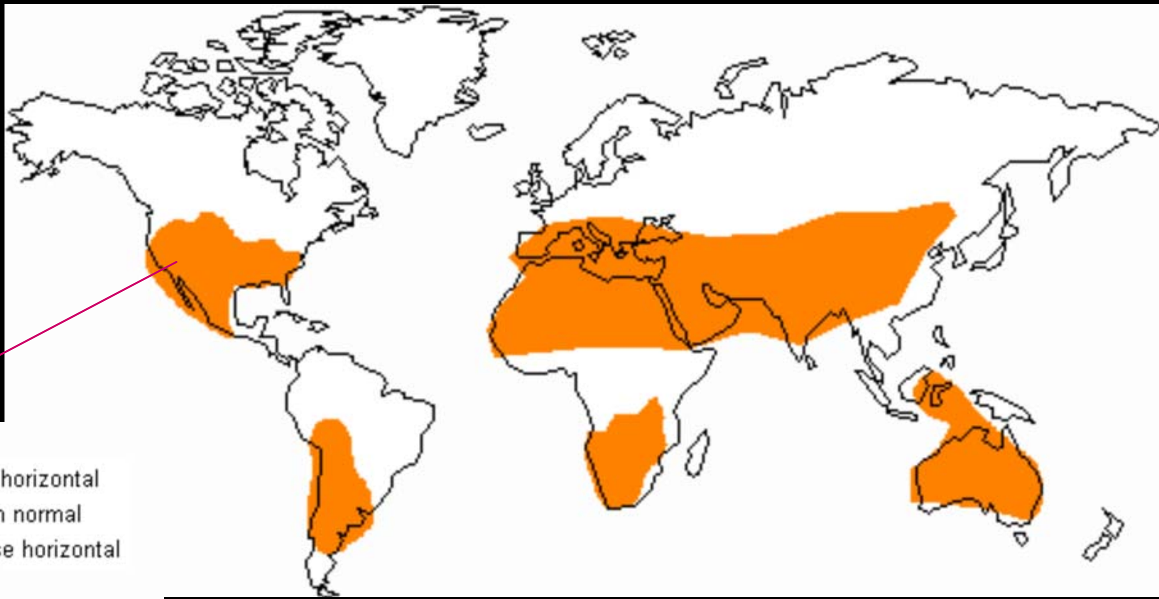
Commercial Solar Plant Costs

Solar Electric Generating Systems (SEGS)

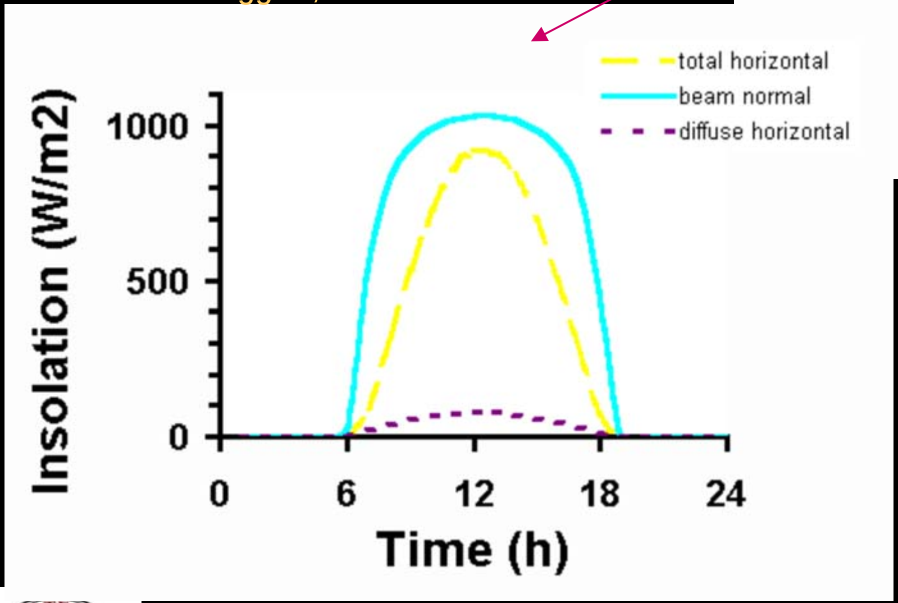


Levelized energy cost

The Solar Resource



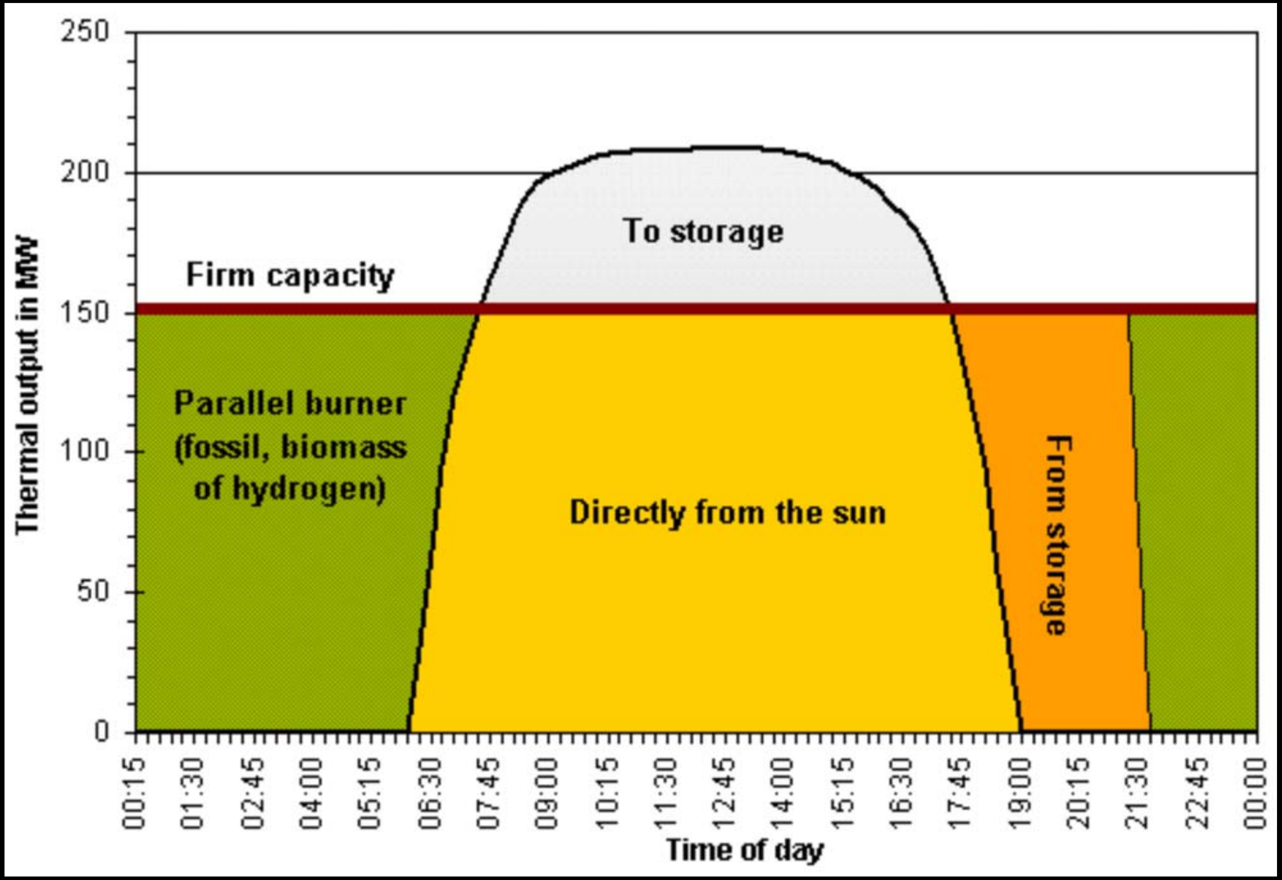
Daggett, California



Peak radiation: 1030 W/m^2

Full Day: 10.6 kWh/m^2

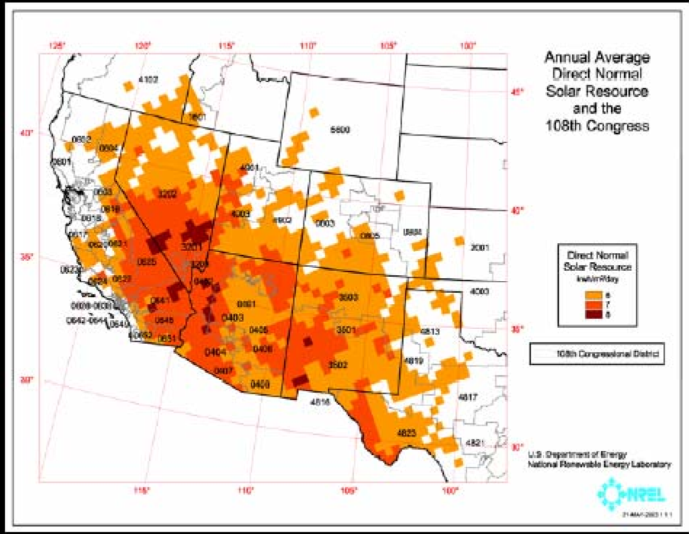
Solar Thermal Plant Power Output



Southwest Strategy

Resource Availability:

State	Solar Capacity (MW)	Land Area (Sq Mi)
AZ	1,652,000	12,790
CA	742,305	5,750
NV	619,410	4,790
NM	1,119,000	9,157
Total	4,132,715	32,487



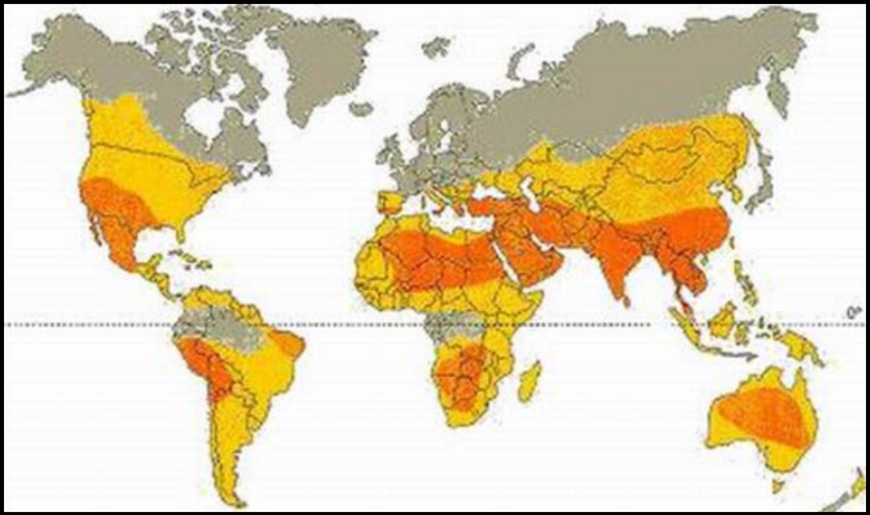
The table and map represent land that has no primary use today, exclude land with slope > 1%, and do not count sensitive lands.

Solar Energy Resource ≥ 7.0 kWhr/m²/day (includes only excellent and premium resource)

Current total generation in the four states is 83,500 MW.

Source: Luc Moens. NREL; GCEP Workshop, October, 2004

Solar Thermal Power Plant Potential



Comparably low power generation costs can be achieved wherever insolation reaches 1,900 kWh per square meter and year or more. Adequate areas would be e.g. Northern and Southern Africa, the Arabic peninsula, large areas of India, Central and Western Australia, the high plateaus of the Andes states, the Northeast of Brazil, northern Mexico and the Southwest of the United States. Potential sites in Europe are located in Spain, Italy, Greece and on some Mediterranean islands.