LECTURE NOTES RADIATION

Dienstag, 26. April 2022 10:22

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Energy Systems & Power Engineering

151-0206-00L

Lecturers: Prof. Aldo Steinfeld, aldo.steinfeld@ethz.ch

Teaching Assistants: Remo Schäppi, schremo@ethz.ch
Sebastian Sas, ssasbrun@ethz.ch

Course website: www.prec.ethz.ch
> Teaching
> Lectures by PREC
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Topics

- 26.4 Principles of Solar Radiation
- 03.5 Solar Flat Plate Collectors
- 10.5 Solar Concentrating Optics
- 17.5 Concentrated Solar Power (CSP)
- 24.5 Solar Photovoltaics (PV)
- 31.5 EXAM

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Bibliography

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  J. A. Duffie and W. A. Beckman
  John Wiley & Sons, Inc., 1991.

- Solar Power Plants
  C.J. Winter, R.L. Sizmann, L.L. Vant-Hull
  Springer Verlag, 1991.

- Thermal Radiation Heat Transfer
  R. Siegel and J. R Howell
  4th edition, Hemisphere, 2002.

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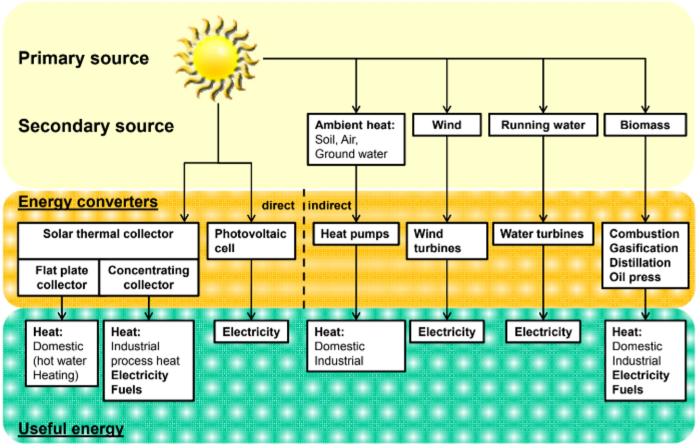
Solar Energy Conversion



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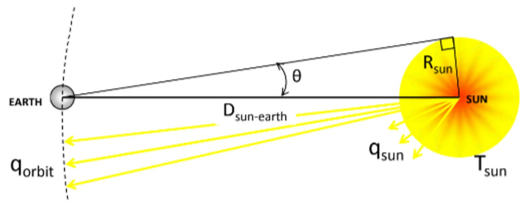
Sun-Earth Geometrical Relations



$$\left.\begin{array}{l} R_{sun} = 6.9599 \cdot 10^{8}\ \text{m} \\ D_{sun-earth} = 1.505 \cdot 10^{11}\ \text{m} \end{array}\right\} \to \theta = \sin^{-1}\left(R_{sun}/D_{sun-earth}\right) = 16' = 4.65\ \text{mrad}$$

$$q_{sun} \cdot 4\pi (R_{sun})^2 = q_{orbit} \cdot 4\pi (D_{sun-earth})^2 \to \frac{q_{sun}}{q_{orbit}} = \left(\frac{D_{sun-earth}}{R_{sun}}\right)^2 = \frac{1}{\sin^2\theta} \approx 46{,}200$$

$$\left.\begin{array}{l} q_{sun} = \sigma T_{sun}^4 \\ q_{orbit} \approx 1353\ \text{W/m}^2 \end{array}\right\} \to T_{sun} = \left[\left(\frac{D_{sun-earth}}{R_{sun}}\right)^2 \frac{q_{orbit}}{\sigma}\right]^{0.25} = 5780\ \text{K}$$

$\sigma = 5.6705 \cdot 10^{-8}\ \text{W} / (\text{m}^2 \cdot \text{K}^4)$

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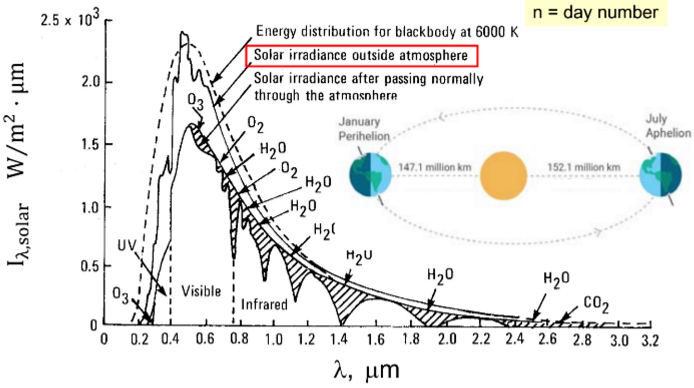
Solar Spectrum

$$q_{orbit} = I_{solar}$$

$$\overline{I}_{solar} = \int_0^{\infty} I_{\lambda,solar}(\lambda)d\lambda \approx 1353\,W/m^2$$

$$I_{solar} = \overline{I}_{solar}\left[1 + 0.034\cos(360 \cdot n/365.25)^{\circ}\right]$$

n = day number



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Planck's Law

Spectral distribution of blackbody hemispherical emissive power:

$$e_{\lambda b}(\lambda,T) = \frac{2\pi C_1}{\lambda^5(e^{C_2/(\lambda T)} - 1)}$$

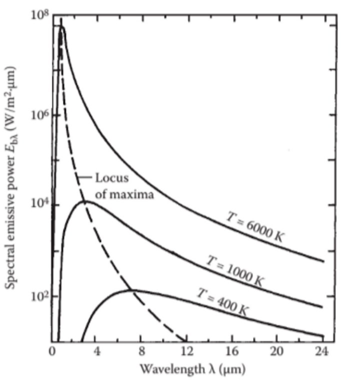
$C_1 = hc_0^2 = 0.59552197 \times 10^8\ W \cdot \mu m^4/(m^2 sr)$

$C_2 = \frac{hc_0}{k} = 14{,}387.69\ \mu m \cdot K$

h = Planck constant $= 6.6260755 \times 10^{-34}\ J \cdot s$

c_0 = speed of light $= 2.99792458 \times 10^8\ m/s$

k = Boltzmann constant $= 1.380658 \times 10^{-23}\ J/s$



Blackbody total emissive power:

$$e_b = \int_{\lambda=0}^{\infty} e_{\lambda b}(\lambda)\,d\lambda = \sigma T^4$$

σ = Stefan-Boltzmann const.

$= \frac{2C_1\pi^5}{15C_2^4} = 5.6705 \cdot 10^{-8}\ W/(m^2 \cdot K^4)$

Wien's Displacement Law

Spectral distribution of blackbody hemispherical emissive power:

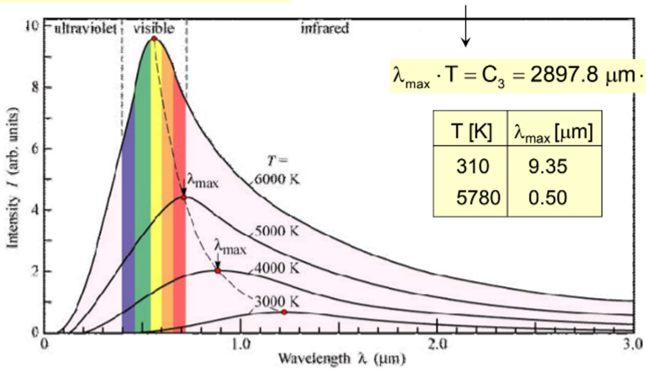
$$e_{\lambda b}(\lambda, T) = \frac{2\pi C_1}{\lambda^5 (e^{C_2/(\lambda T)} - 1)}$$

$$\frac{\partial}{\partial(\lambda T)} e_{\lambda b}(\lambda, T)/T^5 = 0$$

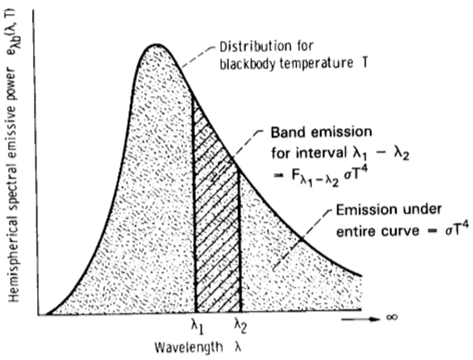
$$\downarrow$$

$$\lambda_{max} \cdot T = C_3 = 2897.8\ \mu m \cdot K$$

T [K]	λ_{max} [μm]
310	9.35
5780	0.50



Fractional Function



$$F_{\lambda_1 - \lambda_2} = \frac{\int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda) d\lambda}{\int_0^{\infty} e_{\lambda b}(\lambda) d\lambda} = \frac{1}{\sigma T^4} \int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda) d\lambda$$

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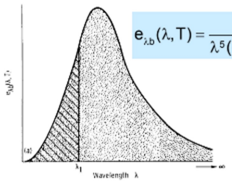
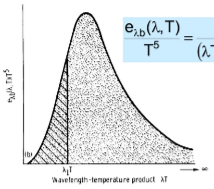
Fractional Function



$$e_{\lambda b}(\lambda, T) = \frac{2\pi C_1}{\lambda^5 (e^{C_2/(\lambda T)} - 1)}$$



$$\frac{e_{\lambda b}(\lambda, T)}{T^5} = \frac{2\pi C_1}{(\lambda T)^5 (e^{C_2/(\lambda T)} - 1)}$$

$$F_{0-\lambda} = \frac{1}{\sigma T^4} \int_0^{\lambda} e_{\lambda b} d\lambda$$

$$= \frac{1}{\sigma} \int_0^{\lambda T} \frac{e_{\lambda b}}{T^5} d(\lambda T) = F_{0-\lambda T}$$

λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$	λT [10^{-6} m K]	$F_{0-\lambda T}$
500	1.299E-09	3150	0.307	5800	0.720	8450	0.873	11100	0.933	13750	0.961
550	1.349E-08	3200	0.318	5850	0.725	8500	0.875	11150	0.934	13800	0.961
600	9.294E-08	3250	0.329	5900	0.729	8550	0.876	11200	0.935	13850	0.962
650	4.674E-07	3300	0.340	5950	0.734	8600	0.878	11250	0.936	13900	0.962
700	1.839E-06	3350	0.351	6000	0.738	8650	0.879	11300	0.936	13950	0.963
750	5.949E-06	3400	0.362	6050	0.742	8700	0.881	11350	0.937	14000	0.963
800	1.644E-05	3450	0.372	6100	0.746	8750	0.883	11400	0.938	14050	0.963
850	3.990E-05	3500	0.383	6150	0.750	8800	0.884	11450	0.938	14100	0.964
900	8.703E-05	3550	0.393	6200	0.754	8850	0.886	11500	0.939	14150	0.964
950	1.735E-04	3600	0.404	6250	0.758	8900	0.887	11550	0.940	14200	0.964
1000	3.208E-04	3650	0.414	6300	0.762	8950	0.889	11600	0.940	14250	0.965
1050	5.559E-04	3700	0.424	6350	0.766	9000	0.890	11650	0.941	14300	0.965
1100	9.113E-04	3750	0.434	6400	0.769	9050	0.891	11700	0.941	14350	0.965
1150	0.001	3800	0.443	6450	0.773	9100	0.893	11750	0.942	14400	0.965
1200	0.002	3850	0.453	6500	0.776	9150	0.894	11800	0.943	14450	0.966
1250	0.003	3900	0.462	6550	0.780	9200	0.895	11850	0.943	14500	0.966
1300	0.004	3950	0.472	6600	0.783	9250	0.897	11900	0.944	14550	0.966
1350	0.006	4000	0.481	6650	0.786	9300	0.898	11950	0.944	14600	0.967
1400	0.008	4050	0.490	6700	0.790	9350	0.899	12000	0.945	14650	0.967
1450	0.010	4100	0.499	6750	0.793	9400	0.901	12050	0.946	14700	0.967
1500	0.013	4150	0.507	6800	0.796	9450	0.902	12100	0.946	14750	0.968
1550	0.016	4200	0.516	6850	0.799	9500	0.903	12150	0.947	14800	0.968
1600	0.020	4250	0.524	6900	0.802	9550	0.904	12200	0.947	14850	0.968
1650	0.024	4300	0.533	6950	0.805	9600	0.906	12250	0.948	14900	0.968
1700	0.029	4350	0.541	7000	0.808	9650	0.907	12300	0.948	14950	0.969
1750	0.034	4400	0.549	7050	0.811	9700	0.908	12350	0.949	15000	0.969
1800	0.039	4450	0.557	7100	0.814	9750	0.909	12400	0.949	15050	0.969
1850	0.045	4500	0.564	7150	0.816	9800	0.910	12450	0.950	15100	0.969
1900	0.052	4550	0.572	7200	0.819	9850	0.911	12500	0.950	15150	0.970
1950	0.059	4600	0.579	7250	0.822	9900	0.912	12550	0.951	15200	0.970
2000	0.067	4650	0.587	7300	0.824	9950	0.913	12600	0.951	15250	0.970
2050	0.075	4700	0.594	7350	0.827	10000	0.914	12650	0.952	15300	0.971
2100	0.083	4750	0.601	7400	0.829	10050	0.915	12700	0.952	15350	0.971
2150	0.092	4800	0.608	7450	0.832	10100	0.916	12750	0.953	15400	0.971
2200	0.101	4850	0.614	7500	0.834	10150	0.917	12800	0.953	15450	0.971
2250	0.110	4900	0.621	7550	0.837	10200	0.918	12850	0.954	15500	0.971
2300	0.120	4950	0.627	7600	0.839	10250	0.919	12900	0.954	15550	0.972
2350	0.130	5000	0.634	7650	0.841	10300	0.920	12950	0.955	15600	0.972
2400	0.140	5050	0.640	7700	0.844	10350	0.921	13000	0.955	15650	0.972
2450	0.151	5100	0.646	7750	0.846	10400	0.922	13050	0.956	15700	0.972
2500	0.161	5150	0.652	7800	0.848	10450	0.923	13100	0.956	15750	0.973
2550	0.172	5200	0.658	7850	0.850	10500	0.924	13150	0.956	15800	0.973
2600	0.183	5250	0.664	7900	0.852	10550	0.925	13200	0.957	15850	0.973
2650	0.194	5300	0.669	7950	0.854	10600	0.925	13250	0.957	15900	0.973
2700	0.205	5350	0.675	8000	0.856	10650	0.926	13300	0.958	15950	0.974
2750	0.217	5400	0.680	8050	0.858	10700	0.927	13350	0.958	16000	0.974
2800	0.228	5450	0.686	8100	0.860	10750	0.928	13400	0.958	16050	0.974
2850	0.239	5500	0.691	8150	0.862	10800	0.929	13450	0.959	16100	0.974
2900	0.251	5550	0.696	8200	0.864	10850	0.930	13500	0.959	16150	0.974
2950	0.262	5600	0.701	8250	0.866	10900	0.930	13550	0.960	16200	0.975
3000	0.273	5650	0.706	8300	0.868	10950	0.931	13600	0.960	16250	0.975
3050	0.285	5700	0.711	8350	0.869	11000	0.932	13650	0.960	16300	0.975
3100	0.296	5750	0.715	8400	0.871	11050	0.933	13700	0.961	16350	0.975

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Fractional Function

$$F_{0-\lambda T} = \frac{1}{\sigma T^4} \int_0^{\lambda} e_{\lambda b}(\lambda) d\lambda$$

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> Teaching
> Lectures by PREC
> Additional material
> Planck’s fractional function

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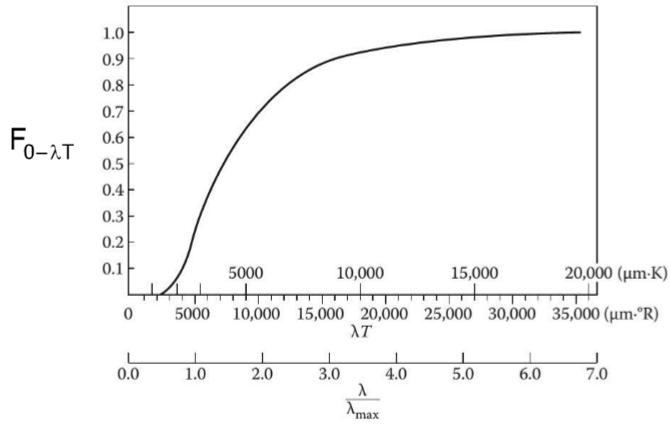
Fractional Function



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Extraterrestrial Solar Irradiance

% of solar constant in 0-λ band ≈ $F_{0-\lambda\cdot 5780K}$

Extraterrestrial Solar Irradiance

λ (μm)	E_λ (W/m² μm)	D_λ (%)	λ (μm)	E_λ (W/m² μm)	D_λ (%)	λ (μm)	E_λ (W/m² μm)	D_λ (%)
0.115	0.00799	3.76E−04	0.43	1389	11.98	0.90	889.60	63.91
0.14	0.07694	1.07E−03	0.44	1848	13.25	1.00	730.70	69.84
0.16	0.20640	1.25E−03	0.45	2131	14.72	1.2	488.60	78.55
0.18	2.06	2.45E−03	0.46	2092	16.26	1.4	342.90	84.58
0.20	7.93	8.68E−03	0.47	2010	17.79	1.6	247.70	88.89
0.22	51.91	0.05	0.48	2102	19.32	1.8	168.20	91.88
0.23	59.09	0.08	0.49	2072	20.78	2.0	115.90	93.91
0.24	42.19	0.12	0.50	1932	22.24	2.2	82.58	95.35
0.25	62.28	0.16	0.51	1915	23.66	2.4	58.47	96.36
0.26	90.16	0.22	0.52	1864	25.00	2.6	43.54	97.10
0.27	297.50	0.38	0.53	1938	26.38	2.8	33.25	97.65
0.28	78.46	0.52	0.54	1813	27.78	3.0	25.60	98.08
0.29	617.70	0.74	0.55	1905	29.16	3.2	20.08	98.42
0.30	416.60	1.14	0.56	1812	30.52	3.4	15.75	98.68
0.31	464.80	1.56	0.57	1803	31.86	3.6	12.83	98.89
0.32	836.30	2.08	0.58	1818	33.19	3.8	10.39	99.06
0.33	1162	2.72	0.59	1716	34.51	4.0	8.30	99.19
0.34	1133	3.42	0.60	1737	35.80	4.5	5.03	99.43
0.35	1081	4.12	0.62	1681	38.29	5.0	3.27	99.58
0.36	1188	4.84	0.64	1591	40.68	6.0	1.64	99.75
0.37	1376	5.67	0.66	1517	42.94	7.0	0.90360	99.84
0.38	1096	6.50	0.68	1474	45.14	8.0	0.53890	99.89
0.39	1301	7.26	0.70	1413	47.25	10.0	0.22720	99.94
0.40	1727	8.12	0.72	1361	49.29	15.0	0.04418	99.98
0.41	1610	9.39	0.75	1273	52.16	20.0	0.01385	99.99
0.42	1787	10.71	0.80	1129	56.54	50.0	0.00036	100.0

Source: Goswami, Principles of Solar Enegineering, 2015

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Radiation Attenuation in a Medium

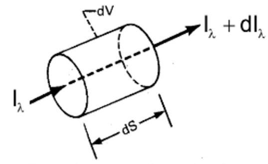
Intensity decrease as a result of being absorbed and scattered away along a path dS:

$$dI_\lambda = -K_\lambda(S) \cdot I_\lambda dS$$

Extinction coefficient (length^{-1})

$$K_\lambda = a_\lambda + \sigma_{s\lambda}$$

Absorption Coefficient — Scattering Coefficient



Intensity incident normally on absorbing-scattering volume element of thickness dS

$$\int_{I_\lambda(0)}^{I_\lambda(S)} \frac{dI_\lambda}{I_\lambda} = -\int_0^S K_\lambda(S) dS$$

$$\ln\left[\frac{I_\lambda(S)}{I_\lambda(0)}\right] = -\int_0^S K_\lambda(S) dS$$

Bouguer's Law

$$I_\lambda(S) = I_\lambda(0) \cdot \exp\left[-\int_0^S K_\lambda(S) dS\right] = I_\lambda(0) \cdot e^{-\kappa}$$

Optical thickness: $\kappa_\lambda(S) = \int_0^S K_\lambda(S) dS$

Transmittance: $\tau_\lambda(S) = \frac{I_\lambda(S)}{I_\lambda(0)} = e^{-\kappa_\lambda(S)}$

$\kappa_\lambda >> 1 \longrightarrow \tau \rightarrow 0$; optically thick

$\kappa_\lambda << 1 \longrightarrow \tau \rightarrow 1$; optically thin

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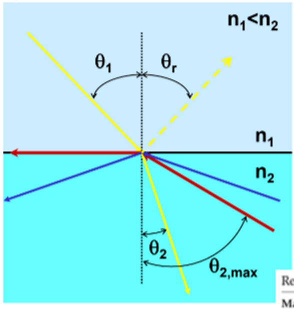
Radiation Properties



Surface properties: α, ε, ρ

Medium properties: K, κ, τ

Fresnel's law:

$$\rho_\lambda = \frac{1}{2}\frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)}\left[1 + \frac{\cos^2(\theta_1 + \theta_2)}{\cos^2(\theta_1 - \theta_2)}\right]$$

$$\rho_\lambda(\theta_1 = 0) = \rho_{\lambda,normal} = \left(\frac{n-1}{n+1}\right)^2$$

$$\theta_{1,max} = \frac{\pi}{2} \longrightarrow \theta_{2,max} = \sin^{-1}\left(\frac{n_1}{n_2}\right)$$

Snell's law: $n = \frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$

Refractive Index for Various Substances in the Visible Range Based on Air

Material	Index of Refraction
Air	1.000
Clean polycarbonate	1.59
Diamond	2.42
Glass (solar collector type)	1.50–1.52
Plexiglass* (polymethyl methacrylate, PMMA)	1.49
Mylar* (polyethylene terephthalate, PET)	1.64
Quartz	1.55
Tedlar* (polyvinyl fluoride, PVF)	1.45
Teflon* (polyfluoroethylenepropylene, FEP)	1.34
Water—liquid	1.33
Water—solid	1.31

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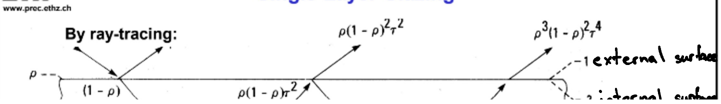
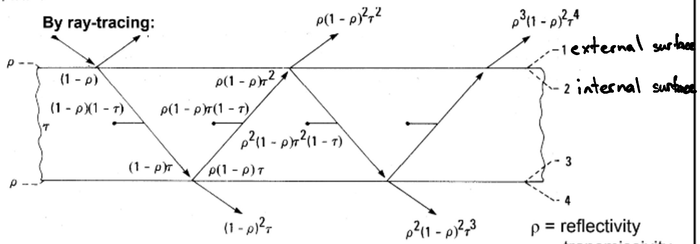
Single-Layer Glazing

By ray-tracing:



By ray-tracing:



ρ = reflectivity
τ = transmissivity

R = Fraction of incident radiation reflected (reflectance):

$$R = \rho\left[1 + (1-\rho)^2\tau^2(1+\rho^2\tau^2+\rho^4\tau^4+\ldots)\right] = \rho\left[1 + \frac{(1-\rho)^2\tau^2}{1-\rho^2\tau^2}\right]$$

T = Fraction of incident radiation transmitted (transmittance):

$$T = \tau(1-\rho)^2\left[1+\rho^2\tau^2+\rho^4\tau^4+\ldots\right] = \frac{\tau(1-\rho)^2}{1-\rho^2\tau^2} = \tau\left(\frac{1-\rho}{1+\rho}\right)\left(\frac{1-\rho^2}{1-\rho^2\tau^2}\right) \approx \tau\left(\frac{1-\rho}{1+\rho}\right)$$

A = Fraction of incident radiation absorbed (absorptance):

$$A = (1-\rho)(1-\tau)\left[1+\rho\tau+\rho^2\tau^2+\rho^3\tau^3+\ldots\right] = \frac{(1-\rho)(1-\tau)}{1-\rho\tau}$$

$$1 = A + T + R$$

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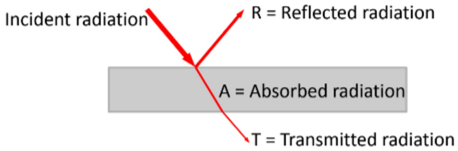
Single-Layer Glazing



$A + R + T = 1$

R = Fraction of incident radiation reflected (reflectance): $R = \rho\left[1 + \frac{(1-\rho)^2\tau^2}{1-\rho^2\tau^2}\right]$

T = Fraction of incident radiation transmitted (transmittance): $T = \tau\left(\frac{1-\rho}{1+\rho}\right)$

A = Fraction of incident radiation absorbed (absorptance): $A = \frac{(1-\rho)(1-\tau)}{1-\rho\tau}$

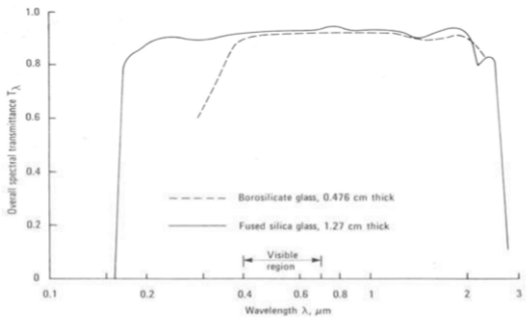
Limiting case: $a \to 0 \longrightarrow \tau \to 1 \longrightarrow$

- $R \longrightarrow \frac{2\rho}{1+\rho}$
- $T \longrightarrow \frac{1-\rho}{1+\rho}$
- $A \longrightarrow 0$

<u>Example</u>: glass layer of absorption coefficient a, thickness d:

$$\lambda = 0.2 - 3\ \mu\text{m}: \quad a \cdot d \to 0 \longrightarrow \tau = \exp(a \cdot d) \to 1$$

$$\text{Typically: } n_{glass} \approx 1.5 \longrightarrow \rho_{glass} = \left(\frac{n-1}{n+1}\right)^2 \approx 0.04 \longrightarrow T = \tau \frac{1-\rho}{1+\rho} \approx 0.92$$



Overall spectral transmittance T_λ of glass plate

Ref.: Y. S. Touloukian, *Thermal Radiative Properties*, 1970.

Absorption Coefficient of Water

Ref. G. Hale, M. Querry, *Appl. Opt.*, Vol. 12, pp. 555-563, 1973.

λ, μm	a_λ, cm^{-1}	λ, μm	a_λ, cm^{-1}
0.20	0.0691	2.4	50.1
0.25	0.0168	2.6	153
0.30	0.0067	2.8	5160
0.35	0.0023	3.0	11,400
0.40	0.00058	3.2	3630
0.45	0.00029	3.4	721
0.50	0.00025	3.6	180
0.55	0.000045	3.8	112
0.60	0.0023	4.0	145
0.65	0.0032	4.2	206
0.70	0.0060	4.4	294
0.75	0.0261	4.6	402
0.80	0.0196	4.8	393
0.85	0.0433	5.0	312
0.90	0.0679	5.5	265
0.95	0.388	6.0	2240
1.0	0.363	6.5	758
1.2	1.04	7.0	574
1.4	12.4	7.5	546
1.6	6.72	8.0	539
1.8	8.03	8.5	543
2.0	69.1	9.0	557
2.2	16.5	9.5	587
		10.0	638

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Fractions of solar radiation transmitted through water

Spectral interval λ, μm	Incident solar-energy distribution	Transmitted energy distribution for water-layer thickness, cm							
		0.001	0.01	0.1	1	10	100	1000	10000
0.3–0.6	0.237	0.237	0.237	0.237	0.237	0.236	0.229	0.173	0.014
0.6–0.9	0.360	0.360	0.360	0.359	0.353	0.305	0.129	0.010	
0.9–1.2	0.179	0.179	0.178	0.172	0.123	0.008			
1.2–1.5	0.087	0.086	0.082	0.063	0.017				
1.5–1.8	0.080	0.078	0.064	0.027					
1.8–2.1	0.025	0.023	0.011						
2.1–2.4	0.025	0.025	0.019	0.001					
2.4–2.7	0.007	0.006	0.002						
Totals	1.000	0.994	0.953	0.859	0.730	0.549	0.358	0.183	0.014

Ref. Y. Kondratyev, *Radiation in the Atmosphere*, 1969.

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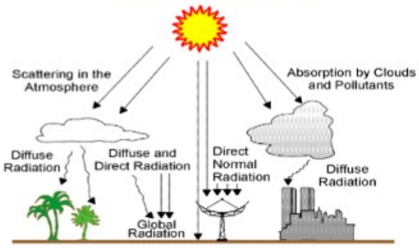
Dr. P.G. Loutzenhiser

Solar Irradiance



I_{DN} = **direct normal solar irradiance:** The solar irradiance received on a surface perpendicular to sunrays without having been scattered by the atmosphere.

I_D = **direct solar irradiance on an horizontal surface:** The solar irradiance received on an horizontal surface from the sun without having been scattered.

I_d = **diffuse solar irradiance on an horizontal surface:** The solar irradiance on a horizontal surface after the direction has been changed by scattering.

I = **global solar irradiance on an horizontal surface:** The sum of the direct and diffuse solar irradiance on a horizontal surface; $I = I_D + I_d$

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Solar Irradiation Measuring Devices

Pyrheliometer: an instrument for measuring direct-normal solar irradiance (I_{DN}) by tracking the sun

Pyranometer: an instrument for measuring global solar irradiance usually on a horizontal surface (**I**).

Pyranometer with a shade disc: an instrument for measuring diffuse irradiance usually on a horizontal surface (I_d).

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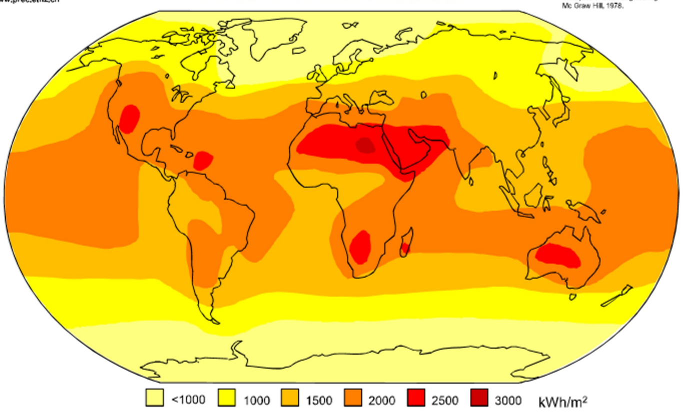
Direct Normal Irradiation

Ref: F. Kreith, J. Kreider, *Principles of Solar Engineering* Mc Graw Hill, 1978.



over the whole year

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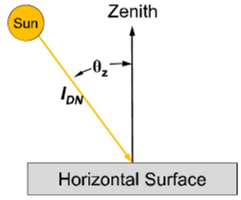
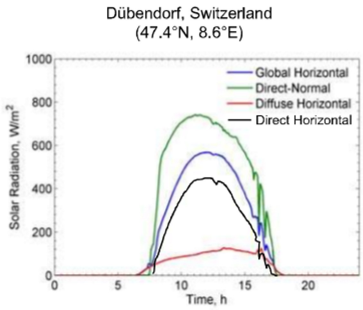
Solar Irradiance on a Horizontal Surface





$I = I_D + I_d$

where $I_D = I_{DN} \cos\theta_z$

- I_{DN} = direct normal solar irradiance
- I_D = direct solar irradiance on an horizontal surface
- I_d = diffuse solar irradiance on an horizontal surface
- I = global solar irradiance on an horizontal surface
- θ_z = zenith angle: angle between the vertical and the line to the sun, i.e., angle of incidence of direct-normal irradiance on a horizontal surface.

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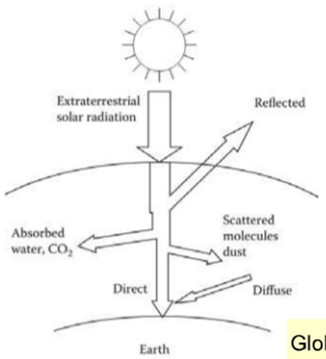
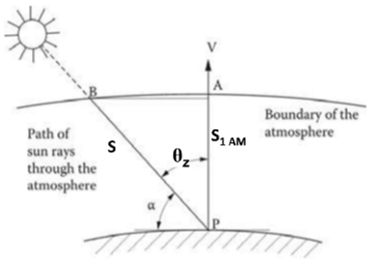
Attenuation by Atmosphere





Global solar irradiane: $I = I_{\substack{\text{solar}\\ \text{extraterrestrial}}} \cdot e^{-K \cdot S}$

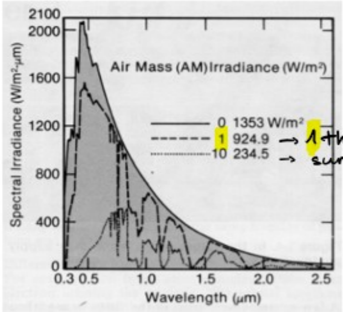
Sun path: $S_{1AM} = S \cdot \cos\theta_z$

Air Mass: $AM = \dfrac{1}{\cos\theta_z}$

Air Mass

	Wavelength Band		
Air Mass	**Ultraviolet**	**Visible**	**Infrared**
0	8.7%	38.2%	53.1%
1	4.6%	46.4%	49.0%
4	1.0%	42.1%	56.9%

$$AM = \frac{1}{\cos\theta_z}$$



→ 1 thickness of atmosphere
→ sunrise, sunset 10 atmospheres

Solar Angle Formulations

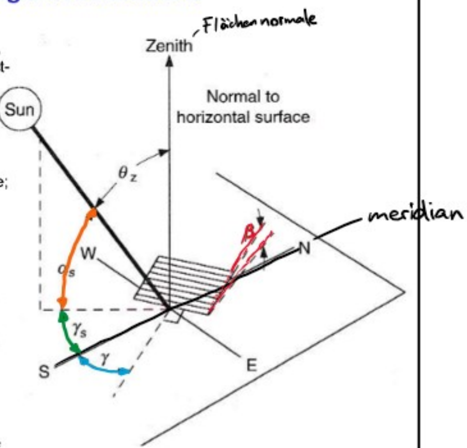
θ_z = **zenith angle:** the angle between the vertical and the line to the sun, i.e., the angle of incidence of direct-normal irradiance on a horizontal surface. $\theta_z + \alpha_s \stackrel{!}{=} 90°$

α_s = **solar altitude angle**: angle between a line collinear with the sun's rays and the horizontal plane; i.e., the complement of θ_z.

γ_s = **solar azimuth angle:** angular displacement from south of the projection of direct-normal irradiance on the horizontal plane.

γ = **surface azimuth angle:** deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, $-180° < \gamma < 180°$

β = **slope:** angle between the plane of the surface and the horizontal; $0 < \beta < 180°$.



Solar Angle Formulations

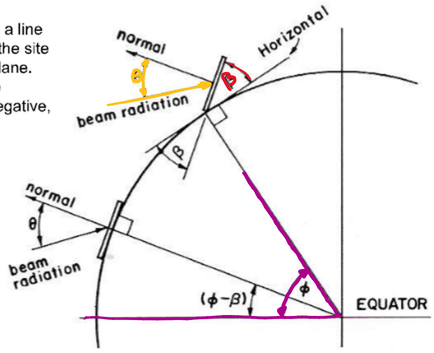
β = **slope:** angle between the plane of the surface and the horizontal; $0 < \beta < 180°$.

θ = **angle of incidence**: angle between

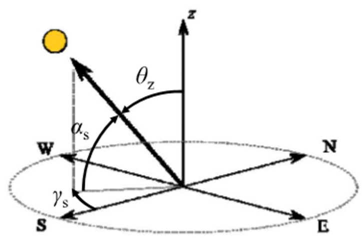
β = **slope:** angle between the plane of the surface and the horizontal; $0<\beta<180°$.

θ = **angle of incidence**: angle between the direct-normal irradiance and the normal to that surface.

Φ = **latitude angle:** angle between a line from the center of the earth to the site of interest and the equatorial plane. Values north of the equator are positive and those south are negative, $-90° < \Phi < 90°$



Sun Position



θ_z : zenith angle

α_s : solar altitude angle

γ_s : solar azimuth angle

<u>Conventions</u>
South → $\gamma_s = 0°$
West → γ_s positive
East → γ_s negative

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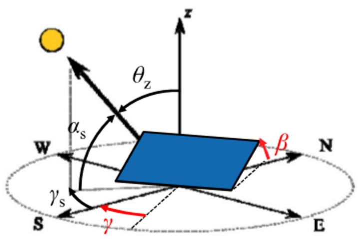
Surface Orientation



θ_z : zenith angle

α_s : solar altitude angle

γ_s : solar azimuth angle

β : slope / tilt angle

γ : surface azimuth angle

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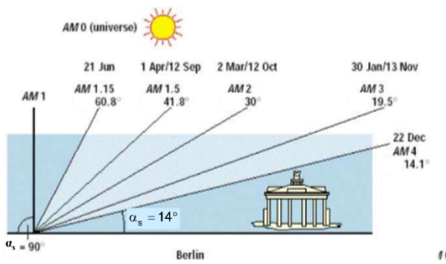
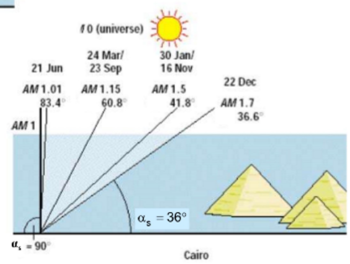
Solar Altitude

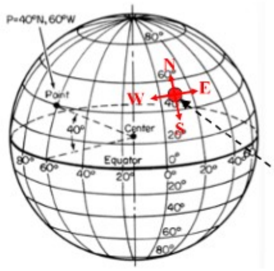
$\overline{I}_{solar} \approx 1353\,W/m^2$





Solstice: June 20-21 and Dec. 21-22, sun reaches the highest/lowest position in the sky.

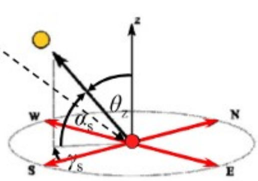
Global vs. Local Coordinate System



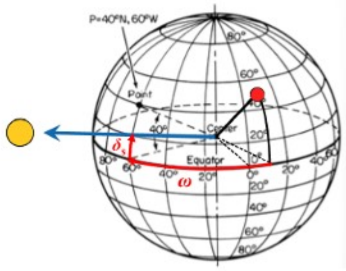
Zürich
Latitude: Φ = 47° 22′ N
Longitude: l_{local} = 8° 32′ E

Sign conventions:
North and West → positive
East and South → negative

Φ = 47° 22′ N = +(47+22/60) = +47.36°
l_{local} = 8° 32′ E = -(8+32/60) = -8.53°



Global Coordinate System – Sun Position



$\boldsymbol{\delta_s}$: solar declination
$-23.45° < \delta_s < 23.45°$

$\boldsymbol{\omega}$: hour angle
$-180° < \omega < 180°$

Sign conventions:
North and West → positive
East and South → negative

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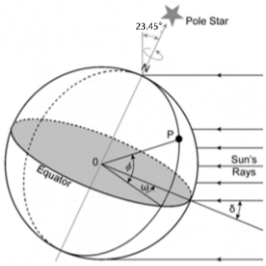
Solar Declination

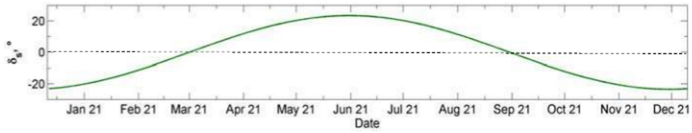
δ_s = solar declination: the angular position of the sun with respect to the equatorial plane. Declinations are for the Northern Hemisphere (the sign is reversed for the Southern Hemisphere)



$$\delta_s = 23.45^\circ \sin\left(\frac{360^\circ(284+n)}{365}\right)$$

$$-23.45^\circ < \delta_s < 23.45^\circ$$

where n is the day number:
Jan 1 = 1
Jan 2 = 2, etc.



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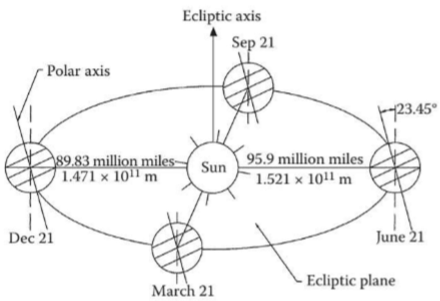
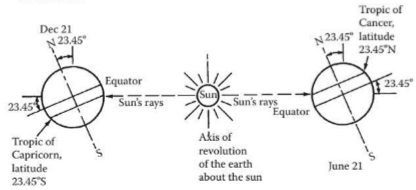
Solar Declination

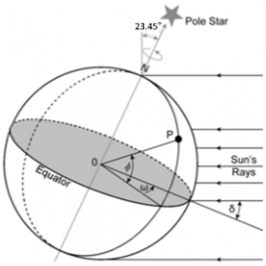


Solstice: June 21, δ_s = 23.45°
Dec. 21, δ_s = -23.45°



Hour Angle

ω = hour angle: the angular displacement of the sun east or west of the local meridian, based on the nominal time of 24 hours for the sun to travel 360° at 15° per hour. Morning values are negative, afternoon values are positive. At solar noon, ω = 0.



$$\omega = 15°/\text{hour} \times (AST - 12) = \frac{\text{minutes from local solar noon}}{4\ \text{min}/°}$$

AST: local solar time

At local solar noon, AST=12:

$$\omega = 0$$
$$\alpha_s = 90° - |\Phi - \delta_s|$$
$$\gamma_s = 0$$

$$\cos\theta_z = \sin\alpha_s = \sin\Phi\sin\delta_s + \cos\Phi\cos\omega\cos\delta_s$$

$$\begin{aligned}\cos\theta &= \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma)\\ &= \sin\delta_s\sin\phi\cos\beta - \sin\delta_s\cos\phi\sin\beta\cos\gamma + \cos\delta_s\cos\phi\cos\beta\cos\omega +\\ &\quad + \cos\delta_s\sin\phi\sin\beta\cos\omega\cos\gamma + \cos\delta_s\sin\beta\sin\omega\sin\gamma\end{aligned}$$

Solar Time

$$AST = LST + ET + (l_{st} - l_{local}) \times 4\ \text{min}/\text{deg}$$

$$l_{st}, l_{local} \begin{cases} < 0 \text{ for East} \\ > 0 \text{ for West}\end{cases}$$

AST: local solar time
LST: local standard time
l_{st}: standard time meridian
l_{local}: local longitude.

The equation of time:

$$ET\ (\text{minutes}) = 229.2\begin{bmatrix} 0.000075 + 0.001868\cos(B) - 0.032077\sin(B) - 0.014615\cos(2B) \\ -0.04089\sin(2B)\end{bmatrix}$$

where: $B(\text{deg}) = \dfrac{360°(n-1)}{365}$

Sunrise/Sunset Local times

At sunrise/sunset → solar altitude: $\alpha_s = 0$.

$$\text{Sunrise}/\text{Sunset} = 12{:}00\ \text{noon} \mp \left[\frac{(\cos^{-1}(-\tan\phi \times \tan\delta_s))}{15\ (\text{deg/hour})}\right]$$

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Standard Time Meridian

l_{st}

Relative to UTC	Description	Standard Meridian, l_{st}
-11	Nome Time (US) Samoa Standard Time	165° W
-10	Hawaiian Standard Time (US) Tahiti Time	150° W
-9	Alaska Standard Time (US) Yukon Standard Time	135° W
-8	US Pacific Standard Time	120° W
-7	US Mountain Standard Time	105° W
-6	US Central Standard Time Mexico Time	90° W
-5	US Eastern Standard Time Colombia Time	75° W
-4	Atlantic Standard Time Bolivia Time	60° W
-3	Eastern Brazil Standard Time Argentina Time	45° W
-2	Greenland Eastern Std. Time Fernando de Noronha Time (Brazil)	30° W
-1	Azores Time Cape Verde Time	15° W
0	Greenwich Mean Time Coordinated Universal Time Western Europe Time	0°
+1	Central Europe Time Middle European Time	15° E
+2	Eastern Europe Time Kaliningrad Time (Russia)	30° E
+3	Moscow Time (Russia) Baghdad Time	45° E
+4	Volga Time (Russia) Gulf Standard Time	60° E
+5	Yekaterinburg Time (Russia) Pakistan Time	75° E
+5.5	Indian Standard Time	82.5° E
+6	Novosibirsk Time (Russia) Bangladesh Time	90° E
+7	Krasnoyarsk Time (Russia) Java Time	105° E
+8	Irkutsk Time (Russia) China Coast Time	120° E
+9	Yakutsk Time (Russia) Japan Standard Time	135° E
+10	Vladivostok Time (Russia) Guam Standard Time	150° E
+11	Magadan Time (Russia) Solomon Islands Time	165° E
±12	Kamchatka Time (Russia) New Zealand Standard Time	180°

Relative to UTC = $x \rightarrow l_{st} = (-15°) \cdot x$

Example: US Pacific Standard Time

$x = -8 \rightarrow l_{st} = (-15°) \cdot (-8) = 120°$ W

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The Equation of Time

$$\text{ET (minutes)} = 229.2\begin{bmatrix} 0.000075 + 0.001868\cos(B) - 0.032077\sin(B) - \\ 0.014615\cos(2B) - 0.04089\sin(2B) \end{bmatrix}$$

$$\text{where:} \quad B(\text{deg}) = \frac{360°(n-1)}{365}$$

Date		Declination		Equation of time		Date		Declination		Equation of time	
		Deg	Min	Min	Sec			Deg	Min	Min	Sec
Jan	1	−23	4	−3	14	Feb	1	−17	19	−13	34
	5	−22	42	−5	6		5	−16	10	−14	2
	9	−22	13	−6	50		9	−14	55	−14	17
	13	−21	37	−8	27		13	−13	37	−14	20
	17	−20	54	−9	54		17	−12	15	−14	10
	21	−20	5	−11	10		21	−10	50	−13	50
	25	−19	9	−12	14		25	−9	23	−13	19
	29	−18	9	−13	5						
Mar	1	−7	53	−12	38	Apr	1	+4	14	−4	12
	5	−6	21	−11	48		5	5	46	−3	1
	9	−5	48	−10	51		9	7	17	−1	52
	13	−3	14	−9	49		13	8	46	−0	47
	17	−1	39	−8	42		17	10	12	+0	13
	21	−0	5	−7	32		21	11	35	1	6
	25	+1	30	−6	20		25	12	56	1	53
	29	3	4	−5	7		29	14	13	2	33
May	1	+14	50	+2	50	Jun	1	+21	57	2	27
	5	16	2	3	17		5	22	28	1	49
	9	17	9	3	35		9	22	52	1	6
	13	18	11	3	44		13	23	10	+0	18
	17	19	9	3	44		17	23	22	−0	33
	21	20	2	3	24		21	23	27	−1	25
	25	20	49	3	16		25	23	25	−2	17
	29	21	30	2	51		29	23	17	−3	7
Jul	1	+23	10	−3	31	Aug	1	+18	14	−6	17
	5	22	52	−4	16		5	17	12	−5	59
	9	22	28	−4	56		9	16	6	−5	33
	13	21	57	−5	30		13	14	55	−4	57
	17	21	21	−5	57		17	13	41	−4	12
	21	20	38	−6	15		21	12	23	−3	19
	25	19	50	−6	24		25	11	2	−2	18
	29	18	57	−6	23		29	9	39	−1	10
Sep	1	+8	35	−0	15	Oct	1	−2	53	+10	1
	5	7	7	+1	2		5	−4	26	11	17
	9	5	37	2	22		9	−5	58	12	27
	13	4	6	3	45		13	−7	29	13	30
	17	2	34	5	10		17	−8	58	14	25
	21	1	1	6	35		21	−10	25	15	10
	25	0	32	8	0		25	−11	50	15	46
	29	−2	6	9	22		29	−13	12	16	10
Nov	1	−14	11	+16	21	Dec	1	−21	41	11	16
	5	−15	27	16	23		5	−22	16	9	43
	9	−16	38	16	12		9	−22	45	8	1
	13	−17	45	15	47		13	−23	6	6	12
	17	−18	48	15	10		17	−23	20	4	47
	21	−19	45	14	18		21	−23	26	2	19
	25	−20	36	13	15		25	−23	25	+0	20
	29	−21	21	11	59		29	−23	17	−1	39

Example

Example: Find sunrise/sunset times in Zurich on Jan. 1

$\Phi_{Zurich} = 47°22'$

$l_{local} = 8°32'\ E = 8.533°\ E$

$l_{st} = 15°00'\ E = 15.0°\ E$

$$\text{Jan. } 1 \rightarrow n = 1 \rightarrow \delta_s = 23.45° \sin\left(\frac{360°\ (284+1)}{365}\right) = -23.01°$$

$$\text{Sunrise}/\text{Sunset} = 12{:}00 \text{ noon} \mp \underbrace{\left[\frac{\left(\cos^{-1}(-\tan\Phi \times \tan\delta_s)\right)}{15\ (\text{deg/hour})}\right]}_{4.17} = \begin{cases} 7.83 = 7{:}50 \\ 16.17 = 16{:}10 \end{cases}$$

$$ET = 229.2\begin{pmatrix} 0.000075 + 0.001868\cos B - 0.032077\sin B - \\ 0.014615\cos 2B - 0.04089\sin 2B \end{pmatrix} = -2.9 \text{ min}$$

$$B = \frac{360°(n-1)}{365} = 0°$$

$$LST = AST - \underbrace{ET}_{-2.9\text{ min}} - \underbrace{(l_{st} - l_{local}) \times 4\ \text{min}/\text{deg}}_{-25.9\text{min}} = \text{Solar Time} + 28.8 \text{ min}$$

$$\left(\text{Sunrise}/\text{Sunset}\right)_{LST} = \begin{cases} 8{:}19 \\ 16{:}39 \end{cases}$$

http://www.timeanddate.com

Example

Example: Calculate the angle of incidence of direct-normal irradiance on a surface located in the roof of ML, facing south, titled 45°, on Dec. 6, at 14:30 solar time.

$\Phi_{Zurich} = 47.22°$

$\omega = 15° \times (AST-12) = 15 \cdot 2.5 = 37.5°$

Dec. 6 $\Rightarrow$ n=340

$$\delta_s = 23.45° \sin\left(\frac{360°(284+n)}{365}\right) = -22.7°$$

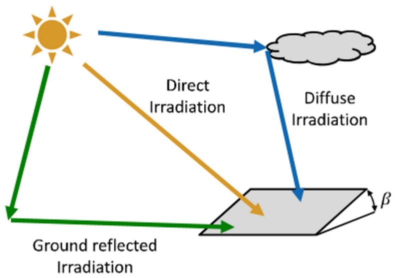
$\beta = 45°$

$\gamma = 0°$

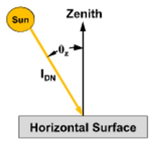
$$\begin{aligned}\cos\theta &= \sin\delta_s \sin\phi\cos\beta - \sin\delta_s \cos\phi\sin\beta\cos\gamma + \cos\delta_s \cos\phi\cos\beta\cos\omega + \\ &\quad \cos\delta_s \sin\phi\sin\beta\cos\omega\cos\gamma + \cos\delta_s \sin\beta\sin\omega\sin\gamma \\ &= \sin(-22.7)\sin 47\cos 45 - \sin(-22.7)\cos 47\sin 45 + \\ &\quad \cos(-22.7)\cos 47\cos 45\cos 37.5 + \cos(-22.7)\sin 47\sin 45\cos 37.5 \\ &= 0.717\end{aligned}$$

$\theta = 44.1°$

Solar Irradiance on a Tilted Surface

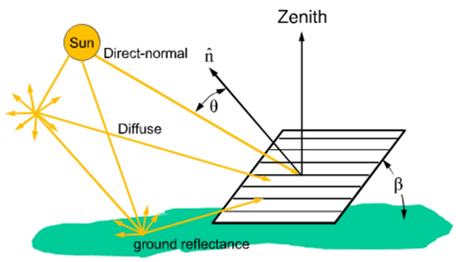


Solar Irradiance on a Tilted Surface



$$I = I_D + I_d$$

$$I_D = I_{DN}\cos\theta_z = I_{DN}\sin\alpha_s$$



θ_z = zenith angle
α_s = solar altitude angle
γ_s = solar azimuth angle
γ = surface azimuth angle
β = slope
θ = angle of incidence
δ_s = solar declination
ω = hour angle
Φ = latitude angle

$$I_T = \underbrace{I_{DN}\cos\theta}_{\text{direct}} + \underbrace{I_d\left(\frac{1+\cos\beta}{2}\right)}_{\text{sky diffuse}} + \underbrace{I\rho_g\left(\frac{1-\cos\beta}{2}\right)}_{\text{ground reflected}}$$

Solar Irradiance on a Tilted Surface

$$I_T = I_{DN}\cos\theta + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right)$$
$$= I_D\underbrace{\left(\frac{\cos\theta}{\cos\theta_z}\right)}_{R_T} + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

$$R_T = \frac{\text{direct irradiance on a tilted surface}}{\text{direct irradiance on a horizontal surface}} = \frac{I_{DN}\cos\theta}{I_D} = \frac{I_{DN}\cos\theta}{I_{DN}\cos\theta_z} = \frac{\cos\theta}{\cos\theta_z}$$

For a tilted surface facing south in the northern hemisphere:

$$R_{T,north} = \frac{\cos(\phi-\beta)\cos\delta_s\cos\omega + \sin(\phi-\beta)\sin\delta_s}{\cos\phi\cos\delta_s\cos\omega + \sin\phi\sin\delta_s}$$

For a tilted surface facing north in the southern hemisphere:

$$R_{T,south} = \frac{\cos(\phi+\beta)\cos\delta_s\cos\omega + \sin(\phi+\beta)\sin\delta_s}{\cos\phi\cos\delta_s\cos\omega + \sin\phi\sin\delta_s}$$

Example

Example: On April 21, 10:00 LST, in San Diego, US (Φ = 32. 733°N, l_{local} = 117.17°W), the measured global horizontal irradiance and direct-normal irradiance were 633 and 465 W/m^2, respectively. Determine the amount of total irradiance on a southwest facing surface tilted up 25°. Assume the ground reflectance is ρ_g = 0.2.

Given
γ = 45° (SW orientation)
β = 25°
Φ= 32.733°
l_{local} = 117.17°W
l_{st} = 120° W
I_{DN} = 465 W/m^2
I = 633 W/m^2

$$\text{April 21} \rightarrow n = 111 \rightarrow \delta_s = 23.45°\sin\left(\frac{360°(284+111)}{365}\right) = 11.6°$$

Equation of time:

$$ET = 229.2\begin{pmatrix}0.000075 + 0.001868\cos B - 0.032077\sin B - \\ 0.014615\cos 2B - 0.04089\sin 2B\end{pmatrix} = 1.22 \text{ min}$$

$$B = \frac{360°(n-1)}{365} = 108.5°$$

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- Solar time:

$$AST = LST + ET + (l_s - l)\frac{4\,\text{min}}{°}$$

$$= 10 + 1.223\,\text{min}\frac{1\text{h}}{60\,\text{min}} + (120 - 117.167°)\frac{4\,\text{min}}{°}\frac{1\text{h}}{60\,\text{min}}$$

$$= 10.209\text{h or } 10{:}13$$

- Hour angle:

$$\omega = 15°\left(AST - 12\right) = -26.9°$$

- Solar altitude:

$$\alpha_s = \sin^{-1}\left(\sin\Phi\sin\delta_s + \cos\Phi\cos\omega\cos\delta_s\right) = 57.5°$$

- Solar azimuth angle:

$$\gamma_s = \sin^{-1}\left(\frac{\cos\delta_s\sin\omega}{\cos\alpha_s}\right) = -55.5°$$

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Example: Irradiance on a Tilted Surface

- Diffuse horizontal irradiance:

$$\theta_Z = 90° - \alpha_s = 32.5°$$

$$I_d = I - I_{DN}\cos\theta_Z = 633\,\tfrac{W}{m^2} - 465\,\tfrac{W}{m^2}\cos 32.5° = 241\,\tfrac{W}{m^2}$$

- Angle of incidence on the tilted surface:

$$\cos\theta_z = \sin\alpha_s \text{ and } \sin\theta_z = \cos\alpha_s$$

$$\theta = \cos^{-1}\left(\sin\alpha_s\cos\beta + \cos\alpha_s\sin\beta\cos(\gamma_s - \gamma)\right)$$

$$\theta = \cos^{-1}\left(\sin 57.5°\cos 25° + \cos 57.5°\sin 25°\cos(-55.6° - 45°)\right)$$

$$\theta = 43.69°$$

- Total irradiance on the tilted surface:

$$I_T = I_D R_T + I_d\left(\frac{1 + \cos\beta}{2}\right) + I\rho_g\left(\frac{1 - \cos\beta}{2}\right)$$

where $I_D = I_{DN}\cos\theta_z$ and $R_T = \dfrac{\cos\theta}{\cos\theta_z}$

$$I_T = 572\,\tfrac{W}{m^2}$$

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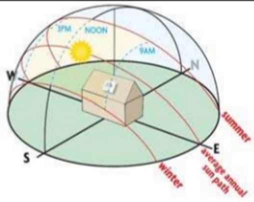
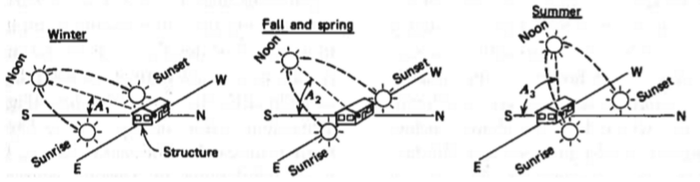
Sun Path Diagram





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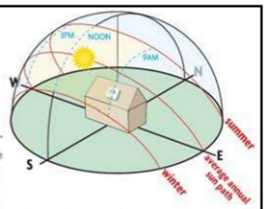
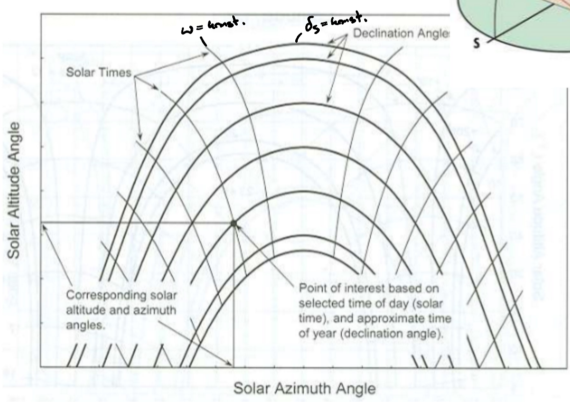
Sun Path Diagram





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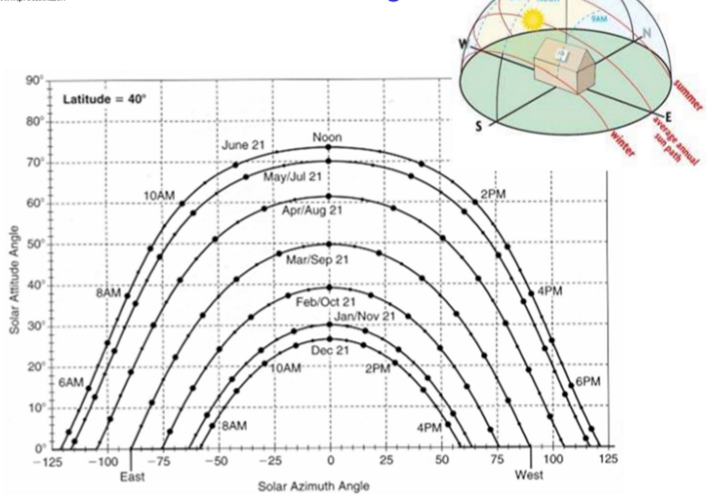
Sun Path Diagram



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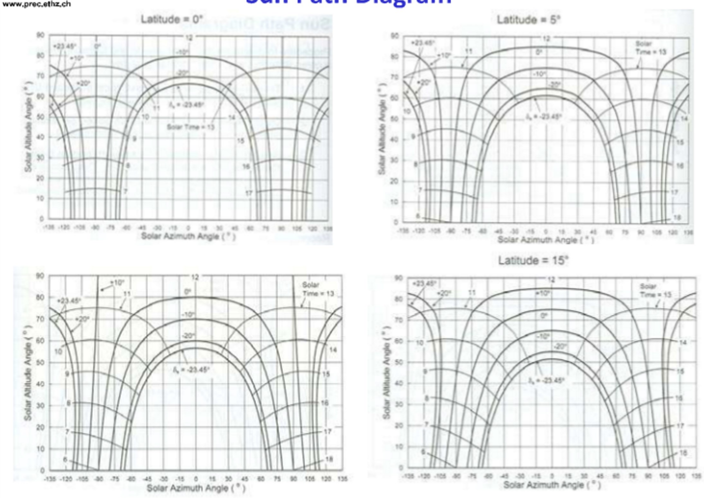
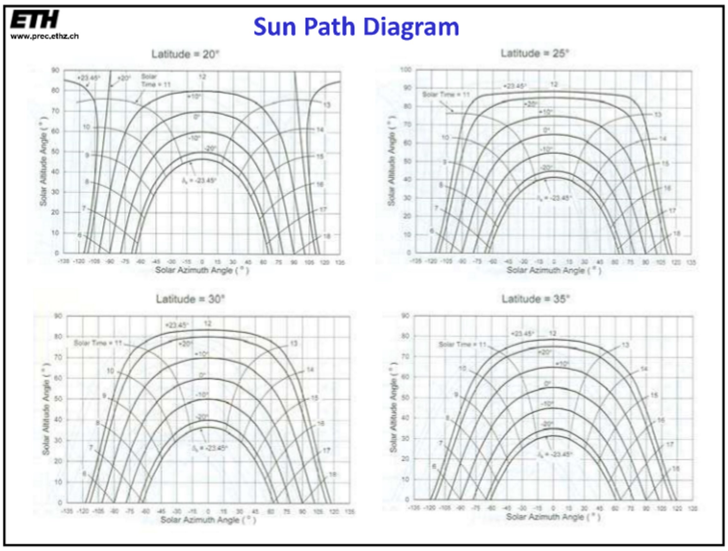
Sun Path Diagram

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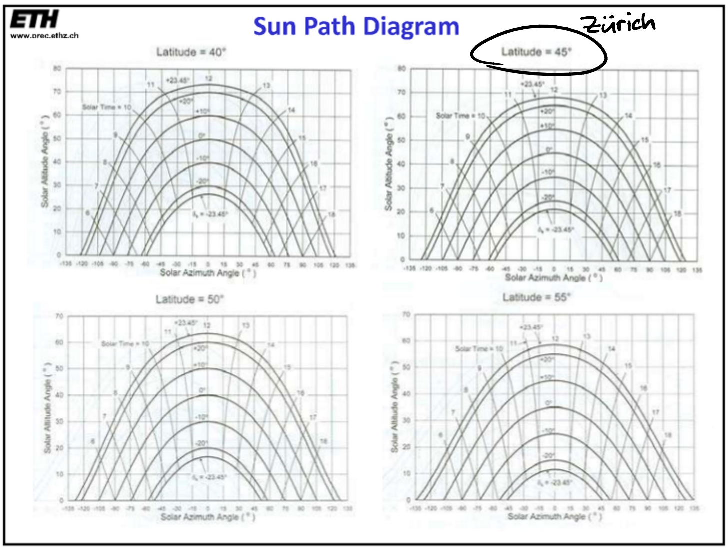
Sun Path Diagram
Latitude = 20°
Latitude = 25°
Latitude = 30°
Latitude = 35°
Solar Altitude Angle (°)
Solar Azimuth Angle (°)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Sun Path Diagram
Zürich
Latitude = 40°
Latitude = 45°
Latitude = 50°
Latitude = 55°
Solar Altitude Angle (°)
Solar Azimuth Angle (°)

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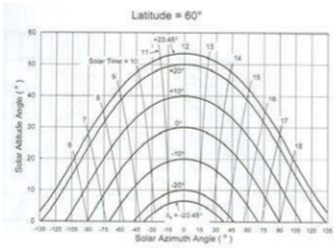
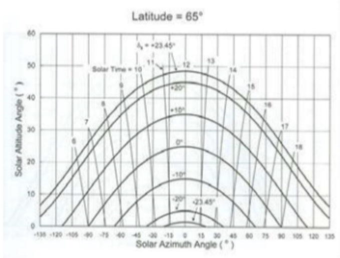
Sun Path Diagram





Note: The sign convention for the declination angle δ_s, is for northern latitudes.
To use the diagrams for southern latitudes, reverse the sign.

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Solar Flat-Plate Collectors

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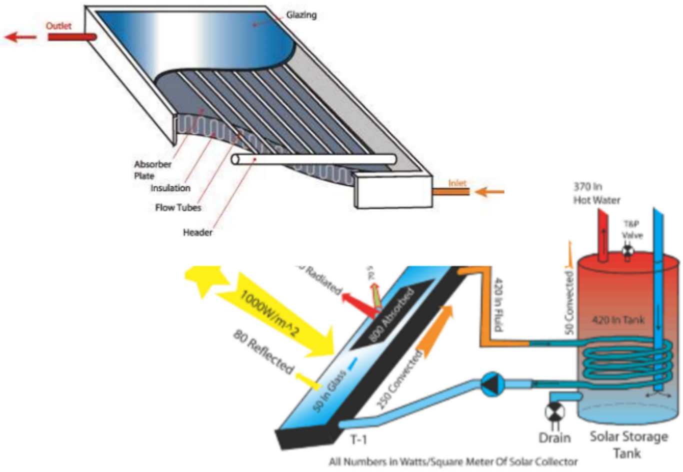
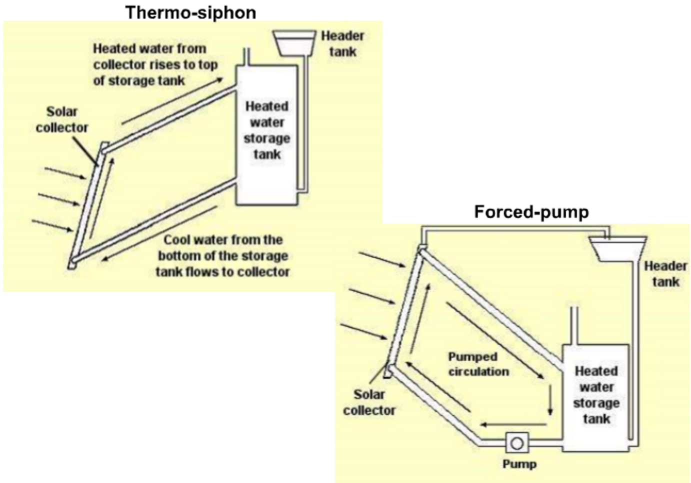
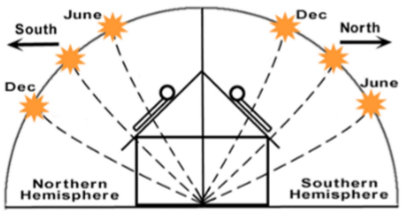
Components



Configurations



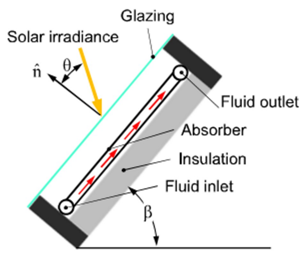
Slope



- Northern hemisphere: collector should point south
- Southern hemisphere: collector should point north
- Tilt angle = latitude of site.

For example:
- In London: collector should face south at a 51 degree angle.
- In Melbourne: collector should face north at a 37 degrees angle.

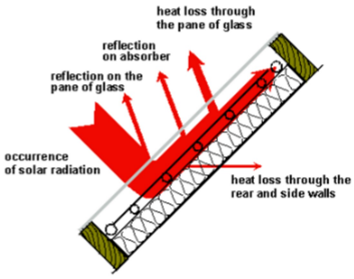
Energy Balance



Useful energy: $\frac{Q_u}{A_c} = \dot{m} c_p \left(T_{f,out} - T_{f,in}\right)$

Efficiency : $\eta = \frac{Q_u}{A_c I_T}$

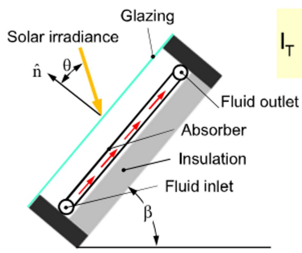
Q_U = useful energy
A_C = collector area
I_T = solar irradiation on a tilted surface



$$\frac{Q_u}{A_c} = S - U_L \left(T_{pm} - T_a\right)$$

S = absorbed solar irradiance
U_L = overall heat loss coefficient
T_{pm} = mean absorber plate temperature
T_a = ambient temperature

Absorbed Solar Irradiance



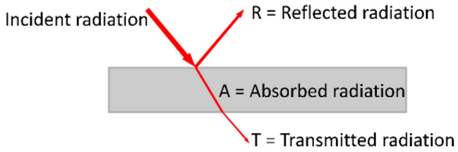
$$I_T = I_D R_T + I_d \left(\frac{1+\cos\beta}{2}\right) + I \rho_g \left(\frac{1-\cos\beta}{2}\right)$$

not $\tau \cdot \alpha$

$$S = I_D R_T (\tau\alpha)_D + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + I \rho_g (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right)$$

$(\tau\alpha)$ = tau-alpha product represents the fraction of incoming solar irradiance that is absorbed in the plate.

Single-Layer Glazing



$$A + R + T = 1$$

R = Fraction of incident radiation reflected (reflectance): $R = \rho\left[1 + \frac{(1-\rho)^2\tau^2}{1-\rho^2\tau^2}\right]$

T = Fraction of incident radiation transmitted (transmittance): $T = \tau\left(\frac{1-\rho}{1+\rho}\right)$

A = Fraction of incident radiation absorbed (absorptance): $A = \frac{(1-\rho)(1-\tau)}{1-\rho\tau}$

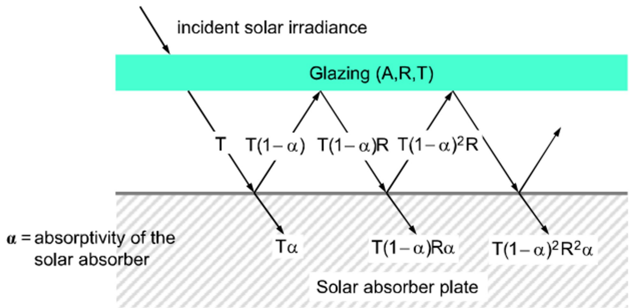
Limiting case: $a \to 0 \longrightarrow \tau \to 1 \longrightarrow$

$$R \longrightarrow \frac{2\rho}{1+\rho}$$

$$T \longrightarrow \frac{1-\rho}{1+\rho}$$

$$A \longrightarrow 0$$

Transmittance-Absorptance Product



$$(\tau\alpha) = T\alpha \sum_{n=0}^{\infty}\left[(1-\alpha)R\right]^n = \frac{T\alpha}{1-(1-\alpha)R}$$

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Incident Angle Modifier

$$S = I_D R_T (\tau\alpha)_D + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + I\rho_g (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) = I_T (\tau\alpha)_{av}$$

The useful energy gain is highest when direct solar irradiance is high, and the tau-alpha product can then be approximated when only tilted solar irradiance is available as:

$$(\tau\alpha)_{av} \cong 0.96 (\tau\alpha)_D$$

$(\tau\alpha)$ is a function of the optical properties of glazing and absorber, which in turn are functions of the incidence angle θ

Incident angle modifier:

$$K_{\tau\alpha} = f(\theta) = \frac{(\tau\alpha)}{(\tau\alpha)_N}$$

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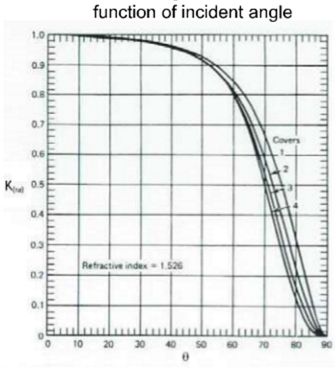
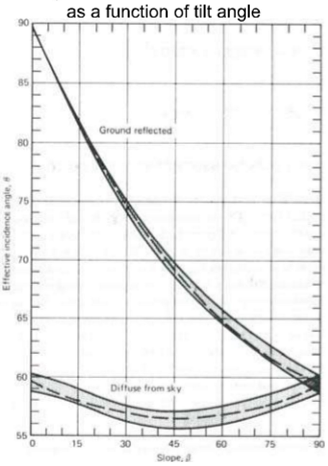
Incident angle modifier as a function of incident angle



Effective incident angles for diffuse and ground reflected solar irradiance as a function of tilt angle



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Example: For an hour 11:00 to 12:00 solar noon on a clear winter day a collector with one cover is sloped at 60°. Determine the absorbed solar radiation. Given are:

ρ_g	0.6
$\rho^*_{Glazing}$	0.05
$\tau^*_{Gl.}$	0.85
α_{plate}	0.93
θ	15°
I	1.79 MJ/m²
I_D	1.38 MJ/m²
I_d	0.41 MJ/m²
R_T	2.11

*normal incident angles

$$T = \tau\left(\frac{1-\rho}{1+\rho}\right) = 0.7690$$

$$R = 1 - T - A = 1 - T - \frac{(1-\rho)(1-\tau)}{1-\rho\tau} = 0.0821$$

$$(\tau\alpha)_N = \frac{T\alpha}{1-(1-\alpha)R} = 0.7193$$

$$K_{\tau\alpha,D}(\theta = 15^\circ) \cong 0.98$$

$$K_{\tau\alpha,g}(\theta_{eff} = 65^\circ) \cong 0.76$$

$$K_{\tau\alpha,d}(\theta_{eff} = 57^\circ) = 0.88$$

$$S = I_D R_T (\tau\alpha)_D + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + I\rho_g (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) = 2.394 \text{ MJ/m}^2$$

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$$T = \tau\left(\frac{1-\rho}{1+\rho}\right) = 0.7690$$

$$R = 1 - T - A = 1 - T - \frac{(1-\rho)(1-\tau)}{1-\rho\tau} = 0.0821$$

$$(\tau\alpha)_N = \frac{T\alpha}{1-(1-\alpha)R} = 0.7193$$

$$K_{\tau\alpha,D}(\theta = 15^\circ) \cong 0.98,\ K_{\tau\alpha,g}(\theta_{eff} = 65^\circ) \cong 0.76,\ K_{\tau\alpha,d}(\theta_{eff} = 57^\circ) = 0.88$$

$$S = I_D R_T (\tau\alpha)_D + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + I\rho_g (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right)$$

$S = 2.394$ MJ/m²

Collector Heat Losses

$$\frac{Q_u}{A_c} = S - \underbrace{U_L\left(T_{pm} - T_a\right)}_{Q_L}$$

$$\frac{Q_L}{A_c} = \frac{Q_t + Q_e + Q_b}{A_c} = U_L\left(T_{pm} - T_a\right) = \left(U_t + U_e + U_b\right)\left(T_{pm} - T_a\right)$$

Q_L = overall heat losses = $Q_t + Q_e + Q_b$

Q_t = heat losses through top of the collector

Q_e = heat losses through edges of the collector

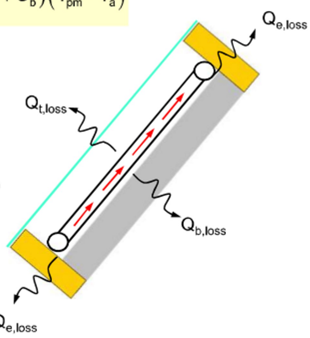
Q_b = heat losses through back of the collector

U_L = overall heat transfer coefficient = $U_t + U_e + U_b$

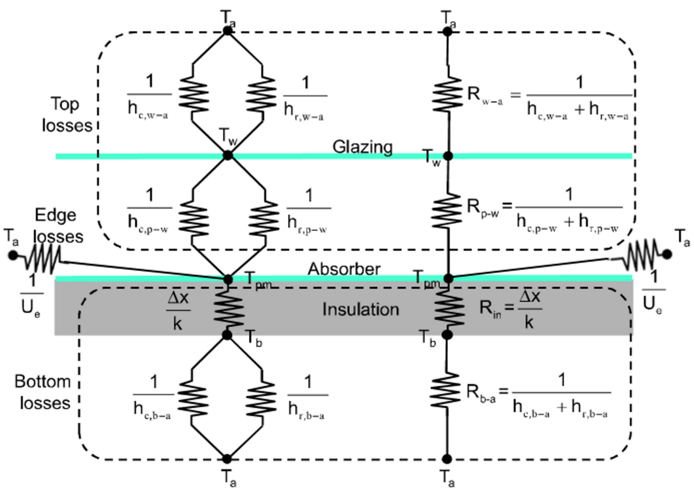
U_t = top loss coefficient: overall heat transfer coefficient through top of the collector

U_e = edge loss coefficient: overall heat transfer coefficient through edges of the collector

U_b = back loss coefficient: overall heat transfer coefficient through back of the collector



Collector Overall Heat Losses Network



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Top Loss Heat Transfer Coefficient

$$U_t = \left(\frac{1}{h_{c,w-a} + h_{r,w-a}} + \frac{1}{h_{c,p-w} + h_{r,p-w}} \right)^{-1}$$

- **Radiative heat transfer:**

Window to the outside:

$$h_{r,w-a} = \frac{\sigma \varepsilon_w \left(T_w{}^4 - T_s{}^4 \right)}{\left(T_w - T_a \right)}$$

Absorber plate to window:

$$h_{r,p-w} = \frac{\sigma \left(T_w{}^2 + T_{pm}{}^2 \right)\left(T_w + T_{pm} \right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_w} - 1}$$

σ = Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}
ε_w = emissivity of the window
ε_p = emissivity of the absorber plate
T_w = surface temperature of the glazing
T_s = effective sky temperature
T_a = ambient air temperature

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- **Convective heat transfer**

Window to the outside: $Nu = 0.86 \cdot Re^{1/2} \cdot Pr^{1/3}$

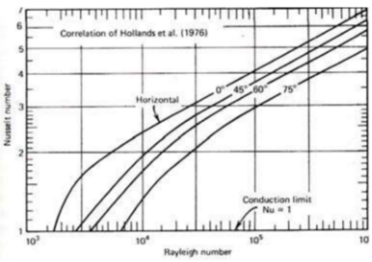
Absorber plate to window (free convection between flat parallel plates at various slopes):

$$Nu = 1 + 1.44 \left[1 - \frac{1708 \left(\sin(1.8\beta) \right)^{1.6}}{Ra \cos(\beta)} \right] \left[1 - \frac{1708}{Ra \cos(\beta)} \right]^{+} + \left[\left(\frac{Ra \cos(\beta)}{5830} \right)^{1/3} - 1 \right]^{+}$$

+ exponent means only positive values are to be used in brackets
(i.e. use zero when the term is negative)

$Nu = \frac{hL}{k}$; $Ra = \frac{g\beta' \Delta T L^3}{\nu\alpha}$; $Pr = \frac{\nu}{\alpha}$; $Re = \frac{\rho v L_c}{\mu}$

h = convective heat transfer coefficient
L = distance between plates
L_c = characteristic length = 4 · area / perimeter
k = thermal conductivity
g = gravitational constant
β' = volumetric coefficient of expansion (ideal gases = 1/T)
ΔT = temperature difference between plates
ν = kinematic viscocity
α = thermal diffusivity



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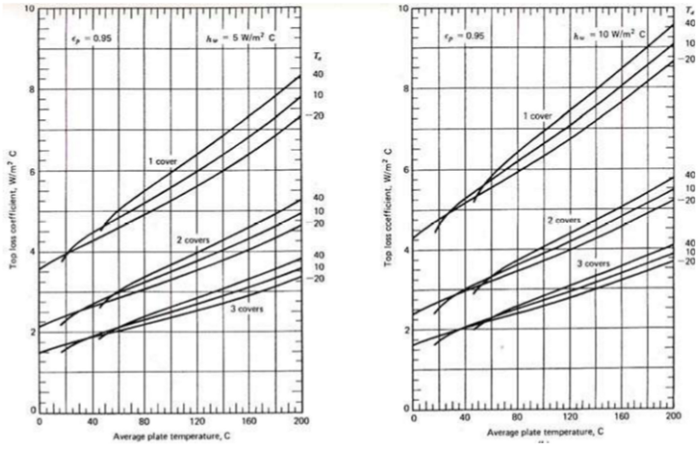
U_t for slope of 45°

L > 15 mm



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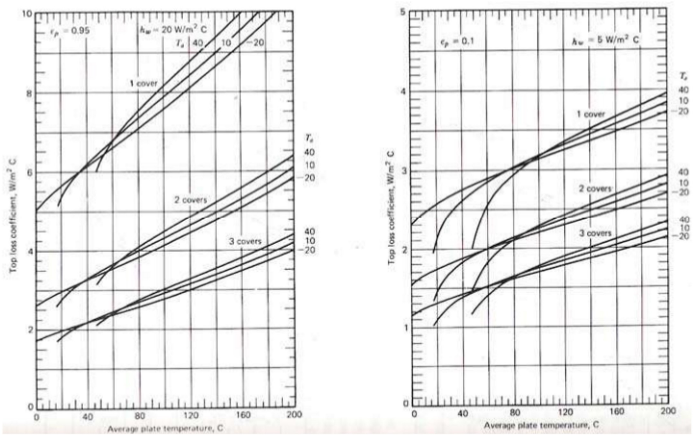
U_t for slope of 45°

L > 15 mm



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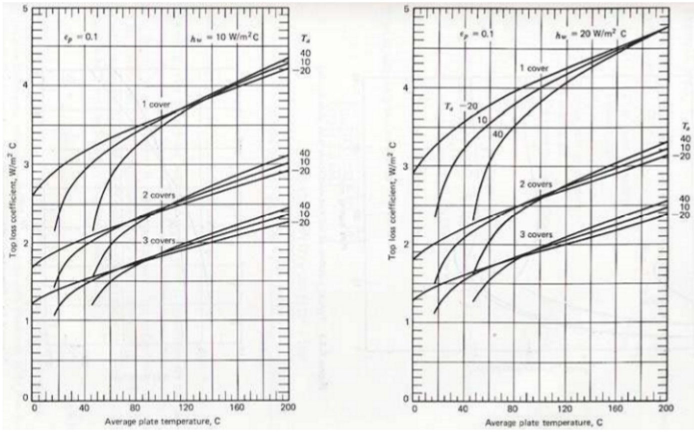
U_t for slope of 45°

L > 15 mm



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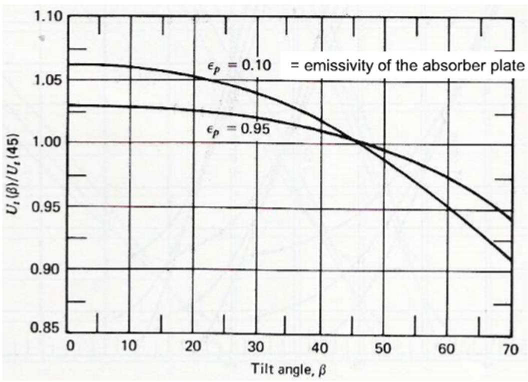
U_t for slope β



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Example: Top Loss Heat Transfer Coefficient

Calculate the top loss heat transfer coefficient for an absorber with a single glass cover with the following specifications:

Plate-to-cover spacing	25 mm
Plate emittance	0.95
Ambient air and sky temperatures	10°C
Wind heat transfer coefficient	10 W/m^2-K
Mean plate temperature	100°C
Collector tilt	45°
Glass emittance	0.88

Hint: Assume a window temperature of 40°C and iterate

$$Ra = \frac{g\beta'\Delta T L^3}{\nu\alpha} = \frac{g\Delta T L^3 \,Pr}{\bar{T}\nu^2} = \frac{9.81\frac{m}{s^2}\times(100-40^\circ C)\times(0.025\text{ m})^3\times 0.7}{343\text{ K}\times\left(1.96e\text{-}5\frac{m^2}{s}\right)^2} = 6.99\times10^4$$

$$Nu = 1 + 1.44\left[1-\frac{1708\left(\sin(1.8\times45^\circ)\right)^{1.6}}{6.99\times10^4\,\cos(45^\circ)}\right]\left[1-\frac{1708}{6.99\times10^4\,\cos(45^\circ)}\right]^+ + \left[\left(\frac{6.99\times10^4\,\cos(45^\circ)}{5830}\right)^{1/3}-1\right]^+ = 3.822$$

$$h_{c,p-w} = Nu\frac{k}{L} = 3.822\frac{0.0293\frac{W}{m\cdot K}}{0.025\text{ m}} = 4.479\frac{W}{m^2\cdot K}$$

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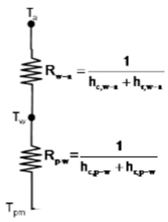
$$h_{r,w-a} = \frac{\sigma\varepsilon_w\left(T_w^4 - T_s^4\right)}{\left(T_w - T_a\right)} = \frac{0.88\times5.67e-8\frac{W}{m^2\cdot K^4}\left((40+273K)^4-(10+273K)^4\right)}{(30K)} = 5.3\frac{W}{m^2\cdot K}$$

$$h_{r,p-w} = \frac{5.67e-8\frac{W}{m^2\cdot K^4}\left((40+273\text{ K})^2+(100+273\text{ K})^2\right)(40+100+2\times273\text{ K})}{\frac{1}{0.95}+\frac{1}{0.88}-1} = 7.76\frac{W}{m^2\cdot K}$$

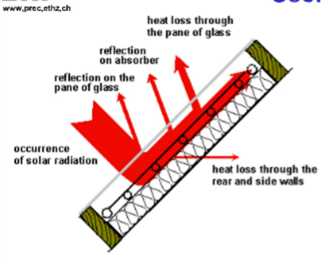
$$U_t = \left(\frac{1}{h_{c,w-a}+h_{r,w-a}}+\frac{1}{h_{c,p-w}+h_{r,p-w}}\right)^{-1} = \left(\frac{1}{10+5.3}+\frac{1}{4.479+7.76}\right)^{-1} = 6.81\frac{W}{m^2\cdot K}$$

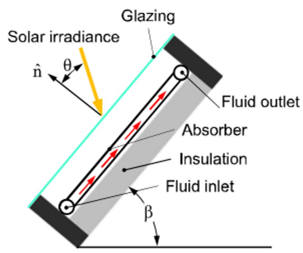
$$U_t\left(T_{pm}-T_a\right) = \left(h_{c,w-a}+h_{r,w-a}\right)\left(T_w - T_a\right) \rightarrow T_w = 50.1\ ^\circ C$$

Iterative process $\longrightarrow$ $U_t = 6.62$ W / m^{2}K



Useful Energy





$$\frac{Q_u}{A_c} = \dot{m}c_p\left(T_{f,out} - T_{f,in}\right)$$

$$\frac{Q_u}{A_c} = S - U_L\left(T_{pm} - T_a\right)$$

S = absorbed solar irradiance
U_L = collector overall heat loss coefficient
T_{pm} = mean absorber plate temperature
T_a = ambient temperature

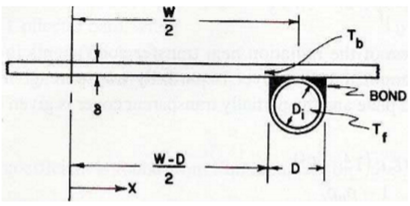
$$\frac{Q_u}{A_c} = F'\left[S - U_L\left(T_f - T_a\right)\right]$$

F' = collector efficiency factor
T_f = fluid temperature

$$\frac{Q_u}{A_c} = F_R\left[S - U_L\left(T_{f,in} - T_a\right)\right]$$

F_R = collector heat removal factor
$T_{f,in}$ = inlet fluid temperature

Collector Efficiency & Heat Removal Factors



h_f = fluid-tube heat trans coeff.
D = tube diameter
δ, δ_b = thickness plate/bond
W, W_b = width plate/bond
k, k_b = thermal cond. plate/bond
F = fin efficiency

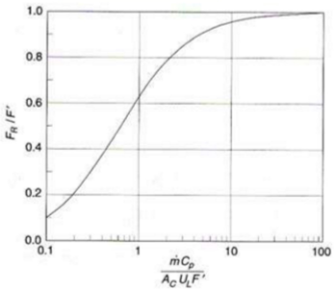
$$F = \frac{\tanh\left[m(W-D)/2\right]}{m(W-D)/2} \qquad m = \sqrt{U_L/k\delta}$$

Collector Efficiency Factor

$$F' = \frac{1/U_L}{W\left[\frac{1}{U_L\left[D+(W-D)F\right]} + \frac{\delta_b}{k_b W_b} + \frac{1}{h_f \pi D_i}\right]}$$

Collector Heat Removal Factor

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{\dot{m}c_p}\right)\right]$$



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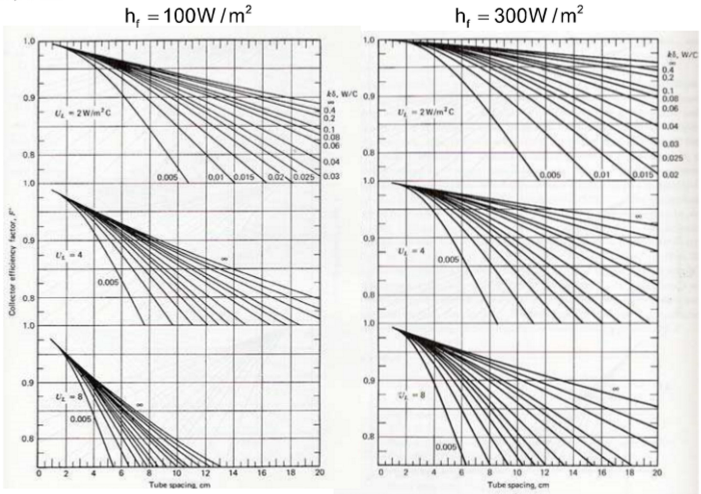
Collector Efficiency Factor

$h_f = 100 W/m^2$ $\qquad$ $h_f = 300 W/m^2$



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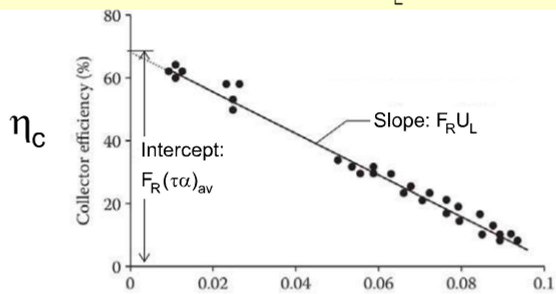
Efficiency

Hottel-Whillier equation $\qquad S = I_T\left(\tau\alpha\right)_{av}$

$$\eta_c = \frac{Q_u}{A_c \cdot I_T} = \frac{F_R\left[S - U_L\left(T_{f,in} - T_a\right)\right]}{I_T} = F_R\left[(\tau\alpha)_{av} - U_L\,\frac{\left(T_{f,in} - T_a\right)}{I_T}\right]$$



$$\frac{\left(T_{f,in} - T_a\right)}{I_T} \quad \frac{°C \cdot m^2}{W}$$

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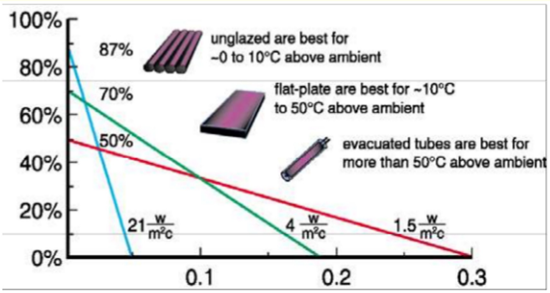
Efficiency

Hottel-Whillier equation

$$S = I_T\left(\tau\alpha\right)_{av}$$

$$\eta_c = \frac{Q_u}{A_c \cdot I_T} = \frac{F_R\left[S - U_L\left(T_{f,in} - T_a\right)\right]}{I_T} = F_R\left[\left(\tau\alpha\right)_{av} - U_L\,\frac{\left(T_{f,in} - T_a\right)}{I_T}\right]$$



$$\frac{\left(T_{f,in} - T_a\right)}{I_T} \quad \frac{°C \cdot m^2}{W}$$

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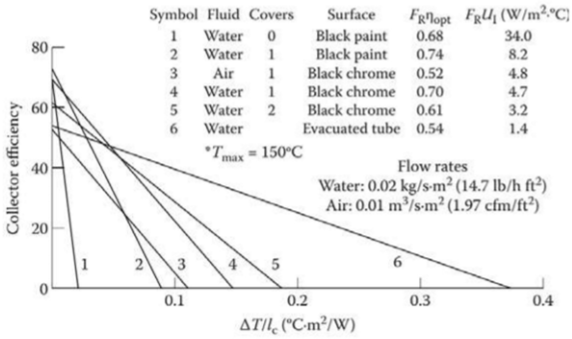
Efficiency

Hottel-Whillier equation

$$S = I_T\left(\tau\alpha\right)_{av}$$

$$\eta_c = \frac{Q_u}{A_c \cdot I_T} = \frac{F_R\left[S - U_L\left(T_{f,in} - T_a\right)\right]}{I_T} = F_R\left[\left(\tau\alpha\right)_{av} - U_L\,\frac{\left(T_{f,in} - T_a\right)}{I_T}\right]$$



Symbol	Fluid	Covers	Surface	$F_R\eta_{opt}$	$F_R U_l$ (W/m²·°C)
1	Water	0	Black paint	0.68	34.0
2	Water	1	Black paint	0.74	8.2
3	Air	1	Black chrome	0.52	4.8
4	Water	1	Black chrome	0.70	4.7
5	Water	2	Black chrome	0.61	3.2
6	Water		Evacuated tube	0.54	1.4

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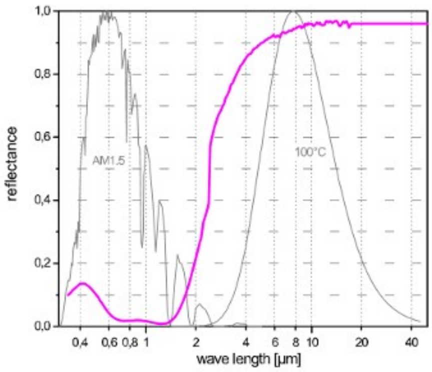
Selective Coatings



Selective coatings based on aluminum cermets

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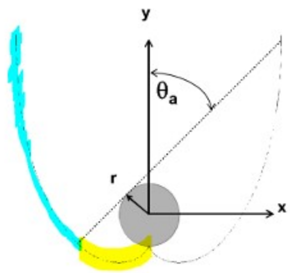
Concentrated water heating collectors

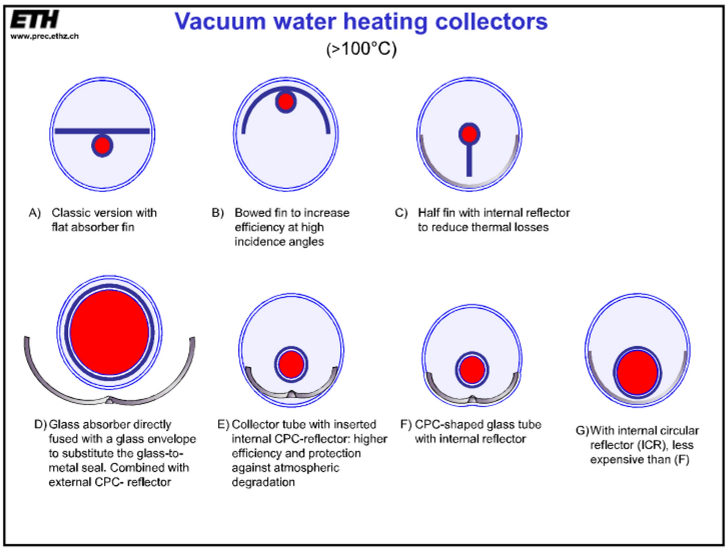
(up to 90°C)



Involute: $\begin{cases} x = r[\sin\theta - M(\theta)\cos\theta] \\ y = r[-\cos\theta - M(\theta)\sin\theta] \end{cases}$

CPC: $M(\theta) = \begin{cases} \theta & \text{for } 0 \le \theta \le \frac{\pi}{2} + \theta_a \\ \dfrac{\pi/2 + \theta_a + \theta - \cos(\theta - \theta_a)}{1 + \sin(\theta - \theta_a)} & \text{for } \frac{\pi}{2} + \theta_a \le \theta \le \frac{3\pi}{2} - \theta_a \end{cases}$

$$C = \frac{1}{\sin\theta_a}$$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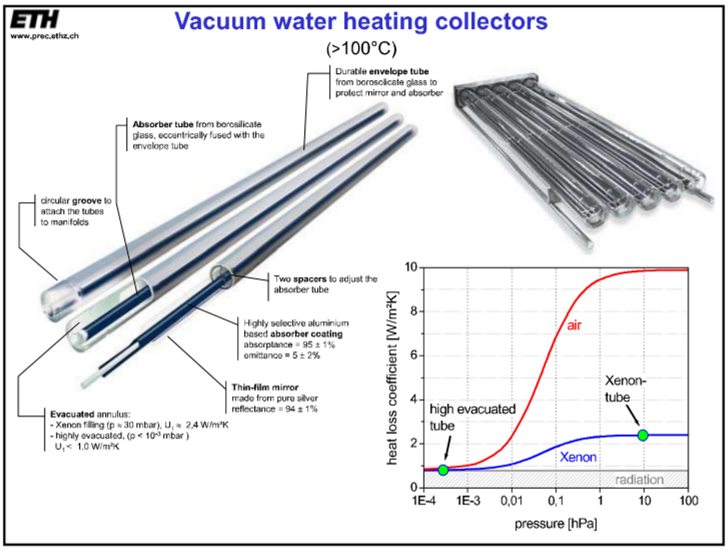
Vacuum water heating collectors
(>100°C)
A) Classic version with flat absorber fin
B) Bowed fin to increase efficiency at high incidence angles
C) Half fin with internal reflector to reduce thermal losses
D) Glass absorber directly fused with a glass envelope to substitute the glass-to-metal seal. Combined with external CPC- reflector
E) Collector tube with inserted internal CPC-reflector: higher efficiency and protection against atmospheric degradation
F) CPC-shaped glass tube with internal reflector
G) With internal circular reflector (ICR), less expensive than (F)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Vacuum water heating collectors
(>100°C)
Durable envelope tube from boroslicate glass to protect mirror and absorber
Absorber tube from borosilicate glass, eccentrically fused with the envelope tube
circular groove to attach the tubes to manifolds
Two spacers to adjust the absorber tube
Highly selective aluminium based absorber coating absorptance = 95 ± 1% emittance = 5 ± 2%
Thin-film mirror made from pure silver reflectance = 94 ± 1%
Evacuated annulus:
- Xenon filling (p ≈ 30 mbar), U1 ≈ 2,4 W/m²K
- highly evacuated, (p < 10-3 mbar) U1 < 1,0 W/m²K
heat loss coefficient [W/m²K]
pressure [hPa]
air
Xenon
Xenon-tube
high evacuated tube
radiation
10
8
6
4
2
0
1E-4
1E-3
0,01
0,1
1
10
100

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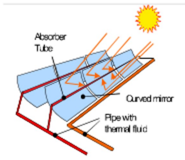
Solar Concentrating Optics

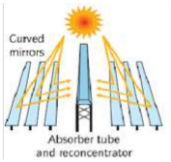
Solar Concentrating Technologies

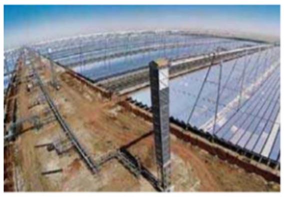
Trough



San Bernardino SEGS, California, USA (354 MW_e)

Linear Fresnel





Reliance Areva, Rajasthan, India (100 MW_e)

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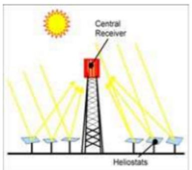
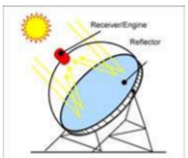
Solar Concentrating Technologies

Tower systems



Ivanpah SEGS, California, USA (377 MW_e)

Dish



Maricopa Solar Power Plant, Arizona, USA (1.5 MW_e)

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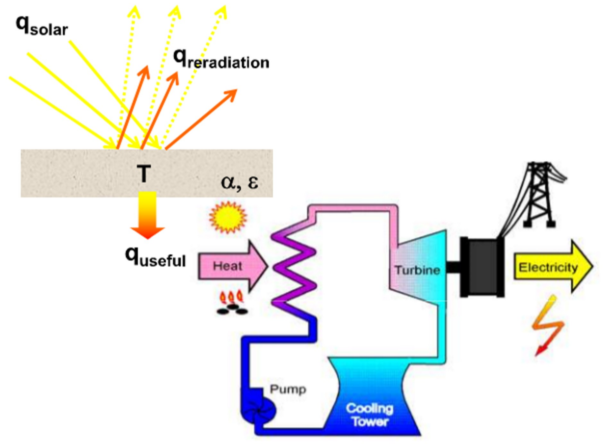
Why Concentrated Solar Power?



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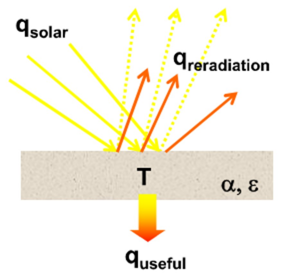
Why Concentrated Solar Power?



For:
$I = 1\ kW/m^2$ (1 sun)
$\sigma = 5.67\cdot10^{-8}\ W/m^2K^4$

C	$T_{stagnation}$
1	364 K
10	648 K
100	1152
1000	2049 K
5000	3064 K
10000	3644 K

Thermal equilibrium:

$$q_{useful} = q_{absorbed} - q_{reradiation} = \alpha q_{solar} - \varepsilon\sigma T^4$$

σ = Stefan-Boltzmann constant $= 5.67051\times10^{-8}\ W/(m^2\cdot K^4)$

$$\text{For } q_{useful} = 0 \xrightarrow[q_{solar} = C\cdot I_{DN}]{\alpha=\varepsilon=1} T_{stagnation} = \left(\frac{C\cdot I}{\sigma}\right)^{0.25}$$

solar concentration

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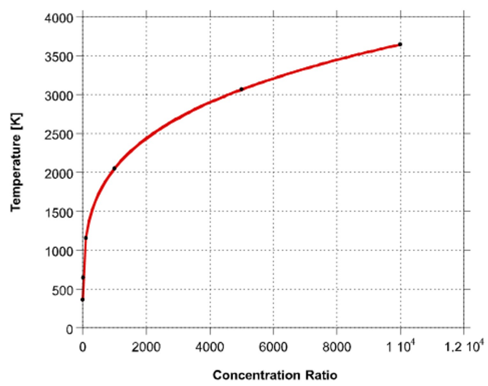
Why Concentrated Solar Power?



C	$T_{stagnation}$
1	364 K
10	648 K
100	1152 K
1000	2049 K
5000	3064 K
10000	3644 K

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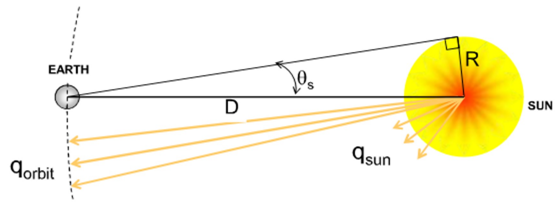
Maximum Solar Concentration



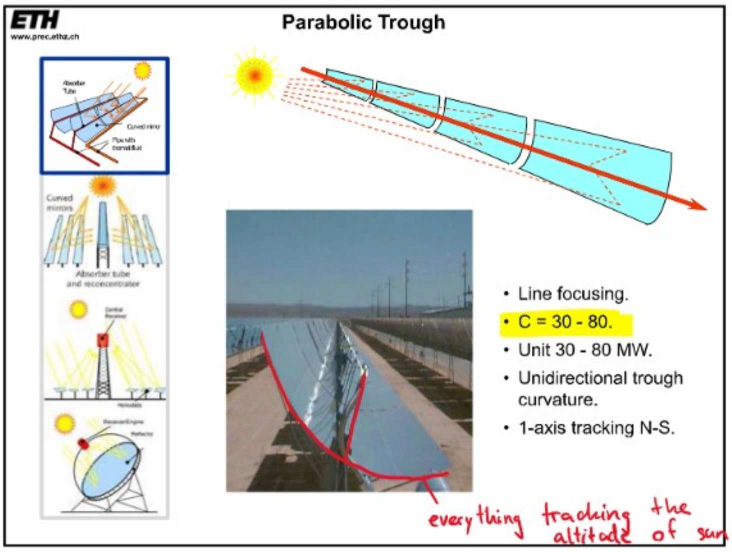
$$\left.\begin{array}{l} R = 6.957 \cdot 10^8 \text{ m} \\ D = 1 \text{ au} \approx 1.496 \times 10^{11} \text{m} \end{array}\right\} \rightarrow \theta_s = \arcsin(R/D) = 0.266° = 4.65 \text{ mrad}$$

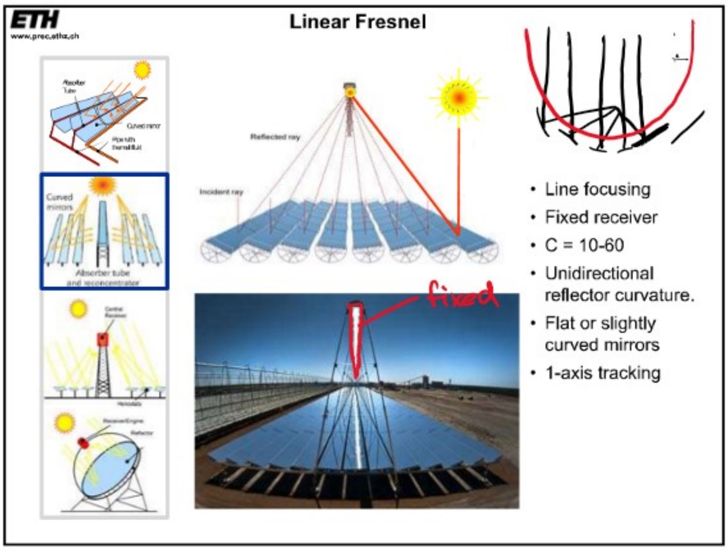
$$q_{sun} \cdot 4\pi R^2 = q_{orbit} \cdot 4\pi D^2 \rightarrow \frac{q_{sun}}{q_{orbit}} = \left(\frac{D}{R}\right)^2 = \frac{1}{\sin^2\theta_s} \approx 46{,}250 \qquad C_{max} = \frac{1}{\sin^2\theta_s} \approx 46{,}250$$

concentration limit

$\rightarrow T_{stag.} = 5780$ K

$$\left.\begin{array}{l} q_{sun} = \sigma T_{sun}^4 \\ q_{orbit} = 1367 \text{ W/m}^2 \end{array}\right\} \rightarrow T_{sun} = \left[\left(\frac{D}{R}\right)^2 \frac{q_{orbit}}{\sigma}\right]^{0.25} = 5780 \text{ K}$$


ETH
www.prec.ethz.ch
Parabolic Trough
Line focusing.
C = 30 - 80.
Unit 30 - 80 MW.
Unidirectional trough curvature.
1-axis tracking N-S.
everything tracking the altitude of sun
Curved mirrors
Absorber tube and reconcentrator


ETH
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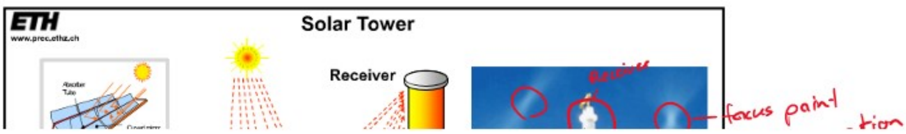
Linear Fresnel
Reflected ray
Incident ray
fixed
Line focusing
Fixed receiver
C = 10-60
Unidirectional reflector curvature.
Flat or slightly curved mirrors
1-axis tracking


ETH
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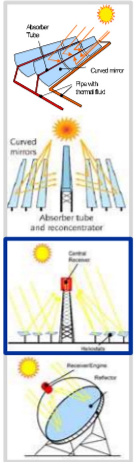
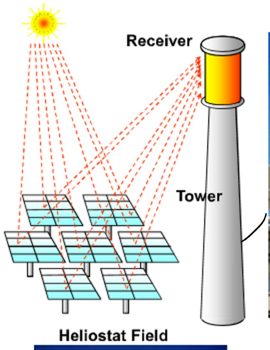
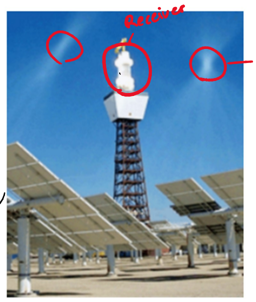
Solar Tower
Receiver
focus point

www.prec.ethz.ch







focus point before operation

- Point focusing.
- C = 200 - 1000.
- Unit 30 - 200 MW.
- 2-axis tracking heliostats: elements of different parabolas with varying focal length.

altitude & azimuth

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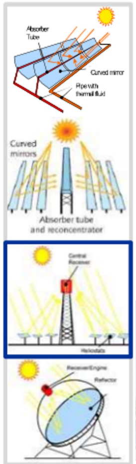
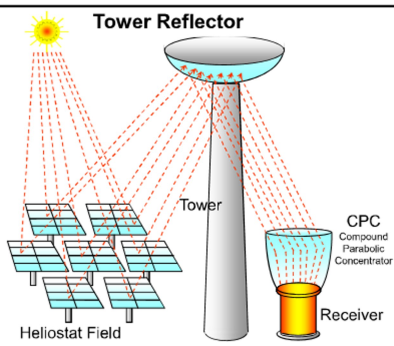
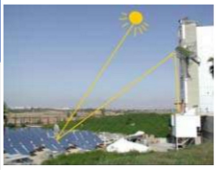
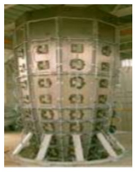
Tower Reflector



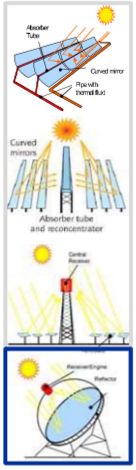


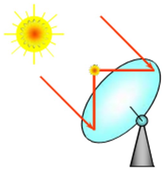


- Heliostat field + Tower Reflector (Cassegrain).
- Beam-down on CPC.
- C = 5,000 - 10,000.
- Major hardware on ground level.



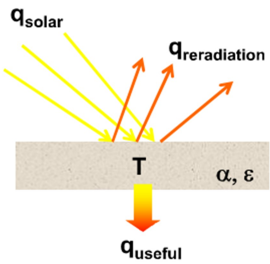
Solar Dish





- Point focusing.
- C = 1000 - 13,000.
- Unit 7.5 - 100 kW.
- 2-axis tracking parabolic dish.
- Modularity.
- Remote applications.

Efficiency and Concentration



In thermal equilibrium:

$$q_{useful} = q_{absorbed} - q_{reradiation}$$

$$q_{useful} = \alpha q_{solar} - \varepsilon \sigma T^4$$

$$Q_{useful} = \alpha Q_{solar} - \varepsilon A \sigma T^4$$

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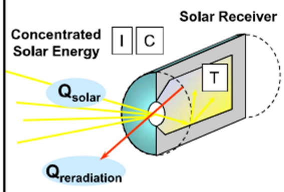
Efficiency and Concentration



$$\eta_{absorption} = \frac{\overbrace{\alpha\, Q_{solar}}^{\text{Power absorbed}} - \overbrace{\varepsilon A \sigma T^4}^{\text{Power re-radiated}}}{\underbrace{Q_{solar}}_{\text{Solar Power Input}}}$$

$$\left.\begin{array}{l} \alpha = \varepsilon = 1 \\ C = \dfrac{Q_{solar}}{A \cdot I} \end{array}\right\} \Longrightarrow \eta_{absorption} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right)$$

convert solar concentration to heat @ temperatur T

$$\eta_{exergy,ideal} = \eta_{absorption} \cdot \eta_{Carnot} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right) \cdot \left(1 - \frac{T_L}{T}\right)$$

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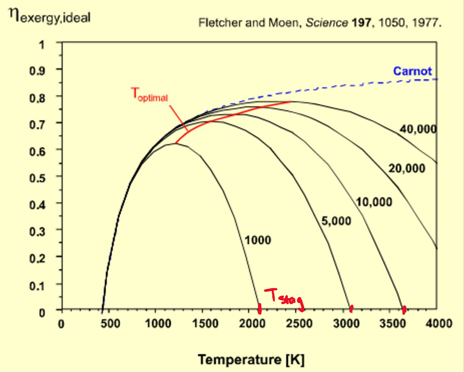
$$\eta_{exergy,ideal} = \eta_{absorption} \cdot \eta_{Carnot} = \left(1 - \frac{\sigma T^4}{C \cdot I}\right) \cdot \left(1 - \frac{T_L}{T}\right)$$

$$\eta_{exergy} = 0 \to T_{stagnation} = \left(\frac{C \cdot I}{\sigma}\right)^{0.25}$$

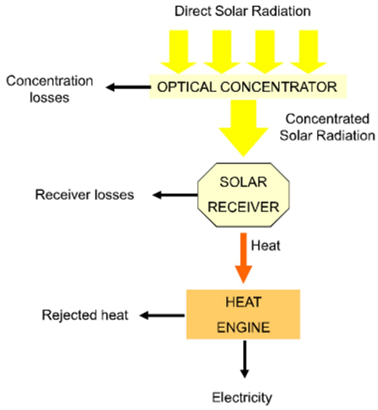
$$\frac{\partial \eta_{exergy}}{\partial T} = 0 \to \left(T_{optimal}\right)^5 - 0.75 T_L \left(T_{optimal}\right)^4 - \left(\frac{T_L I C}{4\sigma}\right) = 0$$

For:
I = 1 kW/m^2 (1 sun)
σ = 5.67·10^{-8} W/m^{2}K^4

C	$T_{stagnation}$	$T_{optimal}$
1000	2049 K	1106 K
5000	3064 K	1507 K
10000	3644 K	1724 K

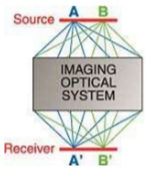


$$\eta_{\text{solar-to-electrcity}} = \eta_{\text{optics}} \cdot \underbrace{\eta_{\text{receiver}}}_{<\eta_{\text{absorption}}} \cdot \underbrace{\eta_{\text{heat-to-electricity}}}_{<\eta_{\text{Carnot}}}$$



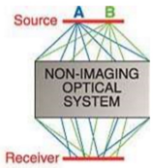
Optics

Imaging optics



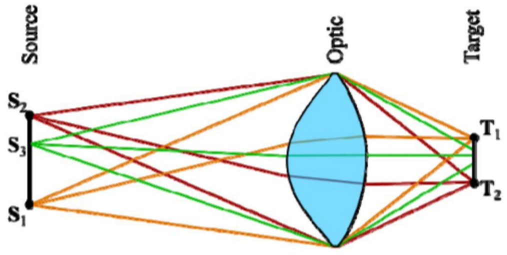
- Point to point mapping
  - Precise imaging of object (A) to image (A')
- Applications
  - Cameras
  - Telescopes
  - …

Nonimaging optics



- Light/energy transfer
  - Minimize losses during light/energy transfer from source to receiver
  - Imaging not required
- Applications
  - Solar concentrators
  - Illumination optics
    - Automotive headlamps
    - LCD backlights

Edge-ray Principle

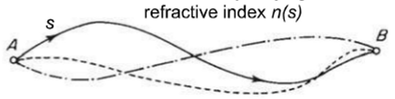


Deflect rays from edges of source **S**$_1$,**S**$_2$ to edges of target **T**$_1$,**T**$_2$
→ All rays from the source are deflected to the target

Chaves, J. (2016). Introduction to nonimaging optics. Boca Raton, CRC Press.

Fermat's Principle

A physically possible ray path is one for which the optical path length along it from A to B is a minimum as compared to neighboring paths.

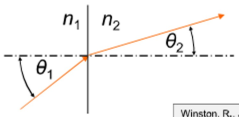


Optical path length

$$S=\int_A^B n(s)ds$$

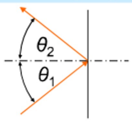
→ Snell's law of refraction

$$\sin(\theta_1)n_1=\sin(\theta_2)n_2$$



→ Specular reflection

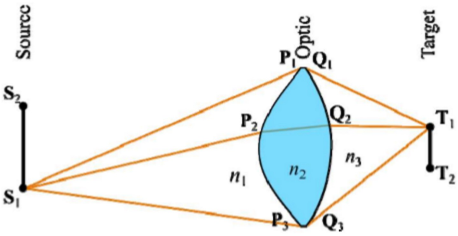
$$\theta_1=\theta_2$$



Winston, R., J. C. Miñano and P. Benítez (2005). Nonimaging Optics. Amsterdam, Elsevier Academic Press

Constant Optical Path Length

The optical path length from object point to image point is the same along all rays, if there is no aberration in the optic.



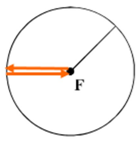
→ Constant S between $\mathbf{S}_1$ and $\mathbf{T}_1$ ensures that all rays from $\mathbf{S}_1$ are deflected to $\mathbf{T}_1$

$$S = n_1\|\mathbf{S}_1\mathbf{P}_1\| + n_2\|\mathbf{P}_1\mathbf{Q}_1\| + n_3\|\mathbf{Q}_1\mathbf{T}_1\| = n_1\|\mathbf{S}_1\mathbf{P}_2\| + n_2\|\mathbf{P}_2\mathbf{Q}_2\| + n_3\|\mathbf{Q}_2\mathbf{T}_1\|$$
$$= n_1\|\mathbf{S}_1\mathbf{P}_3\| + n_2\|\mathbf{P}_3\mathbf{Q}_3\| + n_3\|\mathbf{Q}_3\mathbf{T}_1\|$$

Chaves, J. (2016). Introduction to nonimaging optics. Boca Raton, CRC Press.

Basic Shapes – Conic Sections

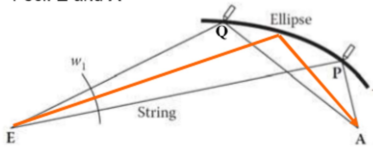
Circle

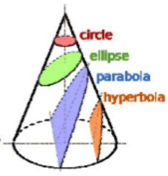


Ellipse

$S = \|\mathbf{AP}\| + \|\mathbf{PE}\| = \|\mathbf{AQ}\| + \|\mathbf{QE}\| = const$

Foci: **E** and **A**

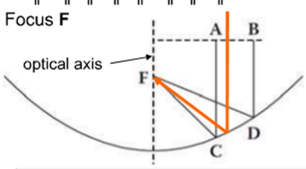




Parabola

$S = \|\mathbf{AC}\| + \|\mathbf{CF}\| = \|\mathbf{BD}\| + \|\mathbf{DF}\| = const$

Focus **F**

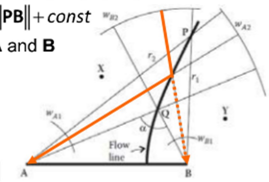


Hyperbola

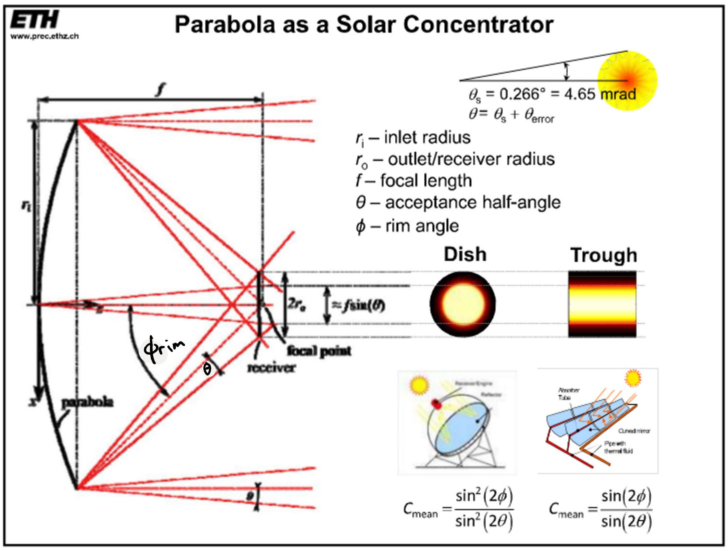
$\|\mathbf{PA}\| - \|\mathbf{PB}\| = \|\mathbf{QA}\| - \|\mathbf{QB}\| = const$

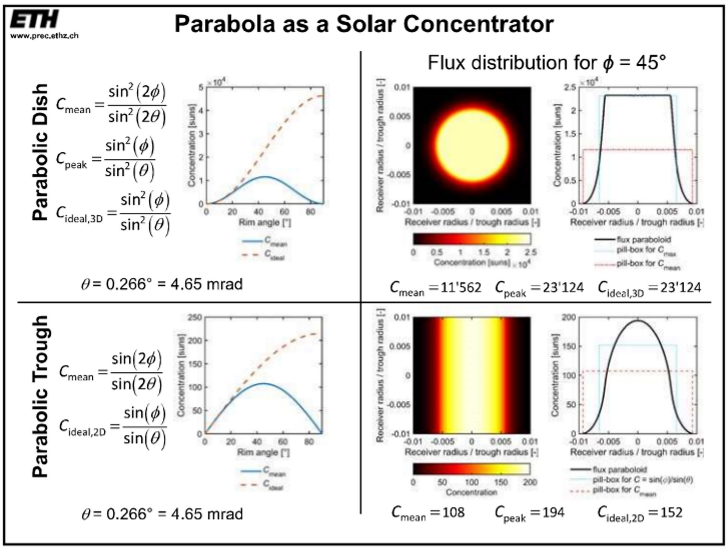
$\|\mathbf{PA}\| = \|\mathbf{PB}\| + const$

Foci: **A** and **B**

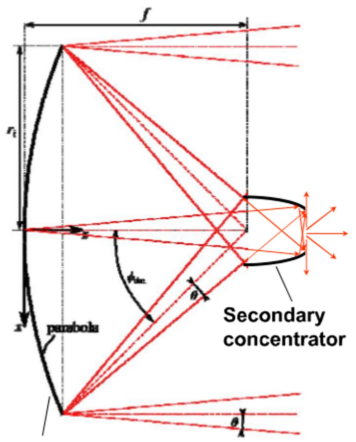


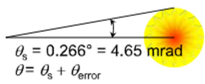
Chaves, J. (2016). Introduction to nonimaging optics. Boca Raton, CRC Press.


ETH
www.prec.ethz.ch
Parabola as a Solar Concentrator
θ_s = 0.266° = 4.65 mrad
$\theta = \theta_s + \theta_{error}$
r_i – inlet radius
r_o – outlet/receiver radius
f – focal length
θ – acceptance half-angle
ϕ – rim angle
Dish
Trough
f
r_i
$2r_o$
$\approx f\sin(\theta)$
ϕ_{rim}
θ
focal point
receiver
parabola
x
$C_{mean} = \frac{\sin^2(2\phi)}{\sin^2(2\theta)}$
$C_{mean} = \frac{\sin(2\phi)}{\sin(2\theta)}$


ETH
www.prec.ethz.ch
Parabola as a Solar Concentrator
Parabolic Dish
$C_{mean} = \frac{\sin^2(2\phi)}{\sin^2(2\theta)}$
$C_{peak} = \frac{\sin^2(\phi)}{\sin^2(\theta)}$
$C_{ideal,3D} = \frac{\sin^2(\phi)}{\sin^2(\theta)}$
θ = 0.266° = 4.65 mrad
Flux distribution for ϕ = 45°
Rim angle [°]
Concentration [suns]
Receiver radius / trough radius [-]
flux paraboloid
pill-box for C_{max}
pill-box for C_{mean}
C_{mean} = 11'562 C_{peak} = 23'124 $C_{ideal,3D}$ = 23'124
Parabolic Trough
$C_{mean} = \frac{\sin(2\phi)}{\sin(2\theta)}$
$C_{ideal,2D} = \frac{\sin(\phi)}{\sin(\theta)}$
θ = 0.266° = 4.65 mrad
Concentration
C_{mean} = 108 C_{peak} = 194 $C_{ideal,2D}$ = 152

Secondary Concentrators



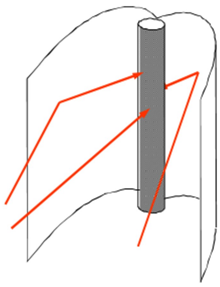


r_i – inlet radius
r_o – outlet/receiver radius
f – focal length
θ – acceptance half-angle
ϕ – rim angle

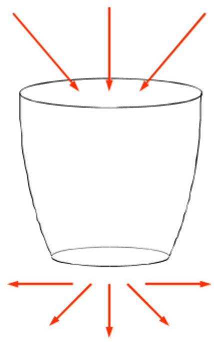
Advantages
- Higher concentration
- Collection of spilled radiation
- More compact design
- Better uniformity of flux at receiver

Disadvantages
- Additional losses at 2nd reflection
- Higher cost
- Cooling of secondary concentrator

Secondary Concentrators



2D – concentrator for tubular absorber



3D - CPC

Ref.: Welford, W. T., and Winston, R. (1989).
High Collection Nonimaging Optics
Academic Press, San Diego, USA.

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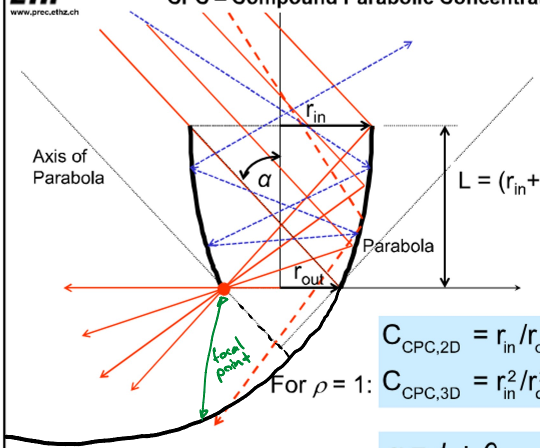
CPC – Compound Parabolic Concentrator



For $\rho = 1$:

$$C_{CPC,2D} = r_{in}/r_{out} = 1/\sin\alpha$$

$$C_{CPC,3D} = r_{in}^2/r_{out}^2 = 1/\sin^2\alpha$$

$$\alpha = \phi + \theta$$

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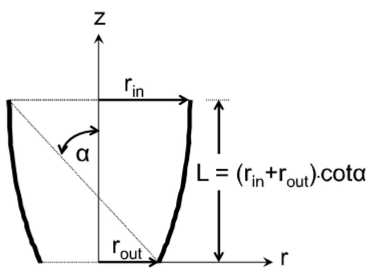
Equations of the CPC



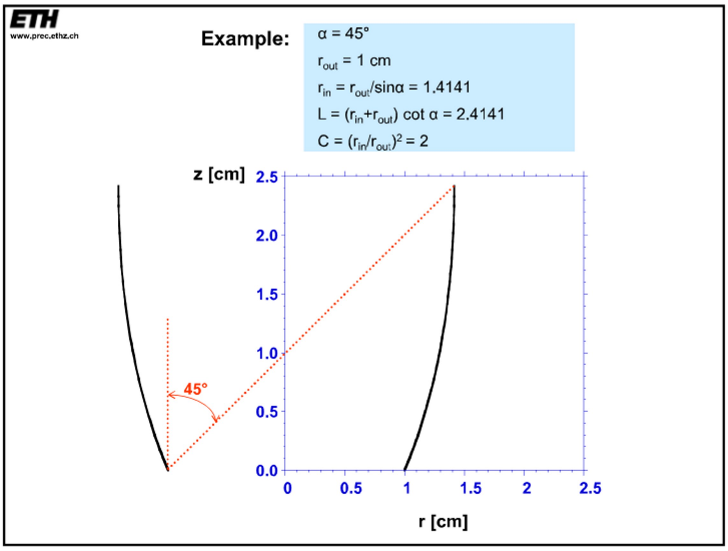
$$\begin{cases} r = \dfrac{2f\sin(\varphi-\alpha)}{1-\cos\varphi} - r_{out} \\[2ex] z = \dfrac{2f\cos(\varphi-\alpha)}{1-\cos\varphi} \end{cases}$$

where:

$$r_{out} = r_{in}\sin\alpha$$

$$f = r_{out}(1+\sin\alpha)$$

$$2\alpha \le \varphi \le \frac{\pi}{2} + \alpha$$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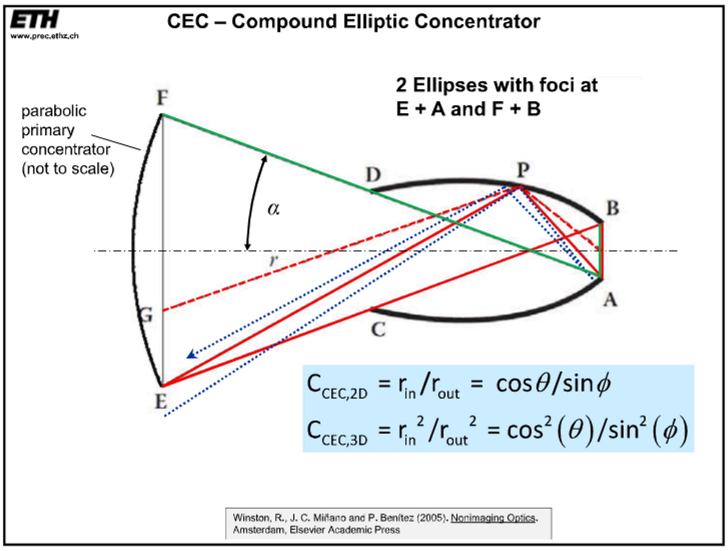
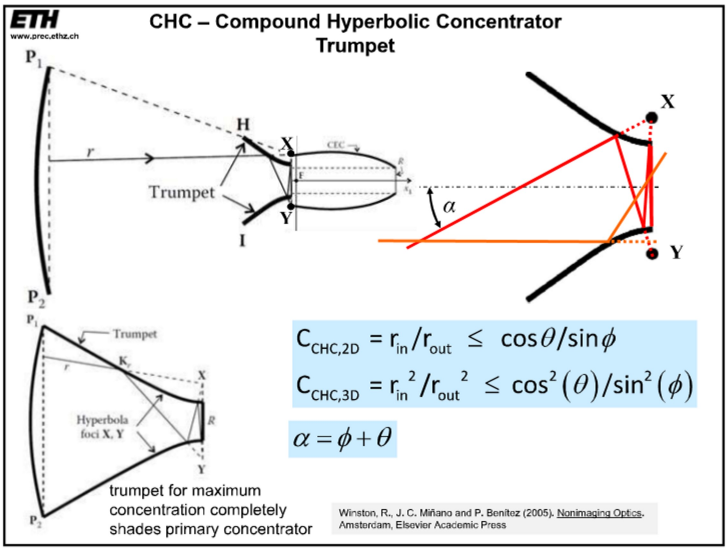
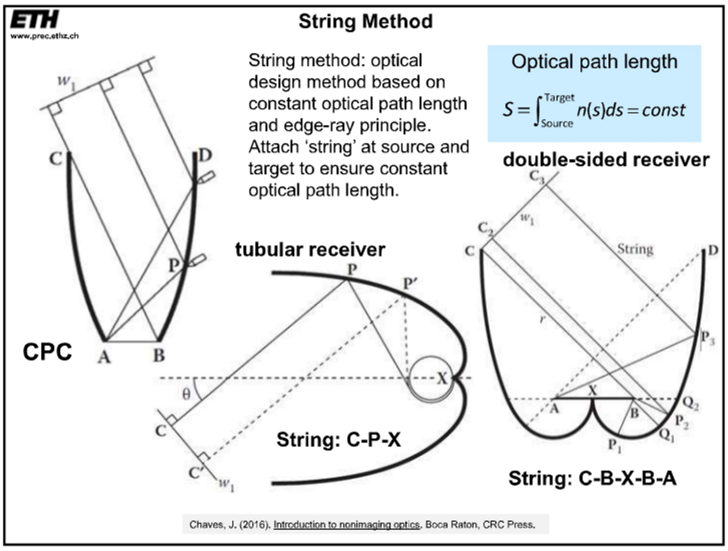
Example:
α = 45°
r_out = 1 cm
r_in = r_out/sinα = 1.4141
L = (r_in+r_out) cot α = 2.4141
C = (r_in/r_out)² = 2
z [cm]
2.5
2.0
1.5
1.0
0.5
0.0
45°
0
0.5
1
1.5
2
2.5
r [cm]


ETH
www.prec.ethz.ch
CEC – Compound Elliptic Concentrator
2 Ellipses with foci at
E + A and F + B
parabolic
primary
concentrator
(not to scale)
F
D
P
B
α
r
G
A
C
E
$C_{CEC,2D} = r_{in}/r_{out} = \cos\theta/\sin\phi$
$C_{CEC,3D} = r_{in}^2/r_{out}^2 = \cos^2(\theta)/\sin^2(\phi)$
Winston, R., J. C. Miñano and P. Benítez (2005). Nonimaging Optics.
Amsterdam, Elsevier Academic Press

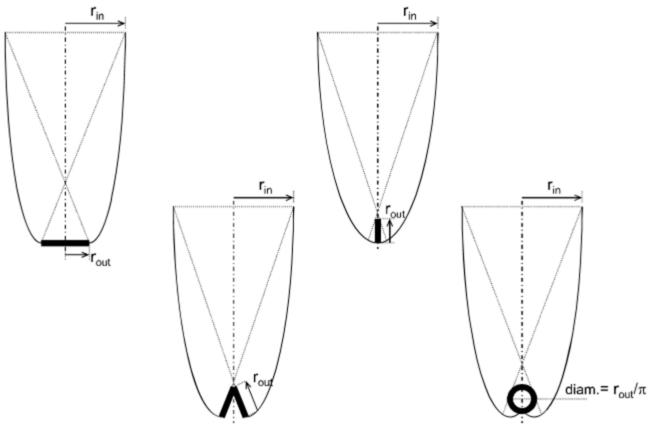

CHC – Compound Hyperbolic Concentrator
Trumpet
P_1
P_2
H
X
Y
I
r
Trumpet
CEC
α
X
Y
Trumpet
Hyperbola foci X, Y
$C_{CHC,2D} = r_{in}/r_{out} \le \cos\theta/\sin\phi$
$C_{CHC,3D} = r_{in}^2/r_{out}^2 \le \cos^2(\theta)/\sin^2(\phi)$
$\alpha = \phi + \theta$
trumpet for maximum concentration completely shades primary concentrator
Winston, R., J. C. Miñano and P. Benitez (2005). Nonimaging Optics. Amsterdam, Elsevier Academic Press


String Method
String method: optical design method based on constant optical path length and edge-ray principle. Attach 'string' at source and target to ensure constant optical path length.
Optical path length
$S = \int_{Source}^{Target} n(s)ds = const$
double-sided receiver
tubular receiver
CPC
C
D
P
A
B
w_1
P
P'
X
θ
C
C'
String: C-P-X
C_3
C_2
C
D
String
P_3
A
X
B
Q_2
P_2
Q_1
P_1
String: C-B-X-B-A
Chaves, J. (2016). Introduction to nonimaging optics. Boca Raton, CRC Press.

ETH www.prec.ethz.ch

Secondary concentrators for various receivers

$C_{2D\text{-}CPC} = r_{in}/r_{out} = 1/\sin\alpha$



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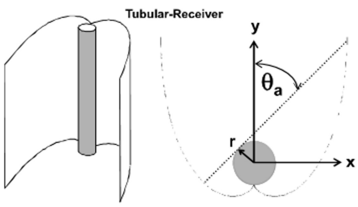
Equations for secondary with tubular receiver

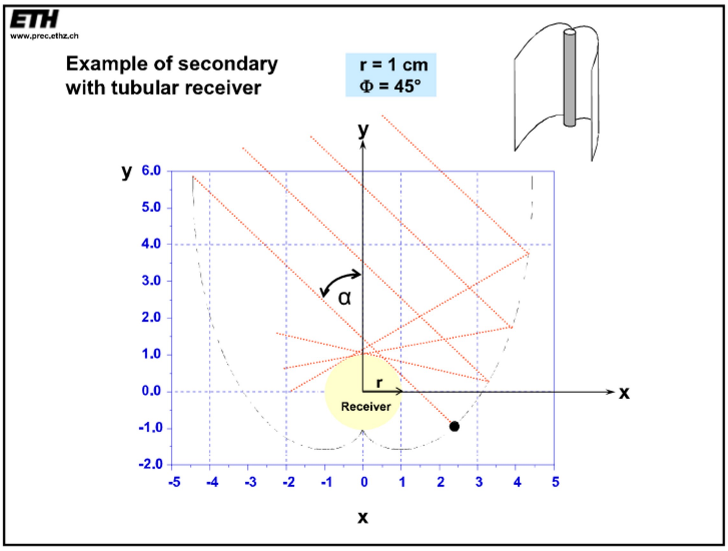


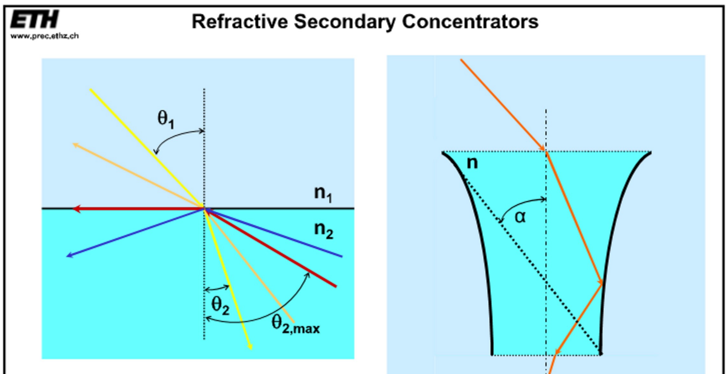
$$\begin{cases} x = r[\sin\theta - M(\theta)\cos\theta] \\ y = r[-\cos\theta - M(\theta)\sin\theta] \end{cases}$$

$$M(\theta) = \begin{cases} \theta & \text{for } 0 \le \theta \le \dfrac{\pi}{2} + \theta_a \\ \dfrac{\pi/2 + \theta_a + \theta - \cos(\theta - \theta_a)}{1 + \sin(\theta - \theta_a)} & \text{for } \dfrac{\pi}{2} + \theta_a \le \theta \le \dfrac{3\pi}{2} - \theta_a \end{cases}$$

θ_a CPC's half acceptance angle and is taken equal to the rim angle of the primary parabolic concentrator.

r radius tubular receiver.





$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\theta_{1,max} = 90° \rightarrow \theta_{2,max} = \sin^{-1}(n_1/n_2)$

$C_{2D\text{-}CPC} = n/\sin\alpha$

$C_{3D\text{-}CPC} = n^2/\sin\alpha$

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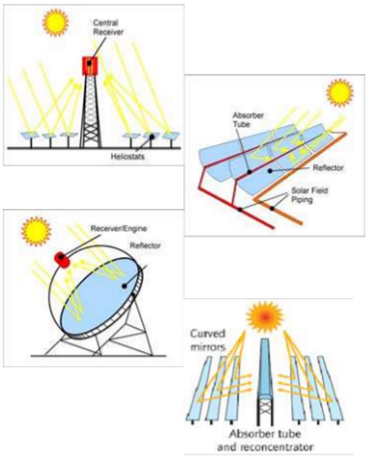
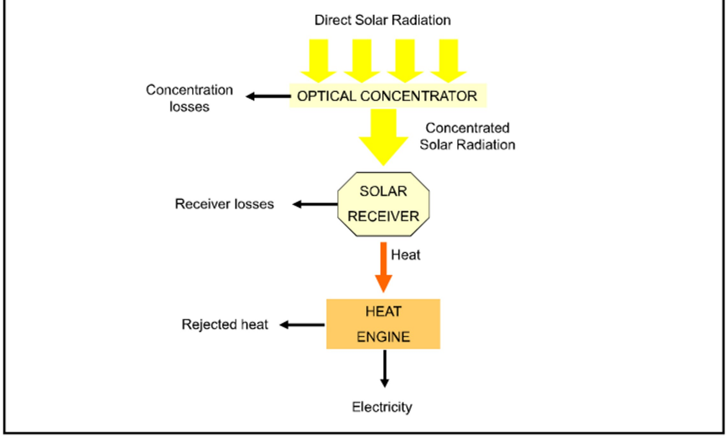
Solar Concentrating Technologies

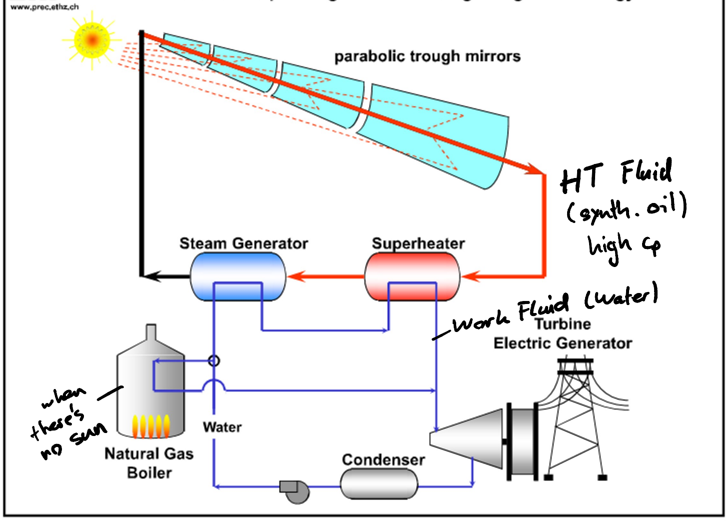
- Tower systems
- Trough systems
- Dish systems
- Linear Fresnel systems



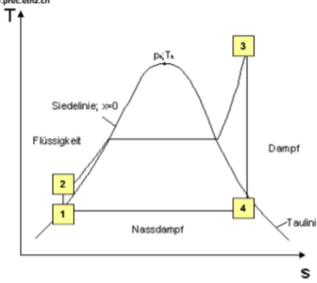
$$\eta_{solar-to-electrcity} = \eta_{optics} \cdot \underbrace{\eta_{receiver}}_{<\eta_{absorption}} \cdot \underbrace{\eta_{heat-to-electricity}}_{<\eta_{Carnot}}$$



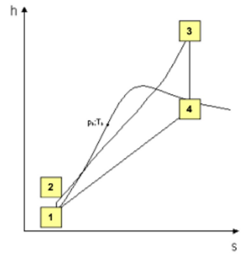
Solar thermal power generation using trough technology



Clausius-Rankine Cycle



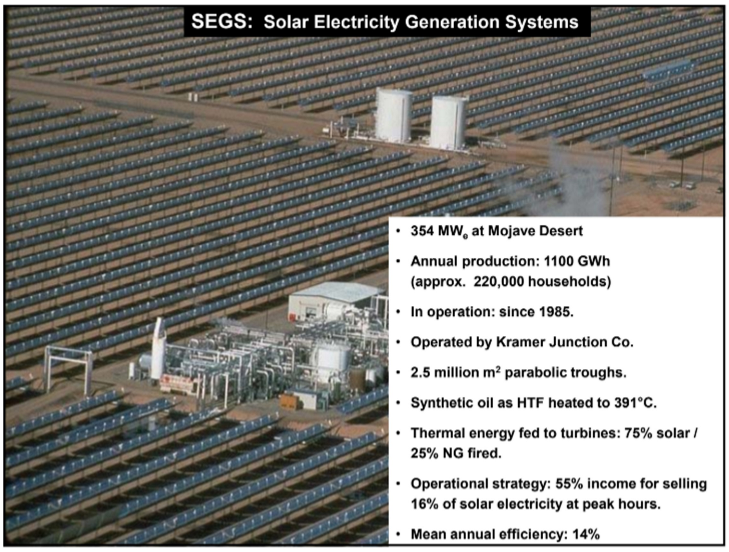
T-s-Diagramm

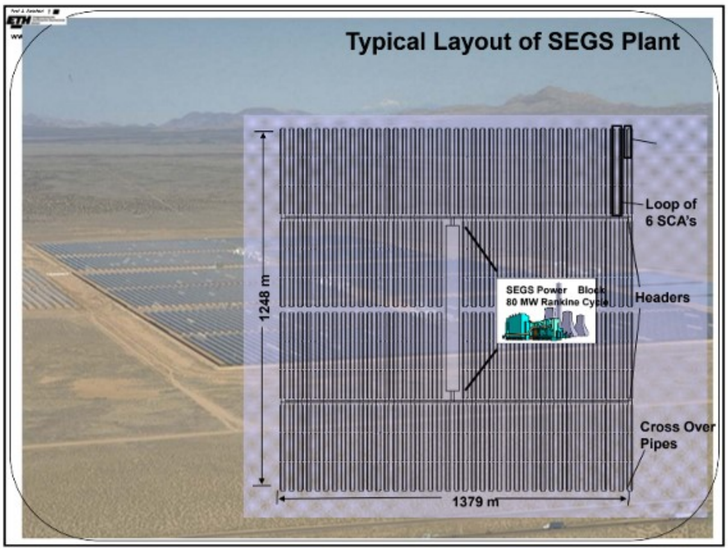


h-s-Diagramm

Zustandsänderungen des Arbeitsmittels:

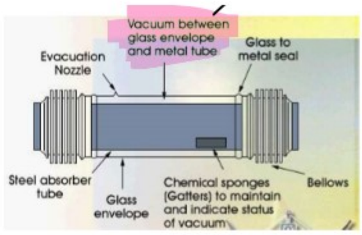
- **1** nach dem **Kondensator** : Flüssigkeit bei gegebenen p und T (Dampftafel)
- **1-2** Isentrope Verdichtung in der flüssigen Phase (Entropie bleibt konstant)
- **2** nach der **Speisepumpe**: komprimierte Flüssigkeit bei hohem Druck
- **2-3** Isobare Wärmezufuhr (Vorwärmung, Verdampfung und Überhitzung)
- **3** nach dem **Solar-Receiver**: überhitzter Dampf (Eigenschaften: Dampftafel)
- **3-4** Isentrope Expansion
- **4** nach der **Turbine**: Mischung aus Flüssigkeit und Dampf (Eigenschaften aus Dampftafel); der Zustand ist durch den Dampfanteil x bestimmt, z.B. $s = s_f + x\, s_{fg}$
- **4-1** Isobare Wärmeabfuhr und Kondensation

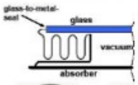


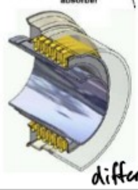

Typical Layout of SEGS Plant
Loop of 6 SCA's
SEGS Power Block
80 MW Rankine Cycle
Headers
1248 m
Cross Over Pipes
1379 m


ETH
Solar Collector Assembly
LS-3 (545 M)
99 Meters
244 Reflector Panels
Aperture
5.76 Meters
Ball Joint Assembly
Drive System
Sun Sensor
Local Controller
24 Heat Collection Elements


ETH
www.prec.ethz.ch
Solar Absorber
no convection
Vacuum between glass envelope and metal tube
Evacuation Nozzle
Glass to metal seal

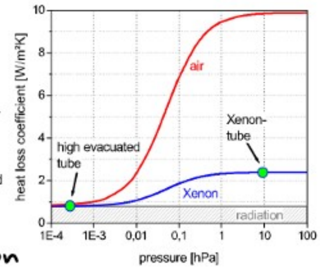






Vacuum isolation:

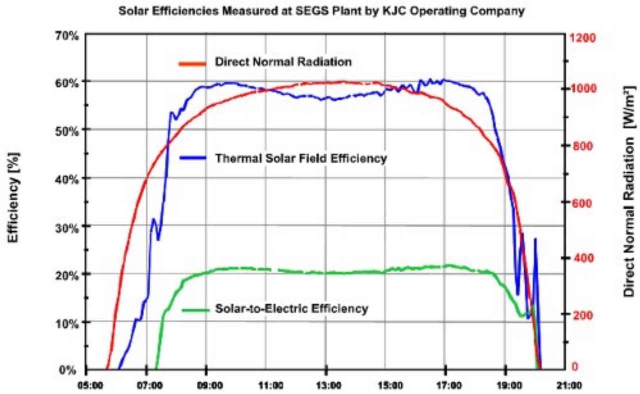
- The evacuated tube collector can be manufactured in a low-pressure-Xenon and in a high vacuum version (< 10^{-3} mbar) as well.
- Heat conduction is strongly reduced (Xenon) or even suppressed (high vacuum).

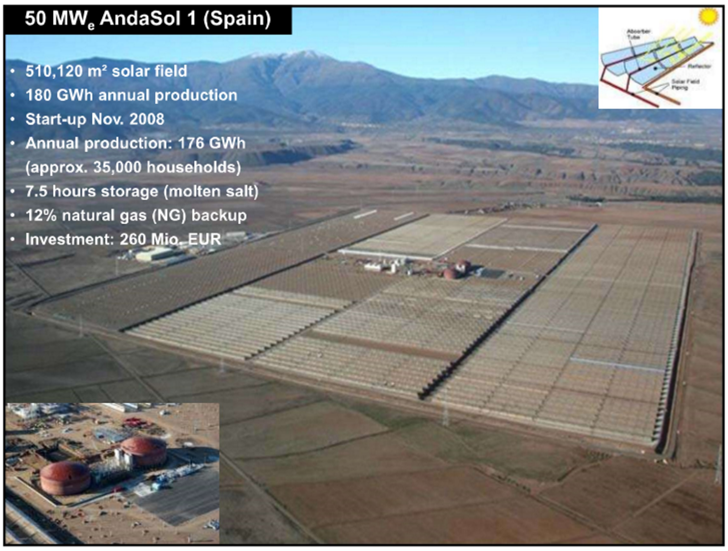


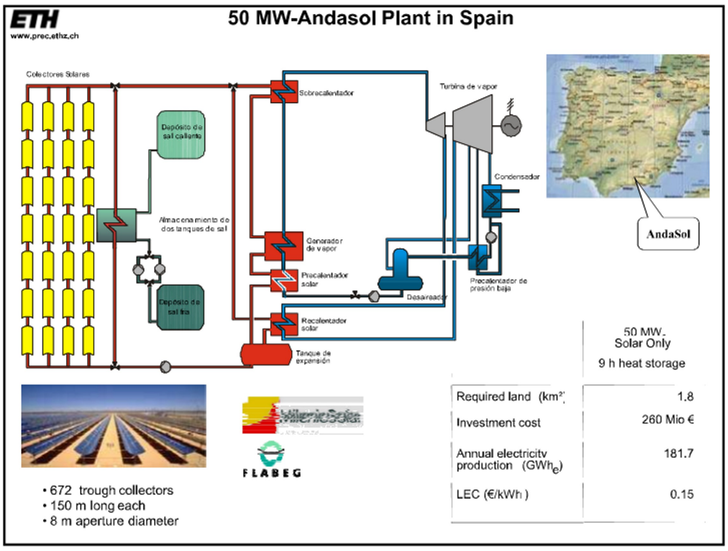
different thermal expansion

ETH

Solar Efficiency

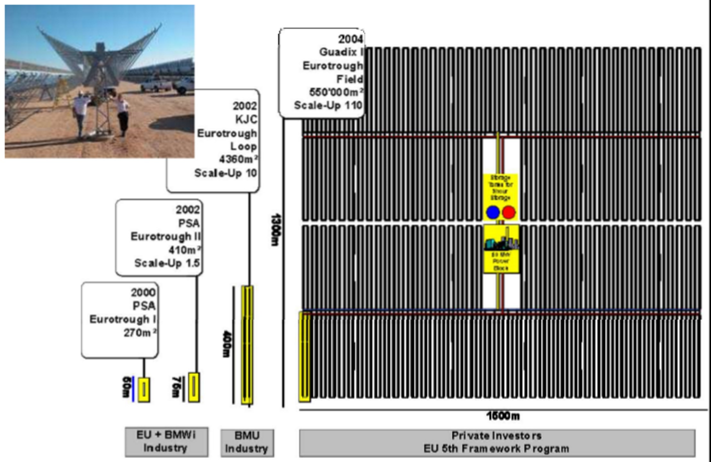



50 MW$_e$ AndaSol 1 (Spain)
• 510,120 m² solar field
• 180 GWh annual production
• Start-up Nov. 2008
• Annual production: 176 GWh (approx. 35,000 households)
• 7.5 hours storage (molten salt)
• 12% natural gas (NG) backup
• Investment: 260 Mio. EUR


ETH
www.prec.ethz.ch
50 MW-Andasol Plant in Spain
Colectores Solares
Depósito de sal caliente
Almacenamiento de dos tanques de sal
Depósito de sal fría
Sobrecalentador
Turbina de vapor
Condensador
Generador de vapor
Precalentador solar
Desaireador
Precalentador de presión baja
Recalentador solar
Tanque de expansión
AndaSol
FLABEG
50 MW$_e$ Solar Only
9 h heat storage
Required land (km²) 1.8
Investment cost 260 Mio €
Annual electricity production (GWh$_e$) 181.7
LEC (€/kWh) 0.15
• 672 trough collectors
• 150 m long each
• 8 m aperture diameter

ETH
www.prec.ethz.ch

50 MW-Andasol Plant in Spain



ETH
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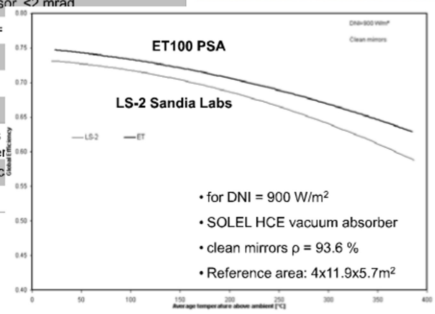
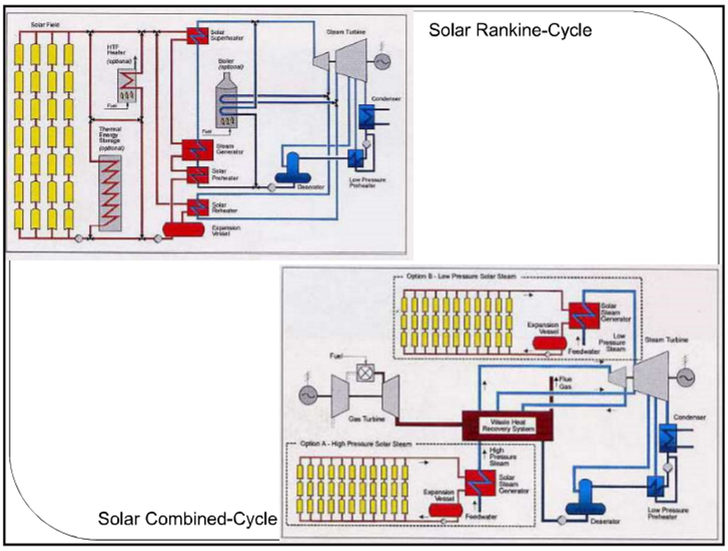
50 MW-Andasol Plant in Spain

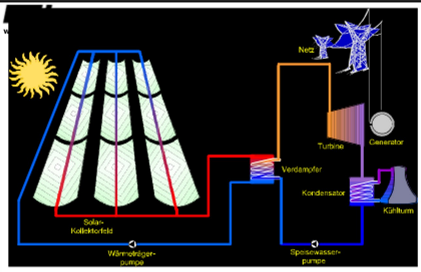
Layout	parabolic trough collector
support structure	steel frame work, pre-galvanized, three variants; light weight, low torsion
collector length	12 m per element; 100 - 150 m collector length
drive	hydraulic drive
max. wind speed	operation: 14 m/s, stow: 40 m/s
Tracking control	clock + sun sensor, <2 mrad
parabola	$y = x^2/4f$ with f =
aperture width	5.8 m
Reflector	4 glass facets
optical efficiency	0.80 (design)
absorber tube	evacuated glass application deper
Fluid	oil, steam, applic
cost	< 200 Euro/m²

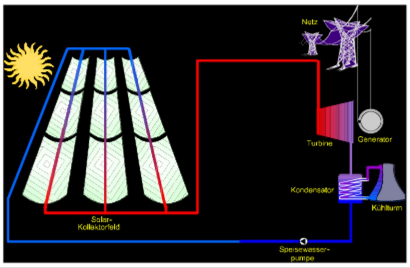



64 MW$_e$ Solar One (Nevada, USA)
357,200 m² solar field
130 GWh annual production
Start-up in June 2008


Solar Rankine-Cycle
Solar Combined-Cycle

Indirect Steam Generation





Direct Steam Generation

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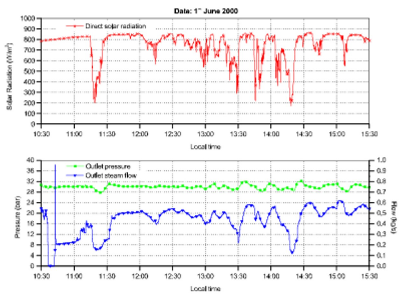
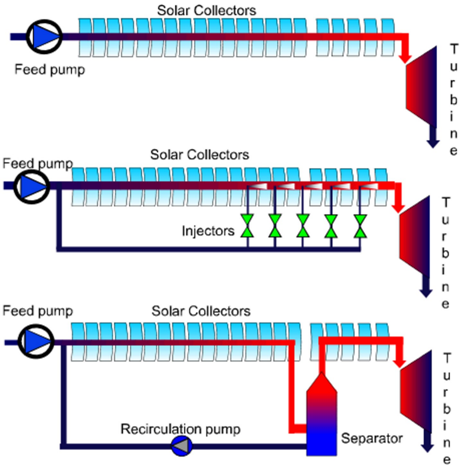
Direct Steam Generation

Technical Data:

- Length: 550 m
- Number of Modules: 40
- Sizes of Modules: 5,8 x 12 m²
- Diameter Absorber Tubes: 70 mm
- Mass Flow: 1.2 kg/s
- Temperature: 375 C
- Pressure: 30 - 100 bar



Direct Steam Generation

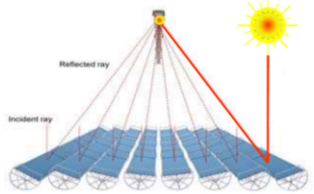


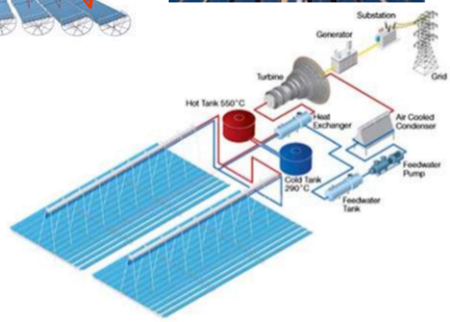
Once Through Boiler
- Lowest Costs
- Least complexity
- Best Performance
- Controllability ?
- Flow Stability ?

Injection Process
- Better Controllability
- Flow stability equally good
- More complex
- Higher investment costs

Recirculation Process
- Better Flow Stability
- Better Controllability
- More complex
- Higher investment costs
- Higher parasitics

Linear Fresnel System





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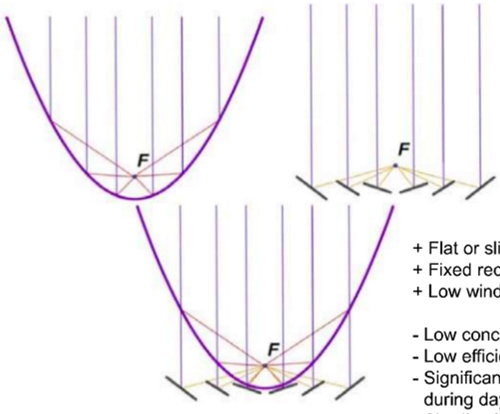
Fresnel Reflector



+ Flat or slightly curved mirrors
+ Fixed receiver
+ Low wind loads on mirrors

- Low concentration C = 10 - 40
- Low efficiency
- Significant change in efficiency during day
- Shading losses

Karathanasis, S. (2019). Linear Fresnel Reflector Systems for Solar Radiation Concentration. Cham, Switzerland, Springer.

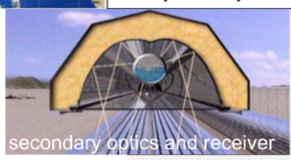
ETH
www.prec.ethz.ch

Novatec, Puerto Errado, Spain

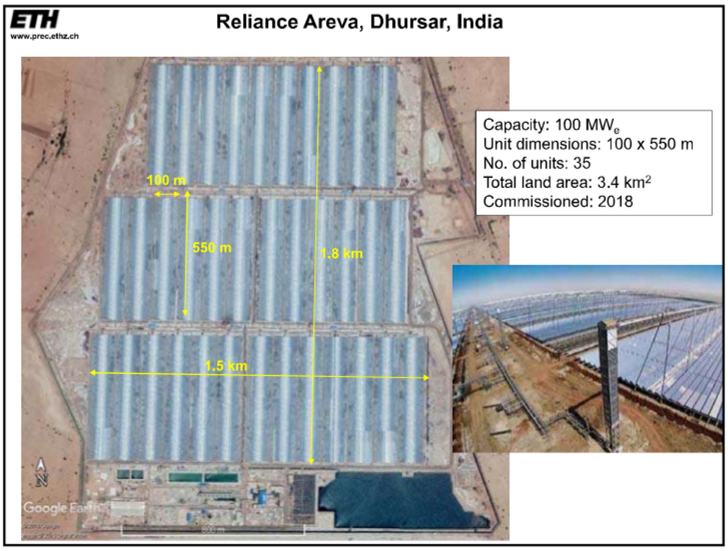
Direct steam generation
T > 500 °C

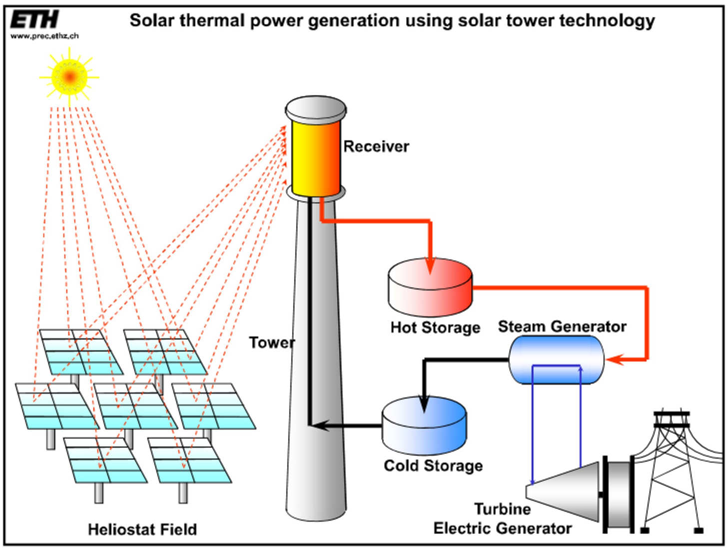
Puerto Errado 1 (Pilot)
Capacity: 1.4 MW_e
Commissioned: 2009
Location: Murcia, Spain

Puerto Errado 2 (Commercial)
Capacity: 30 MW_e
Mirror area: 30 hectares
Number of mirrors: 375'000
Land area: 70 hectares
Receiver piping: 28 km
Commissioned: 2012
Location: Murcia, Spain
Partially owned by ewz & ekz



https://youtu.be/suyoieQ2Gn4


ETH
www.prec.ethz.ch
Reliance Areva, Dhursar, India
100 m
550 m
1.8 km
1.5 km
Capacity: 100 MW$_e$
Unit dimensions: 100 x 550 m
No. of units: 35
Total land area: 3.4 km^2
Commissioned: 2018
Google Earth


ETH
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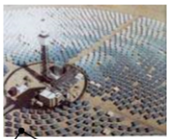
Solar thermal power generation using solar tower technology
Receiver
Tower
Hot Storage
Steam Generator
Cold Storage
Turbine
Electric Generator
Heliostat Field



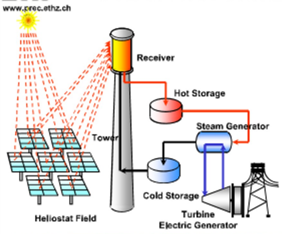
Name	SSPS-CRS	EURELIOS	SUNSHINE	CESA-1	THEMIS	Solar One	Solar Two	SPP-5
Location	Almeria	Adrano (Sicily)	Nio Town	Almeria	Targasonne	Barstow	Barstow	Shchelkino (Crimea)
Country	Spain	Italy	Japan	Spain	France	USA	USA	Russia
Start of Operation	1981	1981	1981	1983	1982	1982	1996	1986
Electric Output	500 kW_e	1 MW_e	1 MW_e	1 MW_e	2-2.5 MW_e	10 MW_e	10 MW_e	5 MW_e
Heliostat field reflective surface area	3655 m^2	6216 m^2	12912 m^2	11880 m^2	10794 m^2	71447 m^2	71447 m^2	40000 m^2
Receiver heat-transfer fluid	Liquid Sodium	Steam	Steam	Steam	Molten salt (HITEC)	Steam	Molten Salt	Steam
Receiver heat-transfer fluid temperature	530 °C	512 °C	249 °C	525 °C	450 °C	516 °C	565 °C	250 °C
Storage medium	Sodium	HITEC salt / hot water	HITEC salt / hot water	HITEC salt	Molten salt (HITEC)	Oil/rock	Molten Salt	Water / steam
Storage capacity (full power hours)	2	0,5	3	3,5	5	3	3	not available

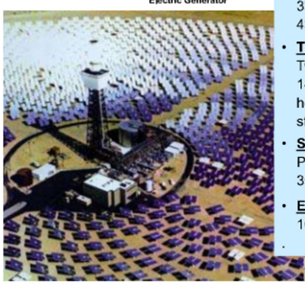




SOLAR TWO: Solar thermal power generation using molten-salt storage

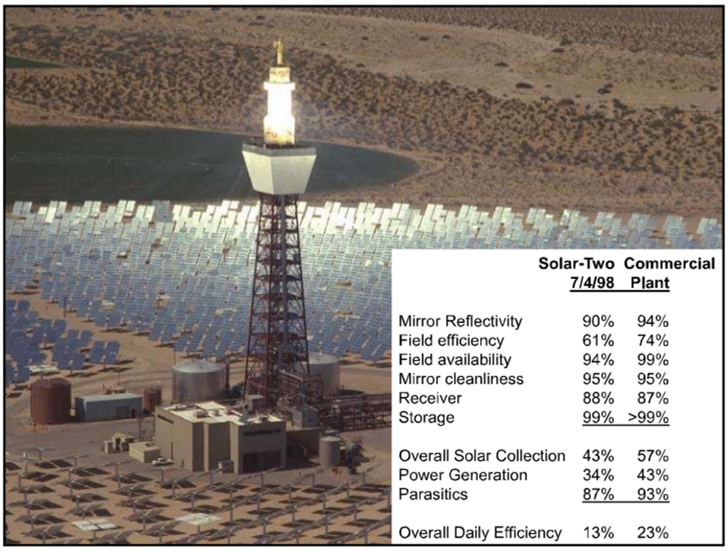
www.prec.ethz.ch





Facts:

- Operated by Sandia National Laboratories at Barstow, CA.
- Solar One (steam) operated 1982-1988.
- Solar Two (molten salt) operated 1996-1999.
- **Heliostats**:
  1,818 heliostats of 39 m^2 each, 108 heliostats 95 m^2 each;
  total reflective area = 81,162 m^2.
- **Solar receiver**:
  Cylindrical shape of 5.1-m ϕ x 6.2-m high;
  33 25-mm ϕ tubes in each of 24 panels;
  43 MW_{th} solar thermal power with 800-sun peak flux.
- **Thermal Storage**:
  Two 12-m f x 8-m high storage tanks;
  1400 tons molten nitrate salt (K, Na) as HTF; m.p. 240 °C;
  hot storage @ 565°C; cold storage @ 280 °C;
  storage capability: 24 hr. power delivery.
- **Steam Generator**:
  Preheater, evaporator, superheater vessels;
  35.5 MW thermal rating at 538 °C, 100 bar.
- **Electric Power Generation System**:
  10 MW_e net electric power rating Rankine-cycle.



	Solar-Two 7/4/98	Commercial Plant
Mirror Reflectivity	90%	94%
Field efficiency	61%	74%
Field availability	94%	99%
Mirror cleanliness	95%	95%
Receiver	88%	87%
Storage	99%	>99%
Overall Solar Collection	43%	57%
Power Generation	34%	43%
Parasitics	87%	93%
Overall Daily Efficiency	13%	23%

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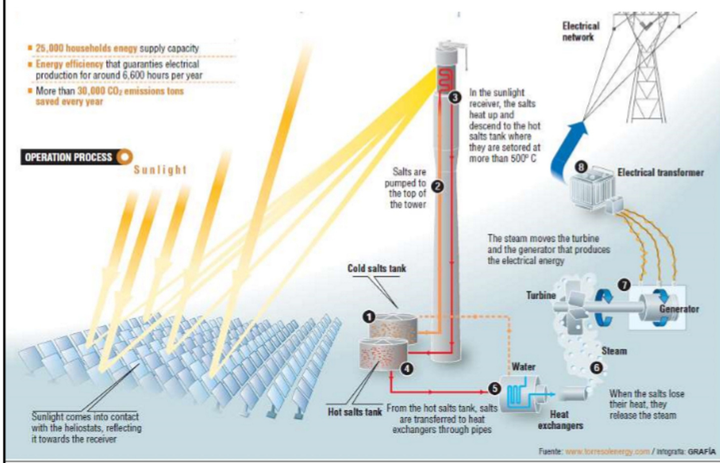
20 MW_e-GEMASOLAR in Spain



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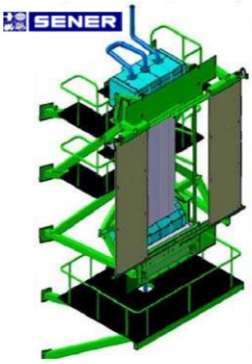
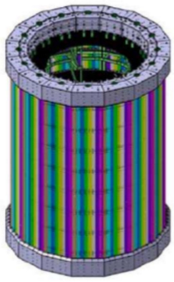
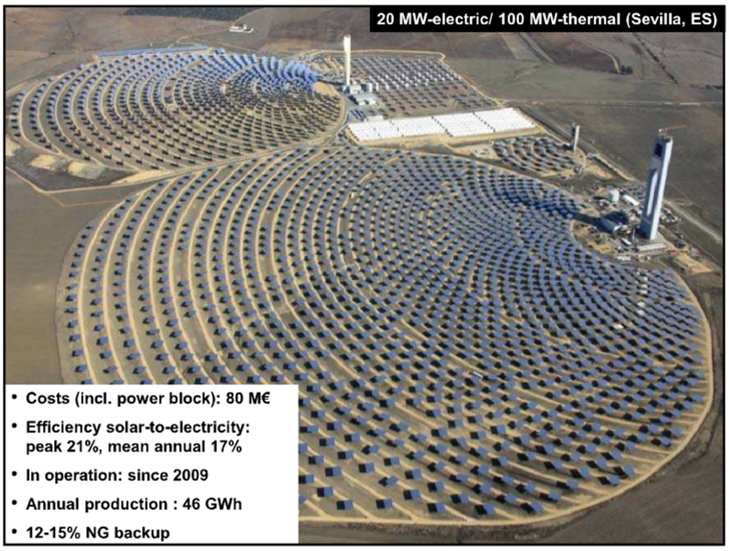
20 MW_e-GEMASOLAR in Spain

Testing absorber panel






11 MW-electric/ 55 MW-thermal(Sevilla, ES)
• 624 Heliostats; each 120 m²
• Tower height: 100 m
• Costs (incl. power block): 35 M€
• Efficiency solar-to-electricity: peak 21%, mean annual 17%
• In operation: since 2007
• Annual production : 23 GWh (approx. 15'000 households)
• 1 hour storage (steam)


20 MW-electric/ 100 MW-thermal (Sevilla, ES)
• Costs (incl. power block): 80 M€
• Efficiency solar-to-electricity: peak 21%, mean annual 17%
• In operation: since 2009
• Annual production : 46 GWh
• 12-15% NG backup

ETH
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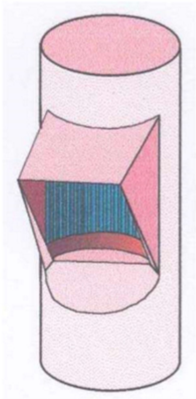
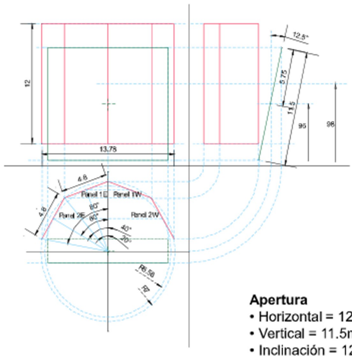
PS10 Solar Receiver - Saturated-vapor





Apertura
- Horizontal = 12.5m
- Vertical = 11.5m
- Inclinación = 12.5º

Absorbedor
- Desplaz. vertical = +2m
- 4 Paneles, 4.8m x 12m
- Angulo apertura 160º
- Radio Max. = 7m

ETH
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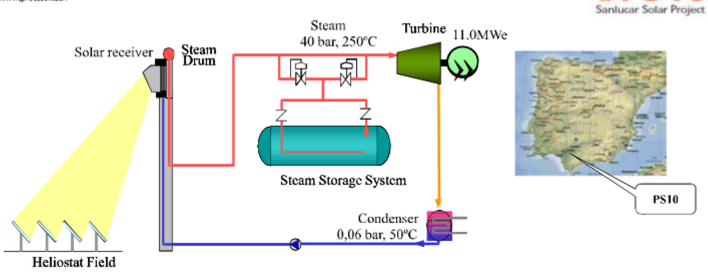
11 MW$_e$ in Sevilla, Spain

PS10
Sanlucar Solar Project

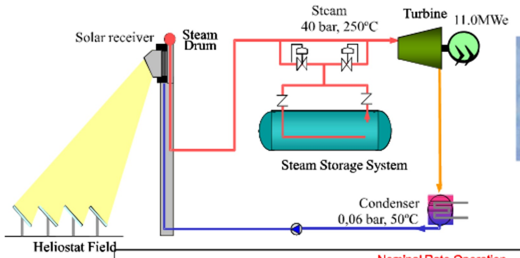


General Description	
Emplacement	Sanlúcar M. (Sevilla), Lat 37.4°, Lon 6.23°
Nominal Power	11.02MWe
Tower Height	100m
Receiver Technology	Saturated Steam
Receiver Geometry	Cavity180°, 4 Pannels 5m x 12m
Heliostats	624 @ 121m2
Thermal Storage Technology	Water/Steam
Thermal Storage Capacity	15MWh, 50min @ 50% Rate
Steam Cycle	40bar 250°C, 2 Pressures
Electric Generation	6.3kV, 50Hz -> 66kV, 50Hz
Land	60Has
Annual Electricity Production	23.0GWh

ETH www.prec.ethz.ch

11 MW_e in Sevilla, Spain

PS10 Sanlucar Solar Project



Nominal Rate Operation		
Optical Efficiency	77.0%	67,5MW -> 51.9MW
Receiver and Heat Handling Efficiency	92.0%	51.9MW -> 47.7MW
Thermal Power to Storage		11.9MW
Thermal Power to Turbine		35.8MW
Thermal Pow. -> Electric Pow. Efficiency	30.7%	35.8MW -> 11.0MW
Total Efficiency at Nominal Rate		21.7%
Energetical Balance in Annual Basis		
Mean Annual Optical Efficiency	64.0%	148.63GWh(useful) -> 95.12GWh
Mean Annual Receiver&Heat Handling Efficiency	90.2%	95.12GWh -> 85.80GWh
Operational Efficiency (Starts Up/Stops)	92.0%	85.80GWh -> 78.94GWh
Operational Efficiency (Breakages, O&M)	95.0%	78.94GWh -> 75.00GWh
Mean Annual Thermal Ener. -> Electric Efficiency	30.6%	75.00GWh -> 23.0GWh
Total Annual Efficiency		15.4%

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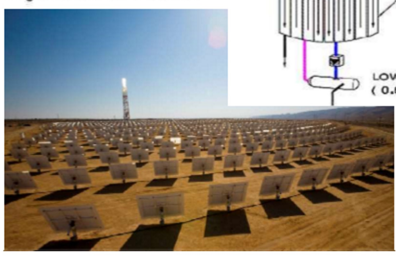
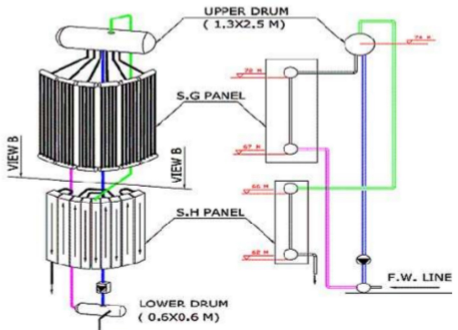
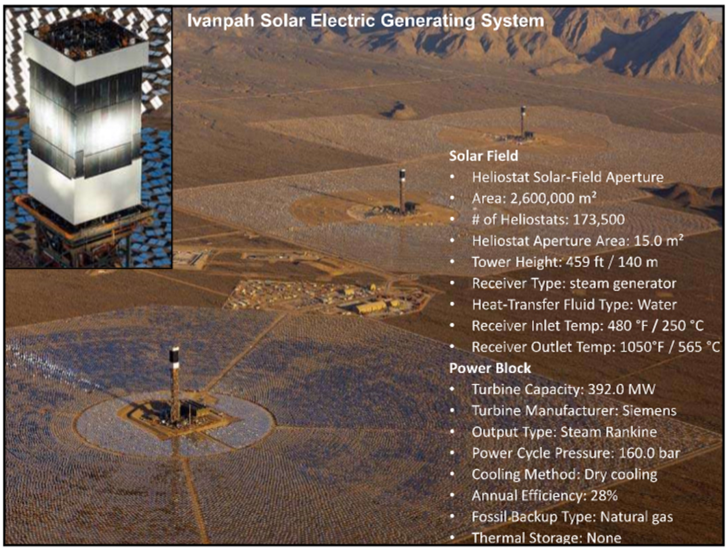
BrightSourceEnergy

Brightsource Dual External





- Direct solar-to-steam at 550° C
- Air-cooled power block
- 15 m^2 heliostat mirrors



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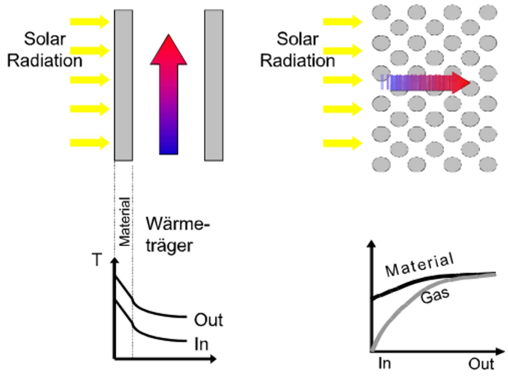
eSolar

eSolar Sierra SunTower
- 2 modules, 20 acres
- 2 towers, 2 x 65-ton thermal receivers
- 1 GE steam turbine generator
- 24,000 mirrors reflecting the power of 20,000 suns
- 5 MW of clean, supplied to 4,000 Southern California Edison households

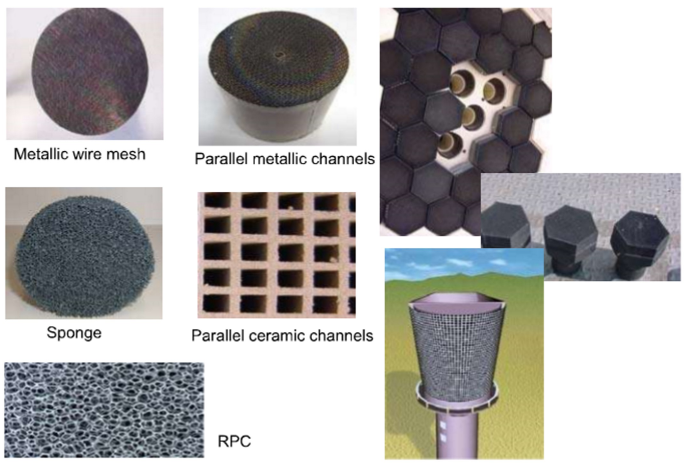
Double-Cavity

Tube vs. Volumetric Absorber



Properties:
- Higher incident flux
- Improved absorption
- Lower extinction
- Higher heat transport
- Higher thermal stability
- Lower cost

Volumetric Absorber



Metallic wire mesh

Parallel metallic channels

Sponge

Parallel ceramic channels

RPC

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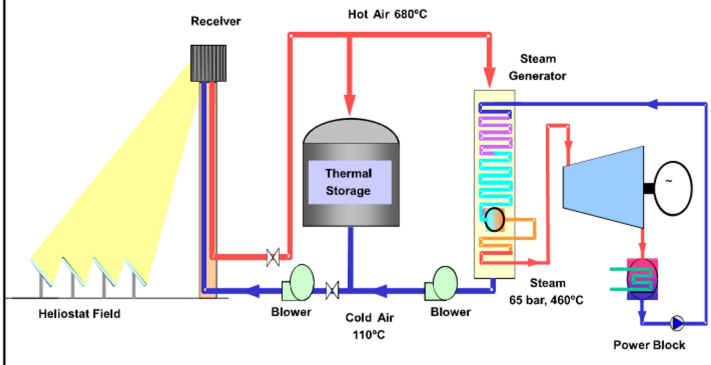
Air-based Solar Tower Scheme



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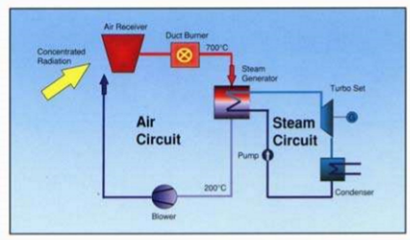
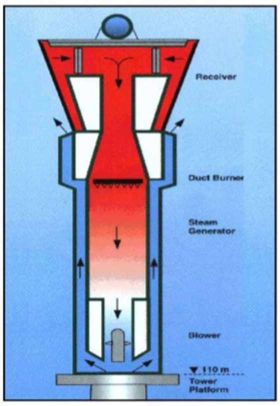
Solar Air-Receiver

Technical Sheet

- Steam Parameters: 700°C, 100 bar
- Heat Transfer Medium: Air
- Backup Options: Thermal Storage, Duct Burners
- Backup Fuels: Natural Gas, Oil
- Technology Status 3 MW Demonstration at PSA





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Heliostats

Faceted

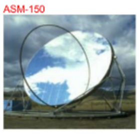
Streched-membrane

GM-100

SAIC-170

ATS-150

ASM-150



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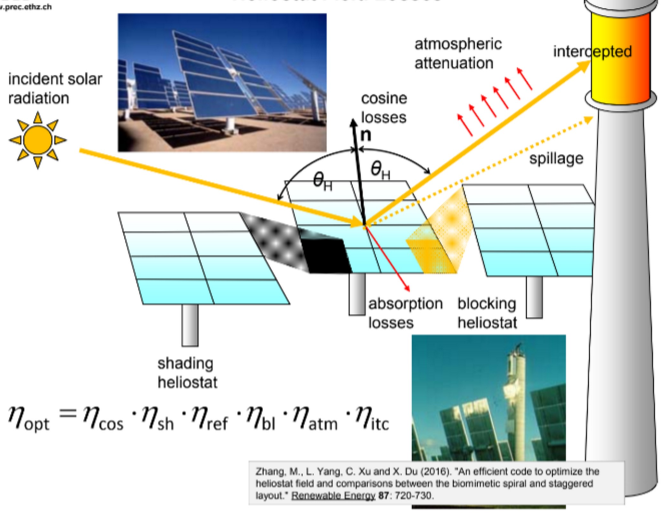
Heliostat Field Losses

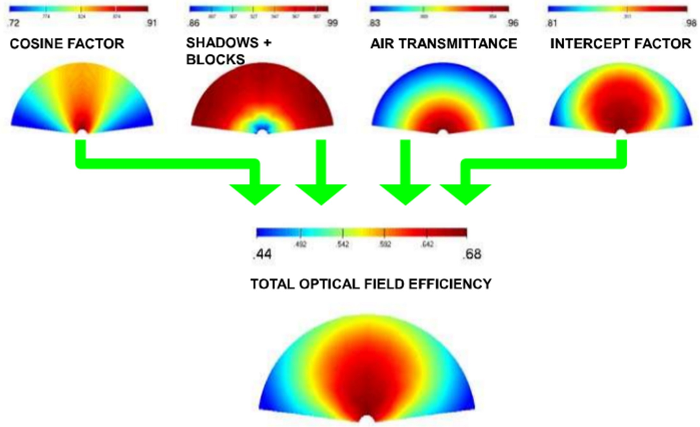


$$\eta_{opt} = \eta_{cos} \cdot \eta_{sh} \cdot \eta_{ref} \cdot \eta_{bl} \cdot \eta_{atm} \cdot \eta_{itc}$$

Zhang, M., L. Yang, C. Xu and X. Du (2016). "An efficient code to optimize the heliostat field and comparisons between the biomimetic spiral and staggered layout." Renewable Energy **87**: 720-730.

Optical Efficiency

$$\eta_{opt} = \eta_{cos} \cdot \eta_{sh} \cdot \eta_{ref} \cdot \eta_{bl} \cdot \eta_{atm} \cdot \eta_{itc}$$



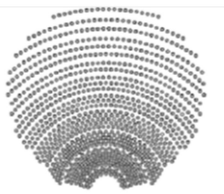
Heliostat Field

closer to equator

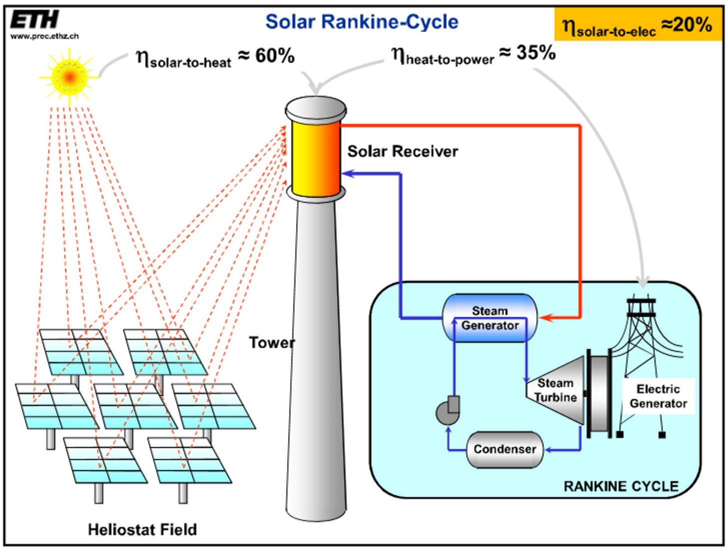
Circular

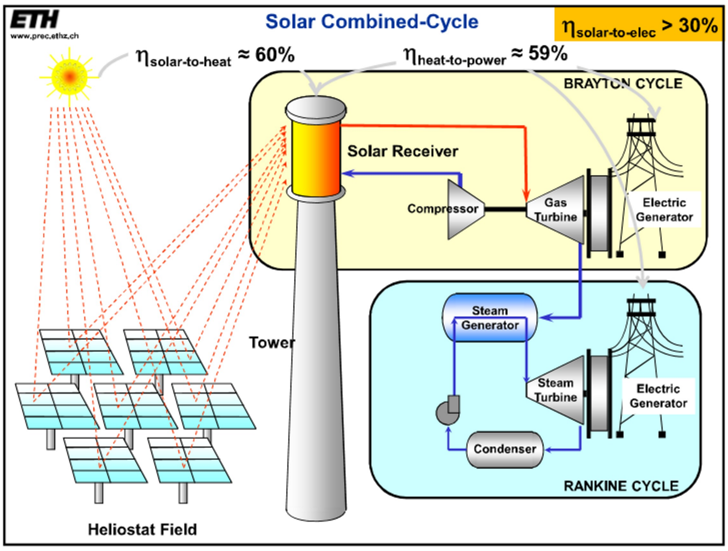
Land use factor: 0,20

North



Land use factor: 0,25


ETH
www.prec.ethz.ch
Solar Rankine-Cycle
$\eta_{solar\text{-}to\text{-}elec} \approx 20\%$
$\eta_{solar\text{-}to\text{-}heat} \approx 60\%$
$\eta_{heat\text{-}to\text{-}power} \approx 35\%$
Solar Receiver
Tower
Steam Generator
Steam Turbine
Electric Generator
Condenser
RANKINE CYCLE
Heliostat Field


ETH
www.prec.ethz.ch
Solar Combined-Cycle
$\eta_{solar\text{-}to\text{-}elec} > 30\%$
$\eta_{solar\text{-}to\text{-}heat} \approx 60\%$
$\eta_{heat\text{-}to\text{-}power} \approx 59\%$
BRAYTON CYCLE
Solar Receiver
Compressor
Gas Turbine
Electric Generator
Tower
Steam Generator
Steam Turbine
Electric Generator
Condenser
RANKINE CYCLE
Heliostat Field

ETH
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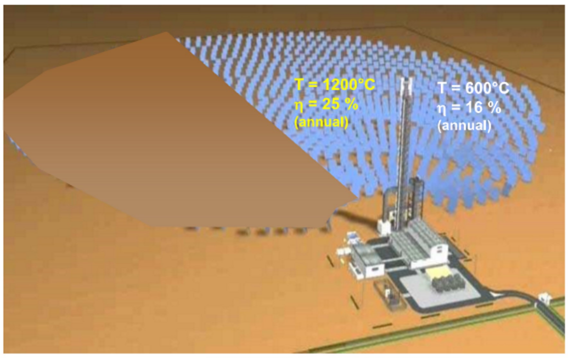
Solar Thermal Combined-Cycle Power Generation

Improved Performance = Cost reduction

- High Temperature
- High Concentration



ETH
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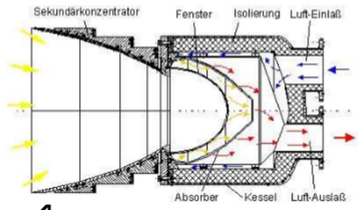
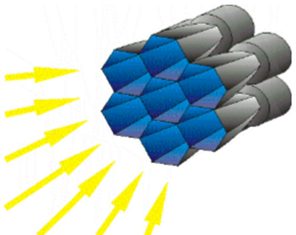
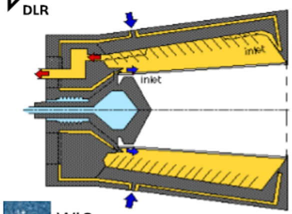
Solar Receiver Technology for CC-plants





DLR



WIS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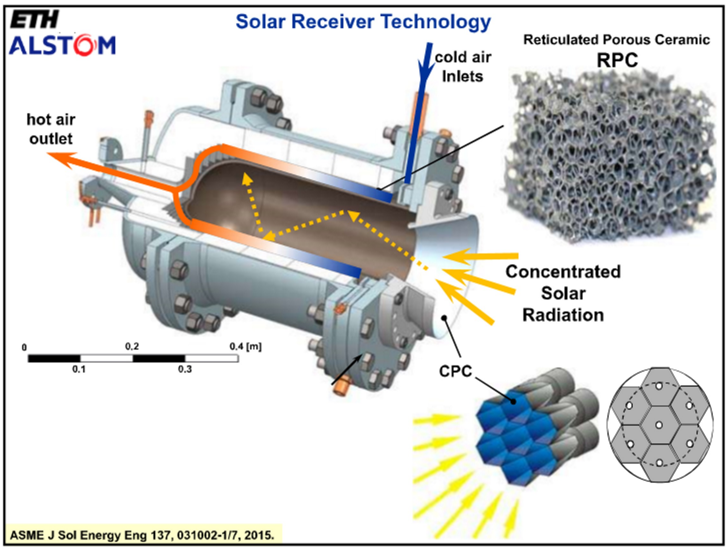
AORA
SOLAR ENERGY. LOCAL POWER.
• 100 kW electricity
• 170 kW heat
• 1,600 sq. meter)


ETH
ALSTOM
Solar Receiver Technology
cold air
Inlets
Reticulated Porous Ceramic
RPC
hot air
outlet
Concentrated
Solar
Radiation
0
0.1
0.2
0.3
0.4 [m]
CPC
ASME J Sol Energy Eng 137, 031002-1/7, 2015.

Solar Dish Technology

Glass-Facet Concentrators

Name	JPL-TBC	Vanguard I	MDAC
Manufacturer	E-Systems	Advanco Corp.	McDonnell Douglas
Year	1979	1984	1984
Aperture Diameter/Area	11 m	10.6 m	10.6 m
Concentration Ratio (geometric)	1500-3000	2700	2793
Output at 1000 W/m² insolation	82 kW	73.1 kW	70-80 kW
Optical Efficiency	89%	89%	88%
Number Built	2	1	8
http://solstice.crest.org/renewables/dish-stirling/index.html			



Solar Dish Technology

Single-Facet Stretched-Membrane Concentrators

Manufacturer	Schlaich Berger-mann und Partner	Schlaich Berger-mann und Partner	Solar Kinetics Inc.
Year	1984	1989 / 1997	1990
Aperture Diameter/Area	17 m	7.5 m / 8.5 m	7 m
Concentration Ratio (geometric)	600	4000 / 4000	
Output at 1000 W/m² insolation	179 kW	36 kW / 45 kw	23.3 kW
Optical Efficiency	79%	82%	67%
Number Built	3	6 and 3	1
http://solstice.crest.org/renewables/dish-stirling/index.html			



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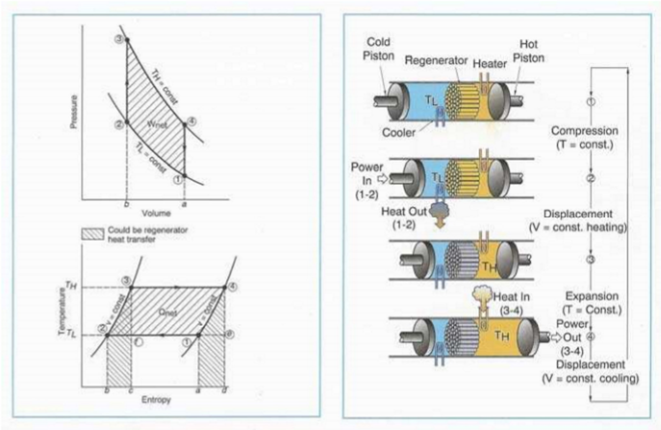
Stirling Heat Engine



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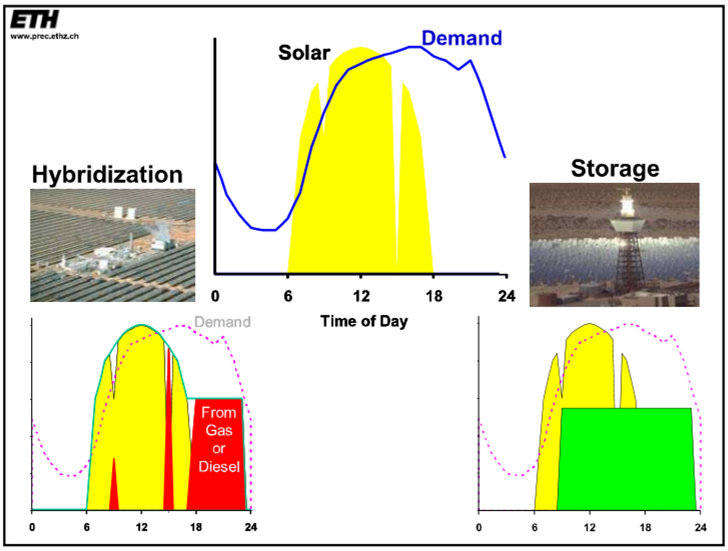
Solar Dish Technology

The Big Dish

Manufacturer	Anutec Ltd
Year	1995
Aperture Diameter/Area	23 m/400 m²
Output	350 kW_{th} / 55 kW_{el} (in test runs) expect to achieve between 60 and 80 kW_{el} at full operation
Number Built	2 MW_{el} power plant soon to be established at Tennant Creek (Northern Territory) using this dish technology
http://www.anutech.com.au/physci/cpps/bigdish.html	



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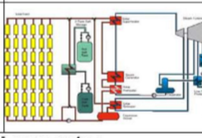
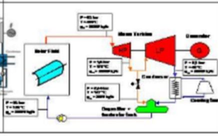
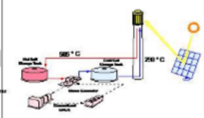
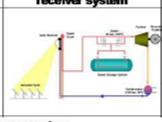
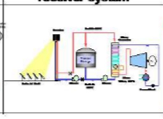
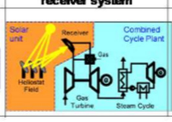
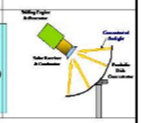
Characteristics of Concentrating Solar Power Systems

Concentrating Solar Power System		Peak Efficiency	Annual Efficiency	Annual Capacity Factor
Trough		14 - 20 %	13 - 15 %	20 - 25 % (no TES) 40 - 53 % (6 h TES)
Linear Fresnel		18 %	9 - 13 %	22 - 24 %
Tower		23 - 35 %	14-18 %	40 - 45 % (6 - 7.5 h TES) 65 - 80 % (12- 15 h TES)
Dish		31 %	22 - 24 %	25 %

•A.C.F = fraction of year the technology can deliver solar energy at rated power
•TES = thermal energy storage

Liu, M., et. al (2016). Renewable and Sustainable Energy Reviews **53**: 1411-1432.

Technology	Parabolic trough / HTF	Parabolic trough DSG	Molten salt Central receiver system
			
Technical design parameter:			
Collector	Parabolic trough	Parabolic trough	Heliostat field
Receiver	Linear receiver (tubes)	Linear receiver (tubes)	Molten salt receiver
Storage system	2-tank-molten-salt storage	No storage system available up to date	2-tank-molten-salt storage
Cycle	Rankine steam cycle	Rankine steam cycle	Rankine cycle
Planed / built power size			
	50 MW Andasol I & II, under preparation, Spain	4.7 MW INDITEP study	Solar Tres (17MW), planed, Spain
Maturity	Several commercial units up to 80 MW_e are in operation in southern USA	Single row experimental plant in Spain	Solar 2 (11 MW) experimental plant in California in the 1990ies
Temperature	393°C	411°C	565°C
Size ref sys	50 MW_e	10 × 4.7 MW_e	3 × 17 MW_e
Capacity factor	29 %	22 %	33 %
LEC for a single ECOSTAR reference system, solar-only			
	0.172 €/kWh_e	0.187 €/kWh_e	0.183 €/kWh_e
LEC for power plant park consisting of several reference systems with total capacity of 50 MW, solar-only			
	0.172 €/kWh_e	0.162 €/kWh_e	0.155 €/kWh_e

Technology	Saturated steam central receiver system	Atmospheric air central receiver system	Pressurized air central receiver system	Dish engine System
				
Technical design parameter:				
Collector	Heliostat field	Heliostat field	Heliostat field	Parabolic dish
Receiver	Saturated steam receiver	Volumetric atmospheric air-cooled receiver	Pressurized air receiver	Cavity receiver with tube bundle
Storage system	Water/steam buffer storage	Ceramic thermocline thermal storage	No storage system available up to date	No storage system available up to date
Cycle	Rankine cycle	Rankine cycle	Combined cycle	Stirling engine
Planed / built power size				
	PS 10 (11MW), under construction, Spain	PS 10 conceptual design study	Solgate study 14.6 MW_e	22 kW_e
Maturity	Several experimental plants up to 2 MW_{th} have been tested	2.5 MW_{th} experimental plant tested in Spain in 1993	2 × 200 kW_e under construction in Italy	About 30 units up to 25 kW_e are in operation at different sites
Temperature	250°C	750°C	800°C	800°C
Size of the reference system	5 × 11 MW_e	5 × 10 MW_e	4 × 14.6 MW_e	2907 × 25 kW_e
Solar capacity factor	26%	33 %	11 % (55%)[1]	22%
LEC for a single ECOSTAR reference system, solar-only				
	0.241 €/kWh_e	0.234 €/kWh_e	0.147 €/kWh_e (0.1 €/kWh_e)	0.281 €/kWh_e
LEC for a power plant park consisting of several reference systems with total capacity of 50 MW, solar-only				
	0.169 €/kWh_e	0.179 €/kWh_e	0.139 €/kWh_e (0.082 €/kWh_e)	0.193 €/kWh_e

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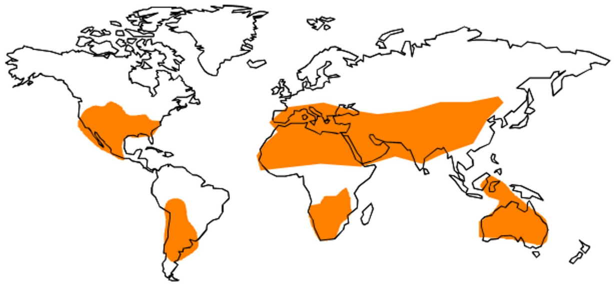
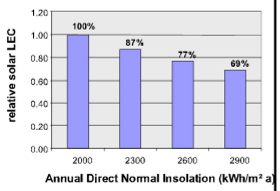
Zones for deployment of CSP



1. Global solar radiation on earth	(TWh/year)	$240 * 10^6$
2. Dessertic areas (7% of earth surface)	(TWh/year)	$16 * 10^6$
3. Solar fraction of DNI available (70%)	(TWh/year)	$11{,}2 * 10^6$
4. Efficiency of CSP plants (15%)	(TWh/year)	$1{,}68 * 10^6$
5. Percentage a rea with good infrastructures (1% of dessert areas)	(TWh/year)	$16{,}8 * 10^3$
6. World electricity demand year 2000	(TWh/year)	$15 * 10^3$

1% of arid/semi-arid areas are enough to supply annual world demand of electricity



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Solar Photovoltaics

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History

1839: A. E. Becquerel discovers the PV effect, "Recherches sur les effets de la radiation chimique de la lumière solaire au moyen de courants éléctriques" *Comptes Rendues à l'Academie des Sciences* 9, 145-149 (1839).

1905: A. Einstein develops the theory of the photoelectric effect, "Über einen die Erzeugung und Erwandlung des Lichtes betreffenden heuristischen Sichtspunkt" *Annalen der Physik*, 17, 132 (1905). Nobel Laureate in Physics (1922).

1949: W. Shockley invents p-n crystals, "The theory of p-n junctions in semiconductors and p-n junction transistors" *Bell Sys. Tech. Jour.* **28** 435 (1949). Nobel Laureate in Physics (1956).

1954: Bell Labs produces 1st solar cell with p-n junction. D.M. Chapin (center), C.S. Fuller (right) and G.L. Pearson (left), "A New Silicon P-N Junction Photocell for Converting Solar Radiation into Electrical Power", *J. Appl. Phys.* **25** 676 (1954).

1955: Hoffman Electronics offers 2% Si cells @ $1500/W. In 1959, it offers 10% Si cells.

The New York Times: 26 April 1954 *"Vast Power is Tapped by Battery Using Sand Ingredient" "…may mark the beginning of a new era, leading eventually to the realization of one of mankind's more cherished dream —the harnessing of the almost unlimited energy of the sun for the uses of civilization*".

Advantages/Disadvantages of PV

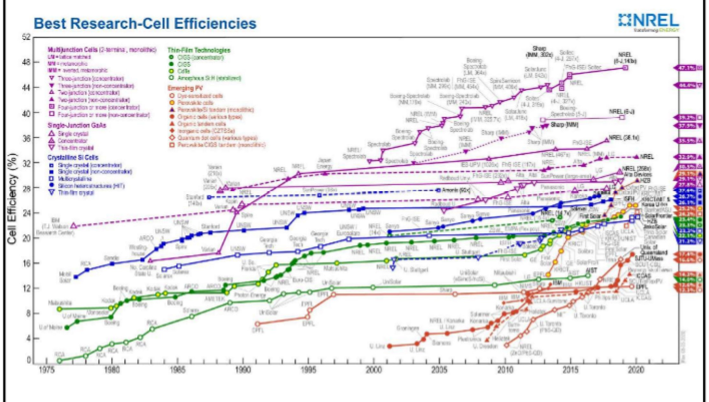
Advantages of PV

- Solar energy is renewable, sustainable, pollution-free.
- No moving parts; silent;
- Fast start-up/shut-down.
- Ambient temperature operation.
- Made of Si from widely-available SiO_2.
- Extremely modular.
- Low maintenance cost.

Disadvantages of PV

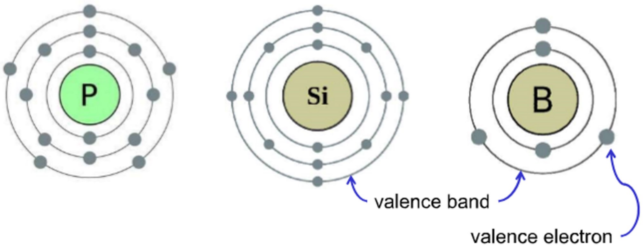
- Solar energy is intermittent.
- Solar energy is non-uniformly distributed.
- Solar energy is dilute (only 1 kW/m^2).
- Production of Si is energy intensive.
- High investment cost.
- Electricity storage.
- Conversion efficiency.

Efficiency History



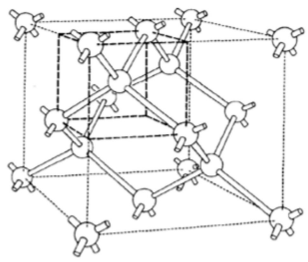
https://www.nrel.gov/pv/cell-efficiency.html

Valence & Conduction Electrons

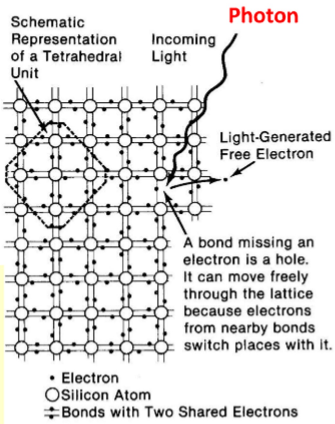


	Phosphorus	Silicon	Boron
Atomic Nr.	15	14	5
Electron shell configuration	2-8-5	2-8-4	2-3

Si crystal lattice



- Si atom makes 4 **covalent** bonds.
- Incoming sunlight photon release electrons from its binding: they move from **valence** to **conduction** band
- This is called **electron-hole** pairs.
- Electrons & holes are negative & positive charge carriers, respectively.
- They move freely until they recombine.



Ref.: *Basic Photovoltaic Principles and Methods*, 1981.

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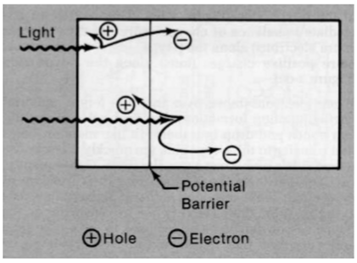
Potential Barrier



- Need to separate the electron so that it does not recombine with a hole.
- Must create a “potential barrier.”
- Electrons and holes are pushed to different sides of the potential barrier, to avoid their recombination.
- This separation of charges creates a voltage that, in turn, can be used for generating electricity through an external circuit.

Ref.: *Basic Photovoltaic Principles and Methods*, 1981.

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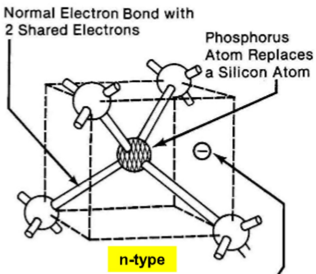
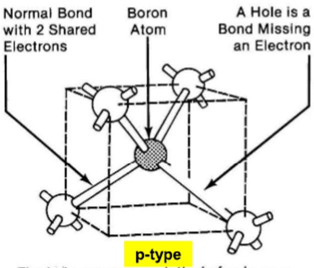
Doping Si crystal

Ref.: *Basic Photovoltaic Principles and Methods*, 1981.



The extra unbound electron from the phosphorus atom is relatively free to move about.

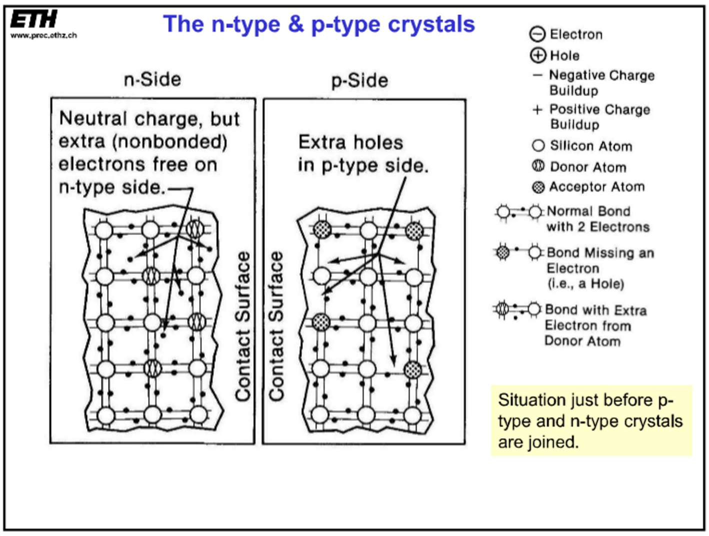
P: negative-carrier dopant (donor)



The hole can move relatively freely as a nearby electron leaves its bond and pops into it, moving the hole to the bond from which the electron came.

B: positive-carrier dopant (acceptor)

- The material is polluted with ‘impure’ atoms, to create n-type and p-type crystals.
- Excess electrons/holes move freely in n-type/p-type crystals; respectively.
- Both materials are electrically neutral: free electrons = positive ions


ETH
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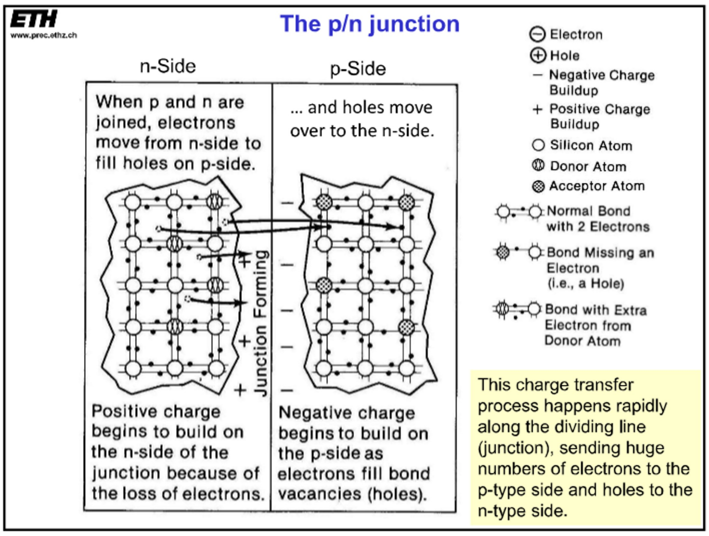
The n-type & p-type crystals
n-Side
p-Side
Neutral charge, but extra (nonbonded) electrons free on n-type side.
Extra holes in p-type side.
Contact Surface
Contact Surface
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom
Situation just before p-type and n-type crystals are joined.


ETH
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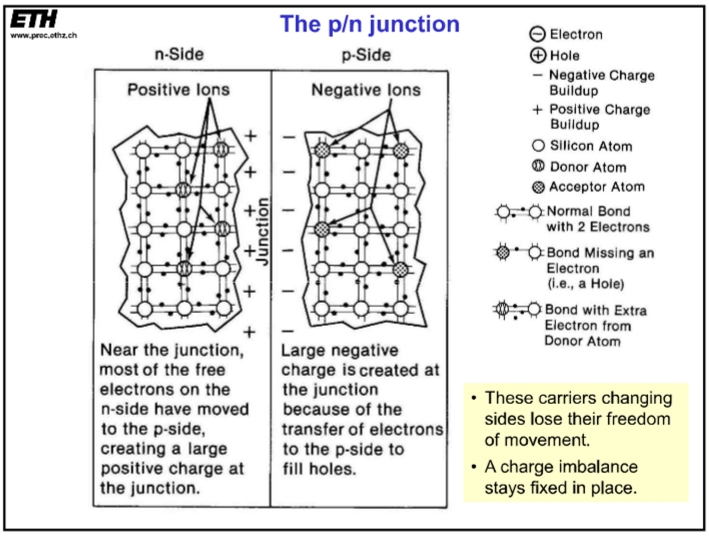
The p/n junction
n-Side
p-Side
When p and n are joined, electrons move from n-side to fill holes on p-side.
... and holes move over to the n-side.
Junction Forming
Positive charge begins to build on the n-side of the junction because of the loss of electrons.
Negative charge begins to build on the p-side as electrons fill bond vacancies (holes).
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom
This charge transfer process happens rapidly along the dividing line (junction), sending huge numbers of electrons to the p-type side and holes to the n-type side.


ETH
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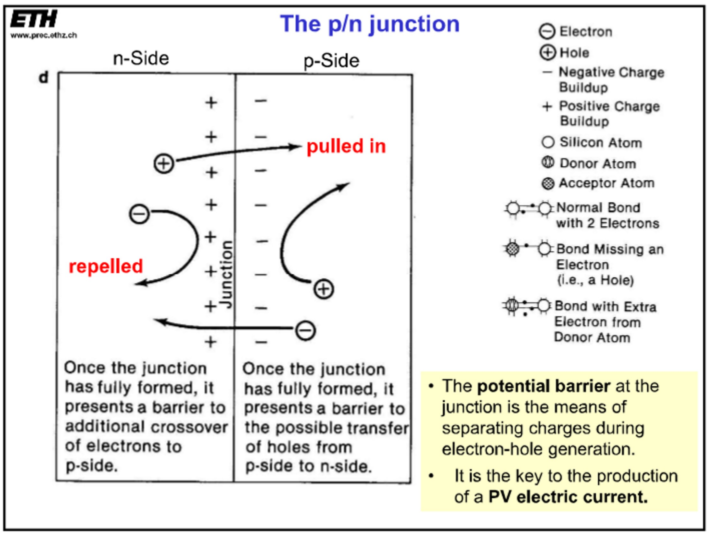
The p/n junction
n-Side
p-Side
Positive Ions
Negative Ions
Junction
Near the junction, most of the free electrons on the n-side have moved to the p-side, creating a large positive charge at the junction.
Large negative charge is created at the junction because of the transfer of electrons to the p-side to fill holes.
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom
• These carriers changing sides lose their freedom of movement.
• A charge imbalance stays fixed in place.


ETH
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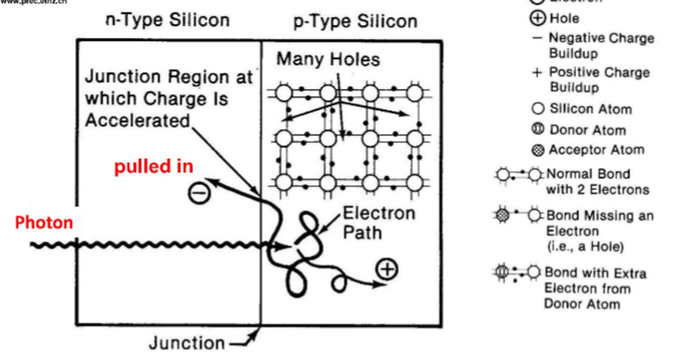
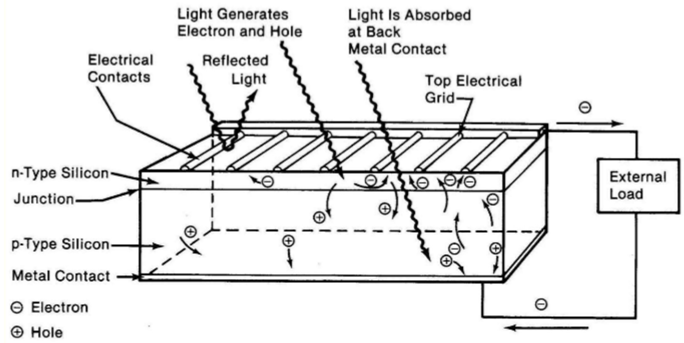
The p/n junction
d
n-Side
p-Side
pulled in
repelled
Junction
Once the junction has fully formed, it presents a barrier to additional crossover of electrons to p-side.
Once the junction has fully formed, it presents a barrier to the possible transfer of holes from p-side to n-side.
Electron
Hole
Negative Charge Buildup
Positive Charge Buildup
Silicon Atom
Donor Atom
Acceptor Atom
Normal Bond with 2 Electrons
Bond Missing an Electron (i.e., a Hole)
Bond with Extra Electron from Donor Atom
• The potential barrier at the junction is the means of separating charges during electron-hole generation.
• It is the key to the production of a PV electric current.

The PV effect



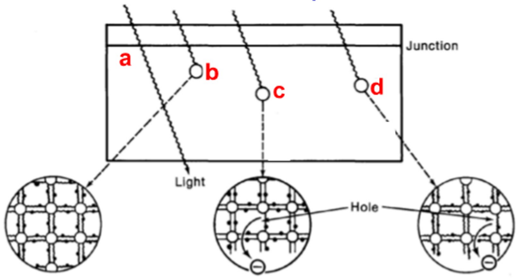
- A photo-generated electron has enough time to move freely and reach the junction before recombination.
- Once on the n-type, the electron is no longer in great danger of recombining. Moreover, there is very little chance of its returning to the p-type side because it would have to overcome the repulsion by the potential barrier at the junction.

The PV effect



- Absorbed light continuously generates electron-hole pairs.
- Electron-hole pairs are separated by the potential barrier.
- A charge imbalance (voltage) is created, inducing an electrical current (electron flow) through an external circuit.

Photon Absorption



a. Photon is transmitted.

b. Photon is absorbed, but has not enough energy to generate electron-hole pair. The vibrations of the atoms in their bonds caused by the absorption of light is heat.

c. Photon has exactly the energy required for generating an electron-hole pair. The energy required is called the **band-gap energy**.

d. Photon with even greater energy than (c) generates electron-hole pair, but it also has excess energy that causes atomic vibration as in (b).

Band-Gap Energy

$$E_{Ph,\lambda} = \frac{h \cdot c}{\lambda}$$

$$E_G = \frac{h \cdot c}{\lambda_G}$$

$c = 3\times10^8$ m/s

$h = 6.63\times10^{-34}$ J·s

1 eV = 1.6×10^{-19} J

Material	E_G in eV	
Ge	0.7	$\lambda_G = 1.78\ \mu m$
$CuInSe_2$	1	
Si	1.13	$\lambda_G = 1.13\ \mu m$
GaAs	1.42	
CdTe	1.45	
AlSb	1.55	
$CuGaSe_2$	1.7	
a Si (amorph)	1.7	
$Al_{0.85}Ga_{0.15}As$	1.9	
GaP	2.3	
CdS	2.45	$\lambda_G = 0.51\ \mu m$

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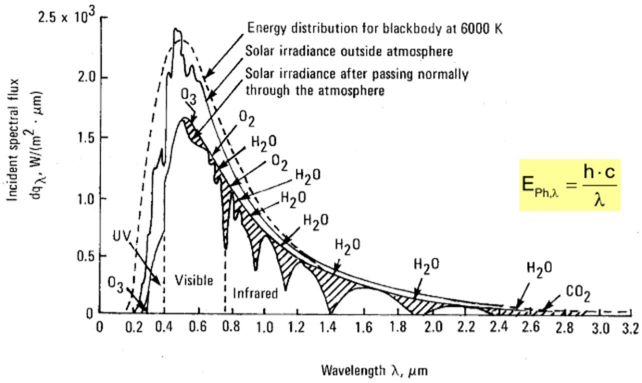
Solar Radiation

$$I_{solar} = \int_0^\infty I_{\lambda,solar}(\lambda)\,d\lambda = 1353\ W/m^2$$

$$I_{\lambda,solar}(\lambda)$$



$$E_{Ph,\lambda} = \frac{h \cdot c}{\lambda}$$

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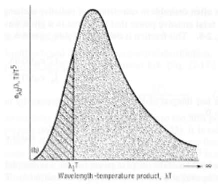
Fractional Function

$$F_{0-\lambda T} = \frac{\int_0^\lambda e_{\lambda b}(\lambda)\,d\lambda}{\sigma T^4}$$



$$\left.\begin{array}{l}\lambda_G = 1.10\text{mm} \\ T\ =\ 5780\ K\end{array}\right\} \rightarrow F_{0-\lambda T} = 77.9\%$$

Material	E_G [eV]	λ_G [μm]	$F_{0-\lambda T}$
Ge	0.7	1.78	91.9%
Si	1.13	1.10	77.9%
CdS	2.45	0.51	25.8%

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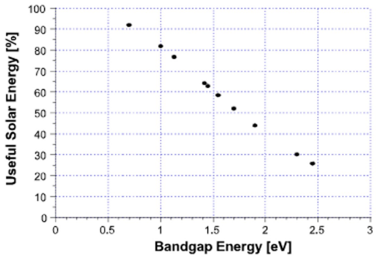
Useful Energy

Material	E_G	λ_G	useful	not useful
	[eV]	[μm]	[%]	[%]
Ge	0.7	1.78	91.94	8.06
CuInSe2	1	1.24	81.84	18.16
Si	1.13	1.10	76.62	23.38
GaAs	1.42	0.88	64.12	35.88
CdTe	1.45	0.86	62.81	37.19
AlSb	1.55	0.80	58.45	41.55
CuGaSe2	1.7	0.73	52.05	47.95
a Si	1.7	0.73	52.05	47.95
AlGaAs	1.9	0.65	43.98	56.02
GaP	2.3	0.54	30.12	69.88
CdS	2.45	0.51	25.80	74.20

$$F_{0-\lambda T} = \frac{\int_0^{\lambda} e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4}$$



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Theoretical Spectral Efficiency

$$\eta = \frac{1}{\sigma T^4} \int_0^{\lambda_G} \left(\frac{E_G}{E_\lambda} \right) e_{\lambda b}(\lambda)\, d\lambda$$

$$= \frac{1}{\sigma T^4} \sum_{i=1}^{N} \left[\int_{\lambda_i}^{\lambda_{i+1}} \left(\frac{E_G}{E_{\lambda_m}} \right) e_{\lambda b}(\lambda)\, d\lambda \right]$$

$$= \sum_{i=1}^{N} \left[\frac{E_G}{E_{\lambda_m}} \left(\frac{\int_{\lambda_i}^{\lambda_{i+1}} e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4} \right) \right]$$

$$= \sum_{i=1}^{N} \left[\frac{E_G}{E_{\lambda_m}} F_{\lambda_i - \lambda_{i+1}} \right]$$

T = temperature of emitter (sun)
E_G = band-gap energy of PV
E_λ = energy of radiation
λ_m = mean of interval $[\lambda_i - \lambda_{i+1}]$
$\lambda_0 = 0$
$\lambda_N = \lambda_G$

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Theoretical Spectral Efficiency

Example: Si-Cell

$$E_G = \frac{h \cdot c}{\lambda_G} \rightarrow \begin{cases} E_G = 1.1\ \text{eV} \\ \lambda_G = 1.10\ \mu\text{m} \end{cases}$$

$$F_{\lambda_1-\lambda_2} = \frac{\int_{\lambda_1}^{\lambda_2} e_{\lambda b}(\lambda)\, d\lambda}{\sigma T^4}$$

$$\frac{E_G}{E_\lambda} F_{\lambda_1-\lambda_2}$$

Interval	Band interval [μm] λ_{start}	λ_{end}	Mean in band E_λ λ [μm]	Energy [eV]	Energy portion $F_{\lambda_1-\lambda_2}$	Useful [%]
1	0.00	0.11	0.057	22.00	0.000	0.000
2	0.11	0.23	0.170	7.33	0.004	0.001
3	0.23	0.34	0.283	4.40	0.056	0.014
4	0.34	0.45	0.396	3.14	0.125	0.044
5	0.45	0.57	0.509	2.44	0.147	0.066
6	0.57	0.68	0.622	2.00	0.133	0.073
7	0.68	0.79	0.735	1.69	0.109	0.071
8	0.79	0.90	0.848	1.47	0.086	0.064
9	0.90	1.02	0.961	1.29	0.066	0.056
10	1.02	1.10	1.074	1.16	0.051	0.049
11	1.10	∞			0.221	0.000
Summe					1.000	**0.438**

$$\eta = \frac{1}{\sigma T^4} \int_0^{\lambda_G} \left(\frac{E_G}{E_\lambda} \right) \cdot e_{\lambda b}(\lambda)\, d\lambda \longrightarrow \eta = \sum_{\text{all intervals}} \left(\frac{E_G}{E_\lambda} \right) \cdot F_{\lambda_i-\lambda_{i+1}}$$

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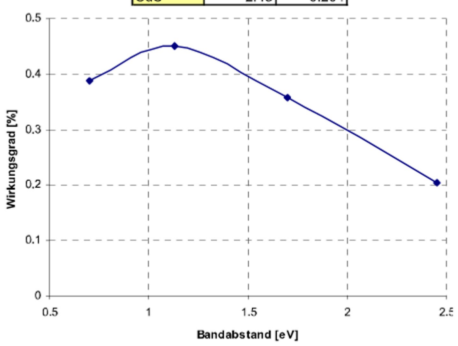
Theoretical Spectral Efficiency

Material	E_g [eV]	η [%]
Ge	0.7	0.389
Si	1.13	0.45
a Si	1.7	0.358
CdS	2.45	0.204

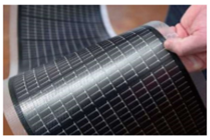


Solar Cell Technology Evolution

1st generation: Silicon wafer

- Absorber thickness ~200 µm
- Rigid
- Heavy
- > 50 years old (mature):
- 90-95% market share
- mono/polycristalline Si

2nd generation: Thin film



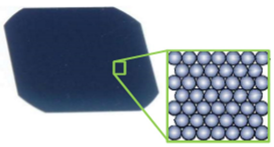
- Absorber thickness <3µm
- Rigid or flexible
- Light weight
- ~40 years old (mature)
- 5-10% market share
- Cu-(In,Ga)-$(Se)_2$), called CIGS
- CdTe

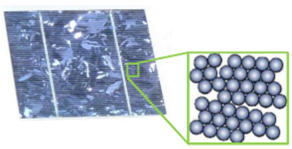
3rd generation: Multi-junction, DS, Perovskite, etc.

- Absorber thickness <3µm
- Rigid or flexible
- Light weight
- <30 years old (R&D)
- Multi-junction: GaAs, InP, etc
- Dye-sensitized solar cells
- Perovskite

Si Solar Cells

Single crystal (mono c-Si) vs **Polycristalline (poly c-Si)**



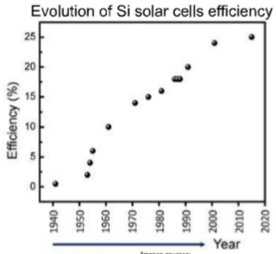


- **Polycrystalline.** Si crystals are oriented randomly, separated by grain boundaries, which introduces efficiency losses. Advantage: cheaper production than mono c-Si
- **Monocrystalline-** Si crystals have no grain boundaries; losses within a solar cell are thus reduced. Drawbacks: more expensive.

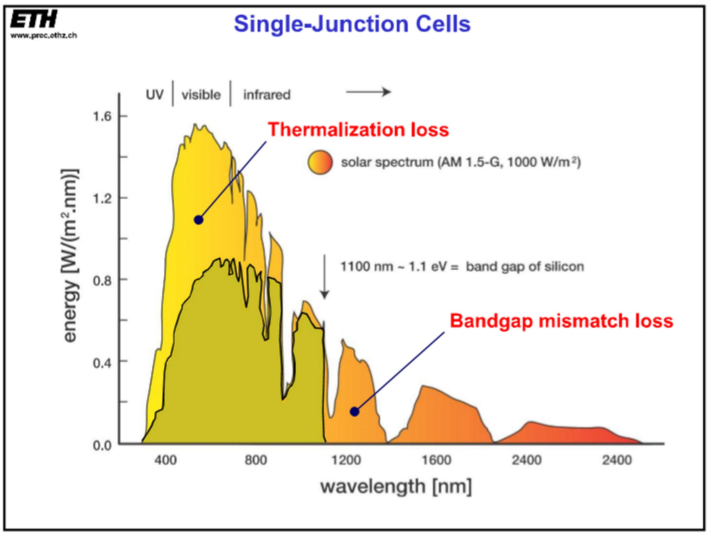
Efficiency in 2020:

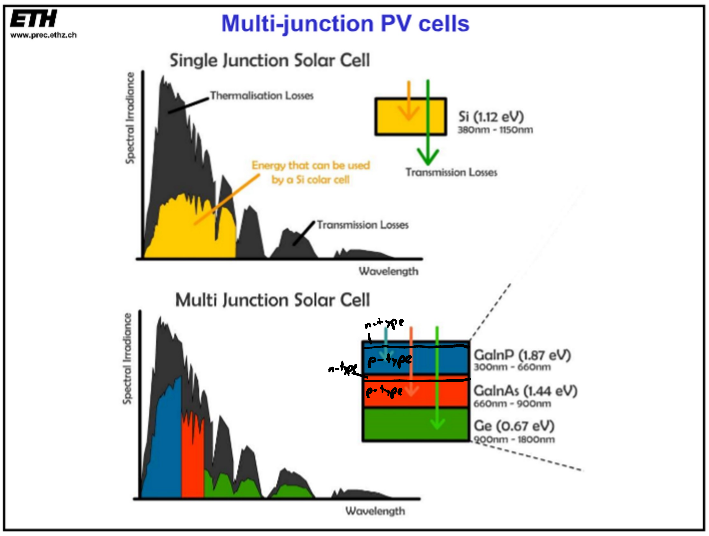
- 26.7% for mono c-Si (Kaneka)
- 23.8% for poly c-Si (Canadian Solar)

Evolution of Si solar cells efficiency

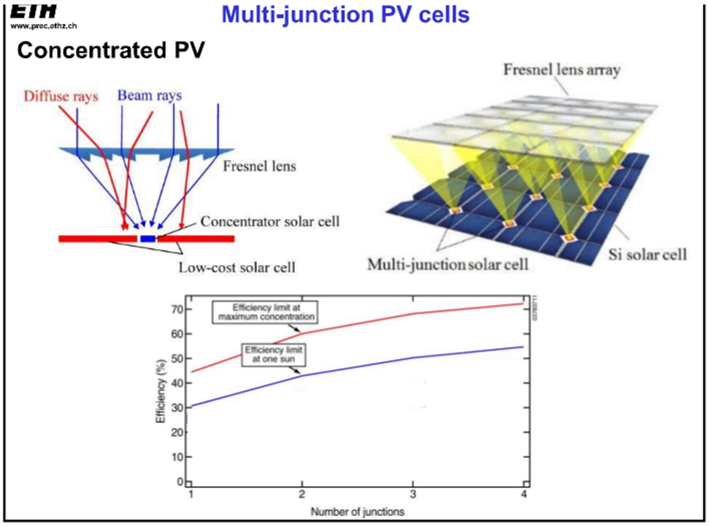


Images sources:
Wikimedia Commons
Aissa B. et al. Front. Nanosci. Nanotech. 2015





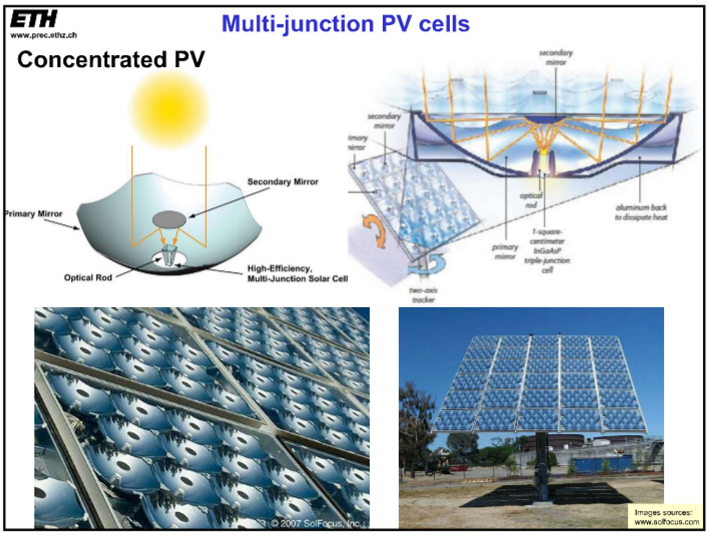
Multijunction only Io
PV Id + In



Multijunction only I_b

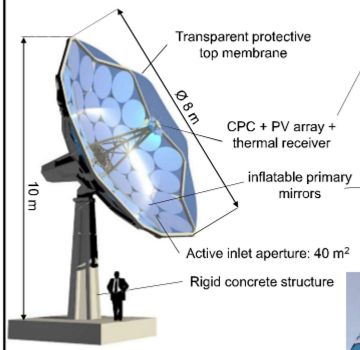
PV $I_d + I_b$

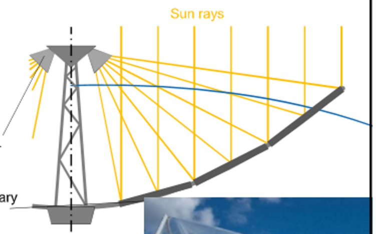
CSP I_b

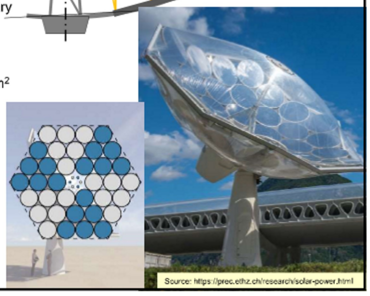


Multi-junction PV cells

Concentrated PV

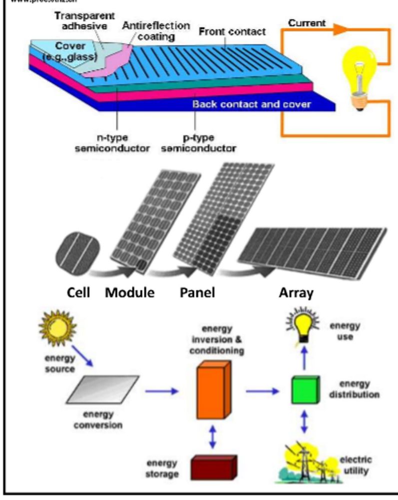






- Size: 12 kW electrical and 21 kW thermal @ 90ºC
- Efficiency: ~30% electrical + ~50% thermal
- Microchannel cooled CPV receiver
- Key Aspects: concrete structure, inflatable mirrors

PV system



- Standard Test Conditions (STC): T = 25°C, I = 1 kW/m², Air Mass = 1.5.
- Actual performance is usually 85-90% of the STC rating.
- Typical service lifetime: 20-30 years
- PV System to control, convert, distribute, and store electrical power.
- BOS: hardware, including wiring, over-current, protection and disconnect devices, and other power processing equipment.
- Battery: storing; supply electrical loads during night and cloudy weather; to operate the PV array near its maximum power point; to power electrical loads at stable voltages; and to supply currents to electrical loads and inverters; battery charge controller to protect the battery from overcharge and over-discharge.

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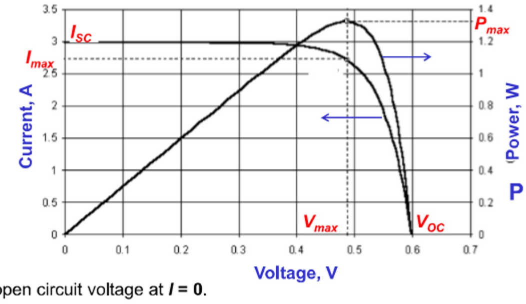
Current–Voltage & Power–Voltage



P = V x I

- V_{OC} : open circuit voltage at $I = 0$.
- I_{SC} : short circuit current at $V = 0$.
- P_{max} : power at maximum power point. $P_{max} = V_{max} \times I_{max}$.
- I_{SC} is proportional to the solar irradiance, and increases with increasing temperature. Standard temperature for reporting short circuit currents is 25°C.
- P_{max} and the cell efficiency decrease with temperature. For most cells, a temperature rise of 20°C causes a power drop of about 10%.

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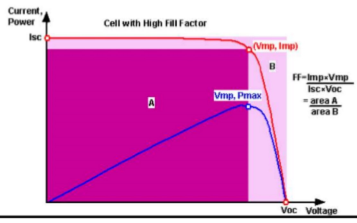
Performance Indicators

Panel efficiency (η_{panel}): percent of solar energy converted to electricity for each panel

$$\eta_{panel} = \frac{\text{Electric Power Output}}{\text{Solar Input}} = \frac{P_{max}}{I_{solar} \cdot A_{panel}}$$

Fill Factor (FF): the ratio of maximum power divided by the product of open circuit voltage and short circuit current

$$FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}} = \frac{\eta_{panel} \cdot A_{panel} \cdot I_{solar}}{V_{oc} \cdot I_{sc}}$$



PV Panel Specifications

Sanyo HIP-190BA3

The HIT 190 panel has a cell conversion efficiency of 18.5% and a panel conversion efficiency of 16.1% that is significantly higher than conventional SANYO solar cells.

High conversion efficiency and lightweight design conserve space and weight. The outstanding conversion efficiency and high power output of the HIT 190 save approximately 20% of installation space. HIT 190 panels can be installed on narrow roof spaces which previously presented difficulties. In addition, with fewer solar panels, there is less weight on the roof.

SANYO HIT 190 Specifications:
Model Number: HIP-190BA3
Max. Power (Pmax): 190 Watts
Max. Power Voltage (Vpm): 54.8 Volts
Max. Power Current (Ipm): 3.47 Amps
Open Circuit Voltage (Voc): 67.5 Volts
Short Circuit Voltage (Isc): 3.75 Amps
Cell Conversion Efficiency: 18.5%
Panel Conversion Efficiency: 16.1%
Warranted Minimum (Pmin): 171.0 Watts
PTC Rating: 178.7 Watts
Max. System Voltage: 600 Volts
Series Fuse: 15 Amps
Temp. Coefficient of Pmax (%/C): -0.3
Dimensions: 51.9" x 35.2" X 1.4" (1319mm X 894mm x 35mm)
Weight: 30.9 lbs. (14kg)
Certificate: UL 1703
Class C fire rating
HIT panels can withstand 1 inch diameter hailstones at 50 mph.

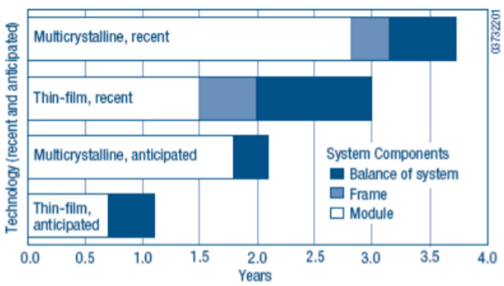
Sanyo HIP-190BA3, HIT 190 Watt Solar Panel
$975.00

RENOGY

Address: 2775 E. Philadelphia St., Ontario, CA, 91761
Tel: 800-330-8678
Fax: 888-543-1164
Web: www.renogy.com

Module Type:	RNG-160P
Max Power at STC (P_{max})	160 W
Open-Circuit Voltage (V_{oc})	22.8 V
Short-Circuit Current (I_{sc})	9.47 A
Optimum Operating Voltage (V_{mp})	18.6 V
Optimum Operating Current (I_{mp})	8.6 A
Temp Coefficient of P_{max}	-0.44%/°C
Temp Coefficient of V_{oc}	-0.30%/°C
Temp Coefficient of I_{sc}	0.04%/°C
Max System Voltage	600VDC (UL)
Max Series Fuse Size Rating	15 A
Fire Rating	Class C
Weight	11.5kgs / 25.4lbs
Dimensions	1482x674x35mm / 58.3x26.5x1.4in
STC	Irradiance 1000 W/m², T = 25°C, AM=1.5

Energy pay-back



- 120 kWh/m2 to make frameless, amorphous-Si PV modules
- PV systems can repay their energy investment in about 2 years.
- Assuming 30-year system life, PV systems will provide a net gain of 26 to 29 years of pollution-free and CO2-free electrical generation, equivalent to 87-97% of the total energy generated.

Sources:
US-DOE
R. Dones; R. Frischknecht, "Life Cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains." Utrecht University, Report 97072, 1997.