Solar Energy Conversion Devices and Plants

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Outline

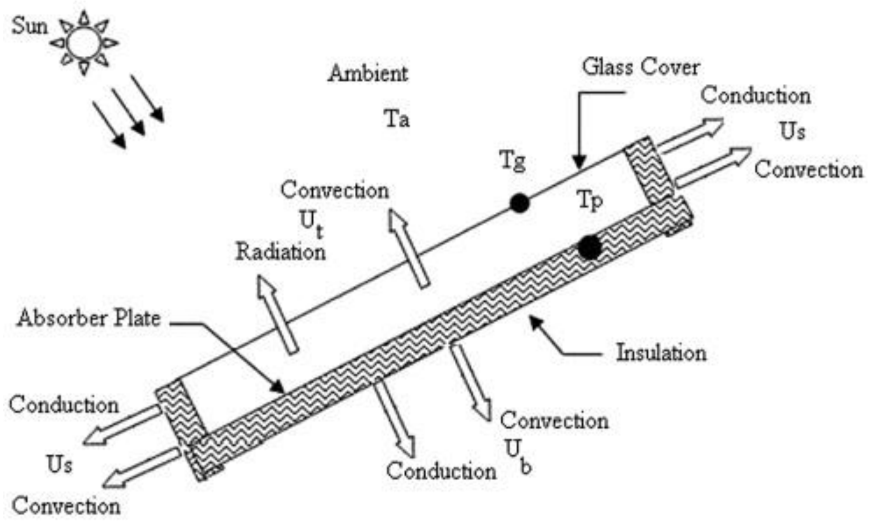
- Solar Collectors
  - Flat plate collectors
  - Evacuated tube collectors
  - 2D CPC-based collectors
  - Applications

Solar collectors

- Solar collector:
  - is a heat exchanger that converts solar energy into heat. It absorbs the solar radiation and transfers the thermal energy to a working fluid.
  - Common working fluids: water, oil, air
    - Air collectors suitable for space heating and convective dry applications.
    - Liquid collectors suitable for domestic and industrial hot water applications.
  - Energy delivery at moderate temperature (~100°C), typically use diffuse and direct radiation, typically do not require sun tracking
  - Applications: solar water heating, building heating, air conditioning, and industrial process heat
  - Passively heated buildings can be seen as special cases of flat-plate collectors
  - Solar collector types: Flat-plate collectors, evacuated tubular collectors, 2D compound parabolic concentrators

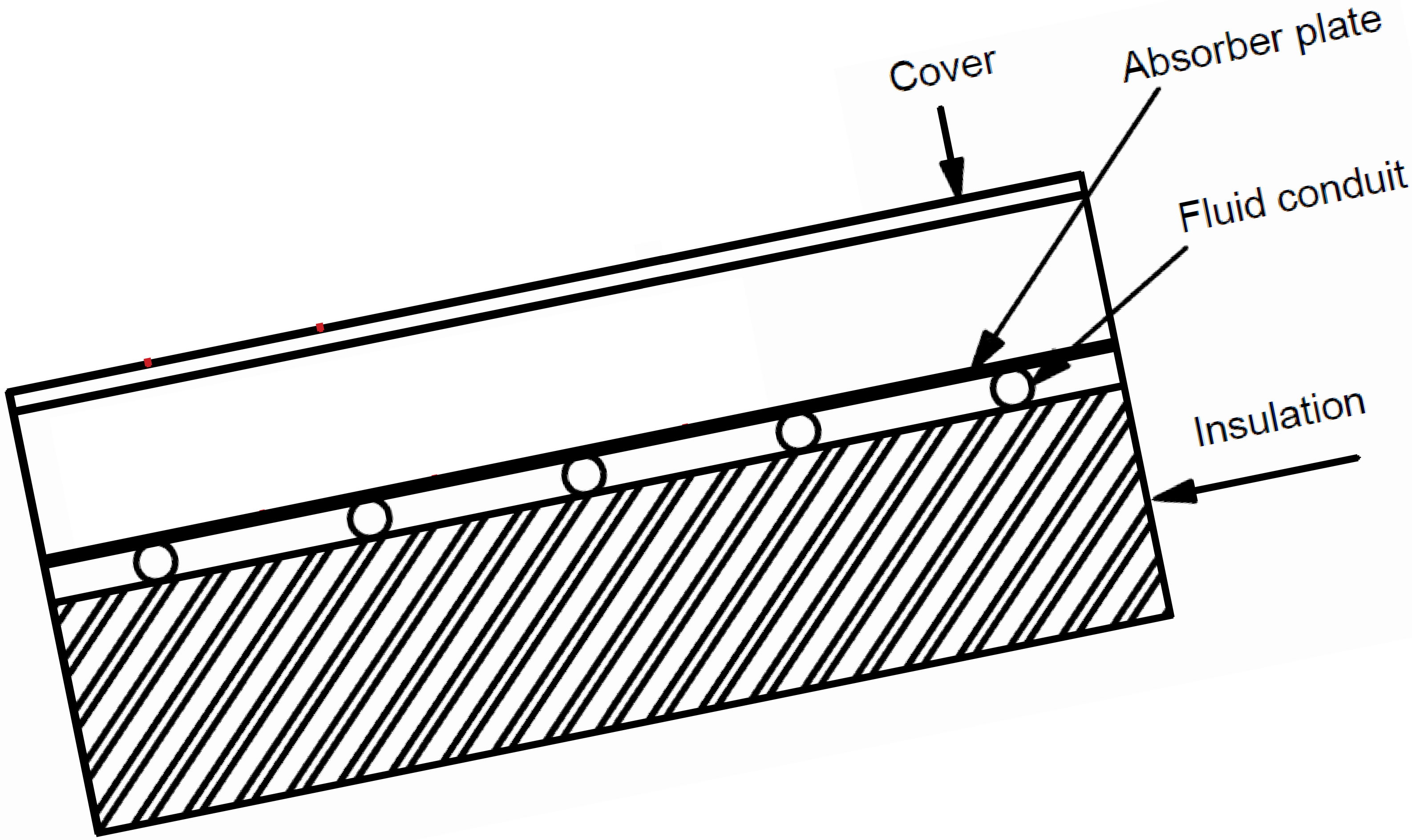
Conversion pathways: Solar to thermal

- Solar to thermal: non or low-concentrating
  - Flat-plate solar collectors
    - Diffuse and direct radiation
    - Losses:
      - Reflection at window
      - Convection at window
      - Convection and conduction through insulation
      - Emission from absorber through window
    - Temperature range: 30-80°C
    - Concentration: 1



Solar collector

- Heat transfer



$$\dot{Q}_c = A_c\left(S - U_L\left(T_{cm} - T_a\right)\right)$$

Solar collector

- Reflection, absorption and transmittance in the cover/glazing:

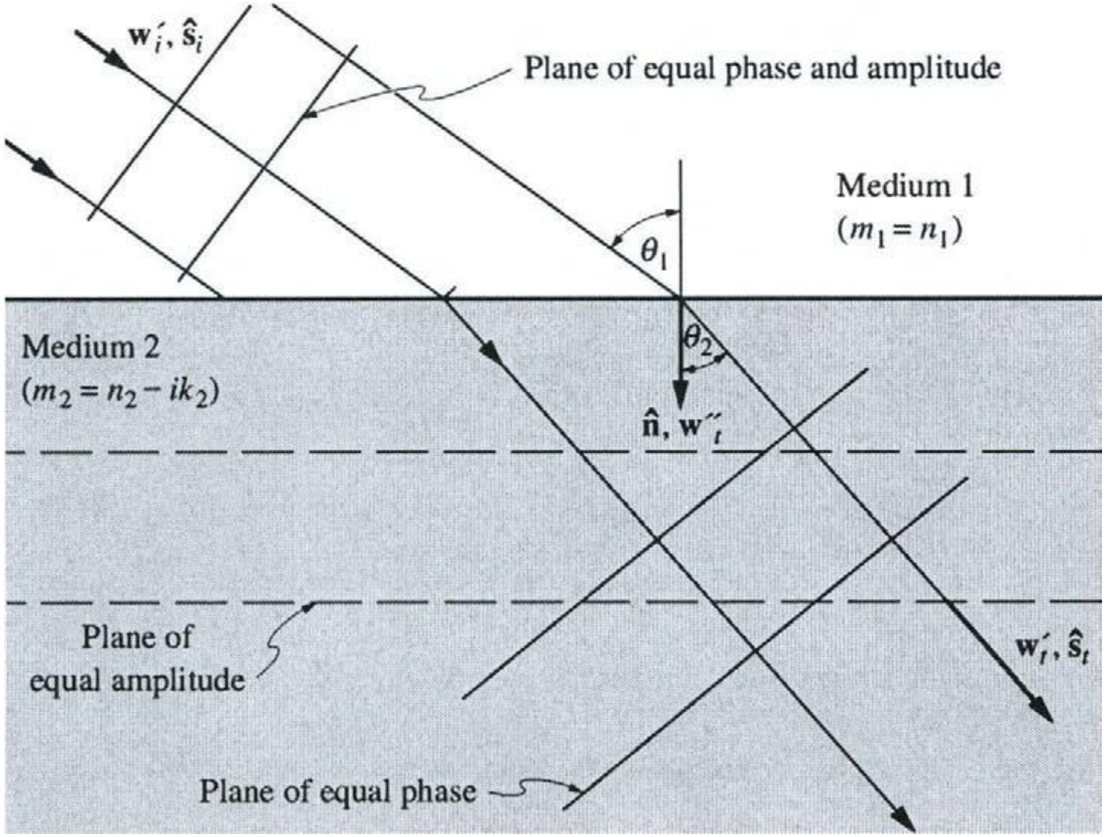
Governed by refraction, reflection and absorption phenomena.

If glazing is thick enough ($t \gg \lambda$), geometrical optics assumptions hold.

Spectral reflectivity

- **Generalized Snell's law**

$$n_{\lambda,1}\sin\theta_1 = p_\lambda \tan\theta_2$$



$$p_\lambda^2 = \frac{1}{2}\left[\sqrt{\left(n_{\lambda,2}^2 - k_{\lambda,2}^2 - n_{\lambda,1}^2\sin^2\theta_1\right)^2 + 4n_{\lambda,2}^2 k_{\lambda,2}^2} + \left(n_{\lambda,2}^2 - k_{\lambda,2}^2 - n_{\lambda,1}^2\sin^2\theta_1\right)\right]$$

$$q_\lambda^2 = \frac{1}{2}\left[\sqrt{\left(n_{\lambda,2}^2 - k_{\lambda,2}^2 - n_{\lambda,1}^2\sin^2\theta_1\right)^2 + 4n_{\lambda,2}^2 k_{\lambda,2}^2} - \left(n_{\lambda,2}^2 - k_{\lambda,2}^2 - n_{\lambda,1}^2\sin^2\theta_1\right)\right]$$

Spectral reflectivity

- **Fresnel's equations** — the directional hemispherical reflectivity of an optically smooth interface between a non-absorbing and an absorbing medium ($k_1 = 0$ and $k_2 > 0$):
  - For parallel-polarized incident radiation

$$\rho'^{\cap}_{\lambda,\parallel}(\lambda,\theta_1) = \frac{\left(p_\lambda - n_{\lambda,1}\sin\theta_1\tan\theta_1\right)^2 + q_\lambda^2}{\left(p_\lambda + n_{\lambda,1}\sin\theta_1\tan\theta_1\right)^2 + q_\lambda^2}\rho'^{\cap}_{\perp}(\lambda,\theta_1)$$

  - For perpendicular-polarized incident radiation

$$\rho'^{\cap}_{\lambda,\perp}(\lambda,\theta_1) = \frac{\left(n_{\lambda,1}\cos\theta_1 - p_\lambda\right)^2 + q_\lambda^2}{\left(n_{\lambda,1}\cos\theta_1 + p_\lambda\right)^2 + q_\lambda^2}$$

  - For unpolarized incident radiation

$$\rho'^{\cap}_{\lambda}(\lambda,\theta_1) = \frac{1}{2}\left[\rho'^{\cap}_{\lambda,\perp}(\lambda,\theta_1) + \rho'^{\cap}_{\lambda,\parallel}(\lambda,\theta_1)\right]$$

  - For normal incidence ($\theta_1 = \theta_2 = 0$)

$$\rho'^{\cap}_{\lambda,\perp}(\lambda,\theta_1 = 0) = \rho'^{\cap}_{\lambda,\parallel}(\lambda,\theta_1 = 0) = \rho'^{\cap}_{\lambda}(\lambda,\theta_1 = 0) = \rho'^{\cap}_{\lambda,n} = \frac{\left(n_{\lambda,1} - n_{\lambda,2}\right)^2 + k_{\lambda,2}^2}{\left(n_{\lambda,1} + n_{\lambda,2}\right)^2 + k_{\lambda,2}^2}$$

Spectral reflectivity

- For an interface between two non-absorbing media ($k_1 = k_2 = 0$)

$$\rho_{\lambda}^{'\cap}(\lambda,\theta_1) = \frac{1}{2}\left[\rho_{\lambda,\perp}^{'\cap}(\lambda,\theta_1) + \rho_{\lambda,\parallel}^{'\cap}(\lambda,\theta_1)\right]$$

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

$$n_{\lambda,2}\sin\theta_2 = n_{\lambda,1}\sin\theta_1$$

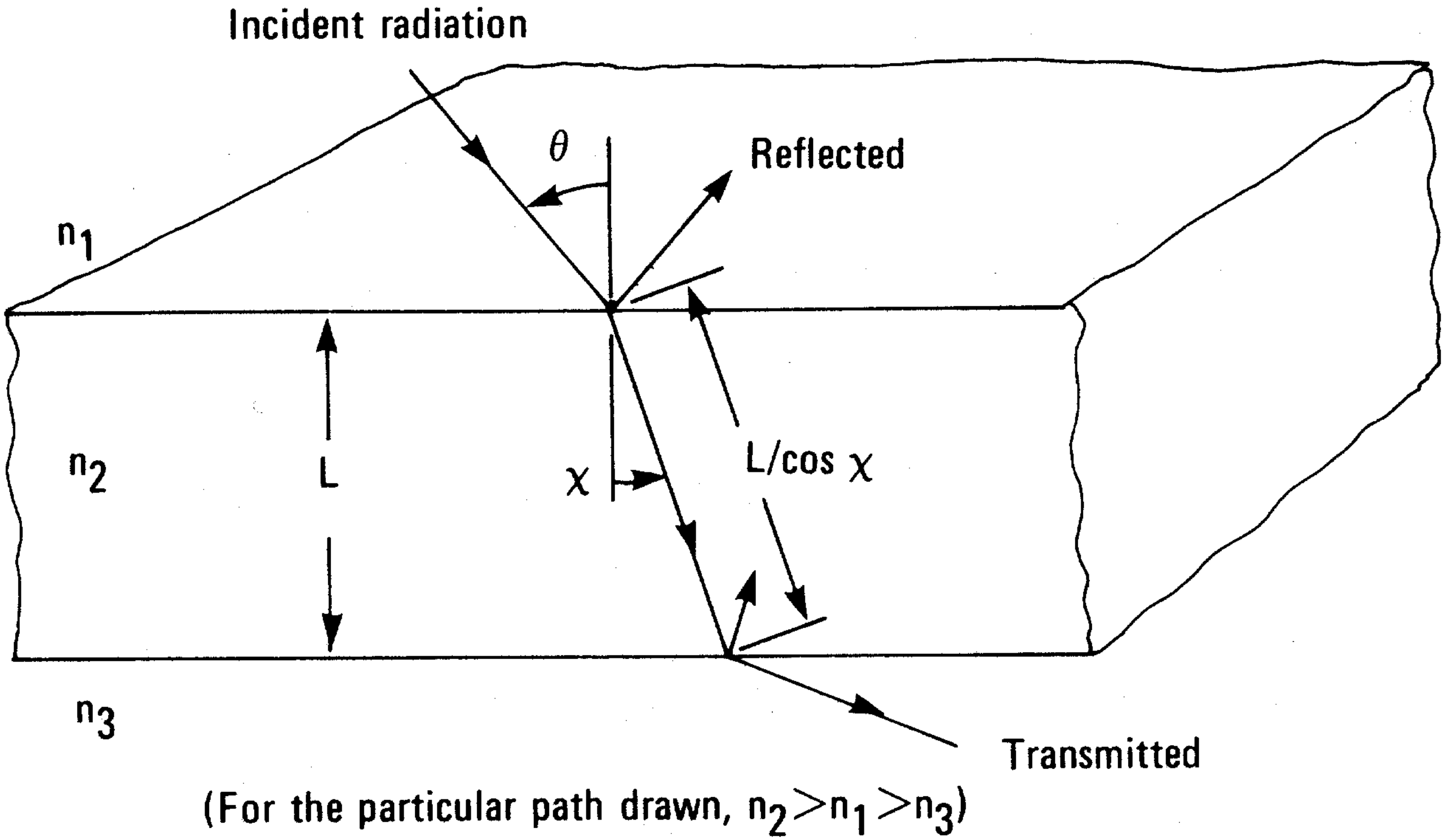
Snell's law for two non-absorbing media

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

- For normal incidence

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

Spectral transmittance



$\beta_\lambda = \text{const}:$ $\tau_\lambda = \exp(-\beta_\lambda s)$

$$\tau_\lambda = \exp(-\beta_\lambda L/\cos\chi)$$

Assumption: no scattering

$$\beta_\lambda = \kappa_\lambda$$

$$\tau_\lambda = \exp(-\kappa_\lambda L/\cos\chi)$$

Single-layer window

Fraction of incident radiation reflected (leaving surface 1):

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

Fraction of incident radiation transmitted (leaving surface 4):

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

Fraction of incident radiation absorbed:

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

Limiting case: $\kappa \to 0$ → $\tau \to 1$ →

$$\bar{\rho} \to \frac{2\rho}{1+\rho}$$

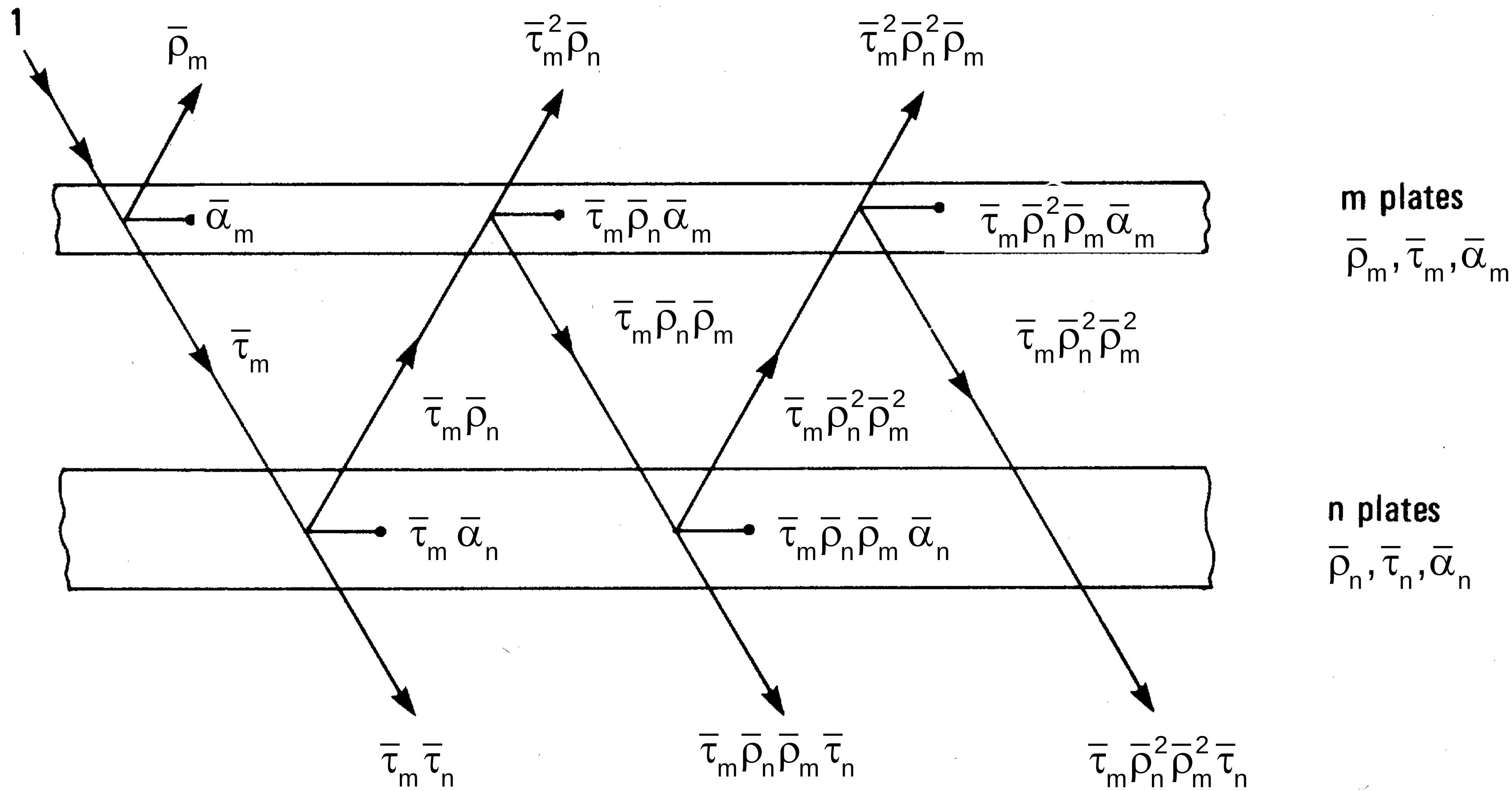
$$\bar{\tau} \to \frac{1-\rho}{1+\rho}$$

$$\bar{\alpha} \to 0$$

Multiple parallel windows

- m identical plates
- n identical plates
- m plates different than n plates

By ray-tracing:



Multiple parallel windows

Fraction reflected:

$$\bar{\rho}_{m+n} = \bar{\rho}_m + \bar{\rho}_n \bar{\tau}_m^{\,2}\left(1 + \bar{\rho}_m \bar{\rho}_n + \bar{\rho}_m^{\,2} \bar{\rho}_n^{\,2} + \ldots\right) = \bar{\rho}_m + \frac{\bar{\rho}_n \bar{\tau}_m^{\,2}}{1 - \bar{\rho}_m \bar{\rho}_n}$$

Fraction transmitted:

$$\bar{\tau}_{m+n} = \bar{\tau}_m \bar{\tau}_n \left(1 + \bar{\rho}_m \bar{\rho}_n + \bar{\rho}_m^{\,2} \bar{\rho}_n^{\,2} + \ldots\right) = \frac{\bar{\tau}_m \bar{\tau}_n}{1 - \bar{\rho}_m \bar{\rho}_n}$$

Fraction absorbed:

$$\bar{\alpha}_{m+n} = 1 - \bar{\rho}_{m+n} - \bar{\tau}_{m+n}$$

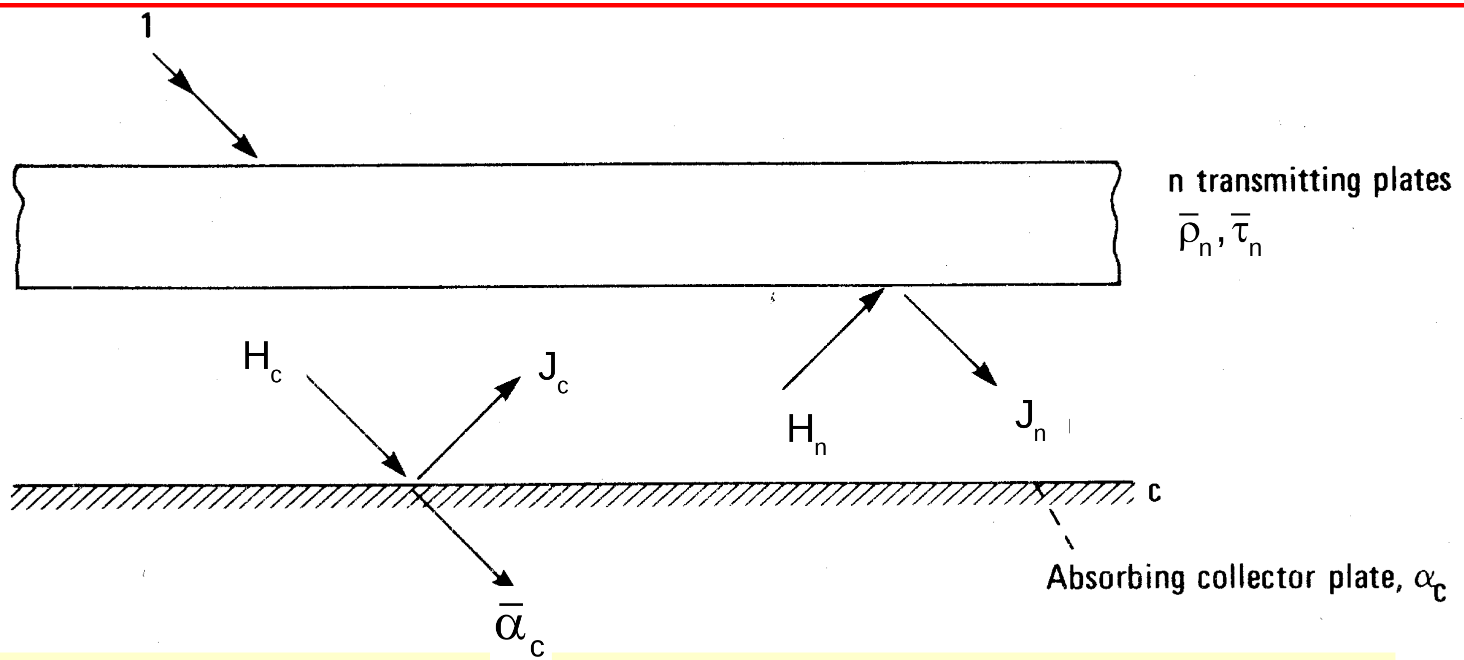
For 2 plates:

$$\bar{\rho}_2 = \bar{\rho}_{1+1} = \bar{\rho}_1 + \frac{\bar{\rho}_1 \bar{\tau}_1^2}{1 - \bar{\rho}_1^2} \qquad \bar{\tau}_2 = \bar{\tau}_{1+1} = \frac{\bar{\tau}_1^2}{1 - \bar{\rho}_1^2}$$

For 3 plates:

$$\bar{\rho}_3 = \bar{\rho}_{1+2} = \bar{\rho}_1 + \frac{\bar{\rho}_2 \bar{\tau}_1^2}{1 - \bar{\rho}_1 \bar{\rho}_2} \qquad \bar{\tau}_3 = \bar{\tau}_{1+2} = \frac{\bar{\tau}_1 \bar{\tau}_2}{1 - \bar{\rho}_1 \bar{\rho}_2}$$

Effective absorptance



$\bar{\alpha}_c$ = Fraction of incident radiation absorbed by opaque collector $\quad \bar{\alpha}_c = H_c - J_c$

Since: $J_c = (1-\alpha_c)H_c$

$J_c = H_n$

$J_n = H_c$

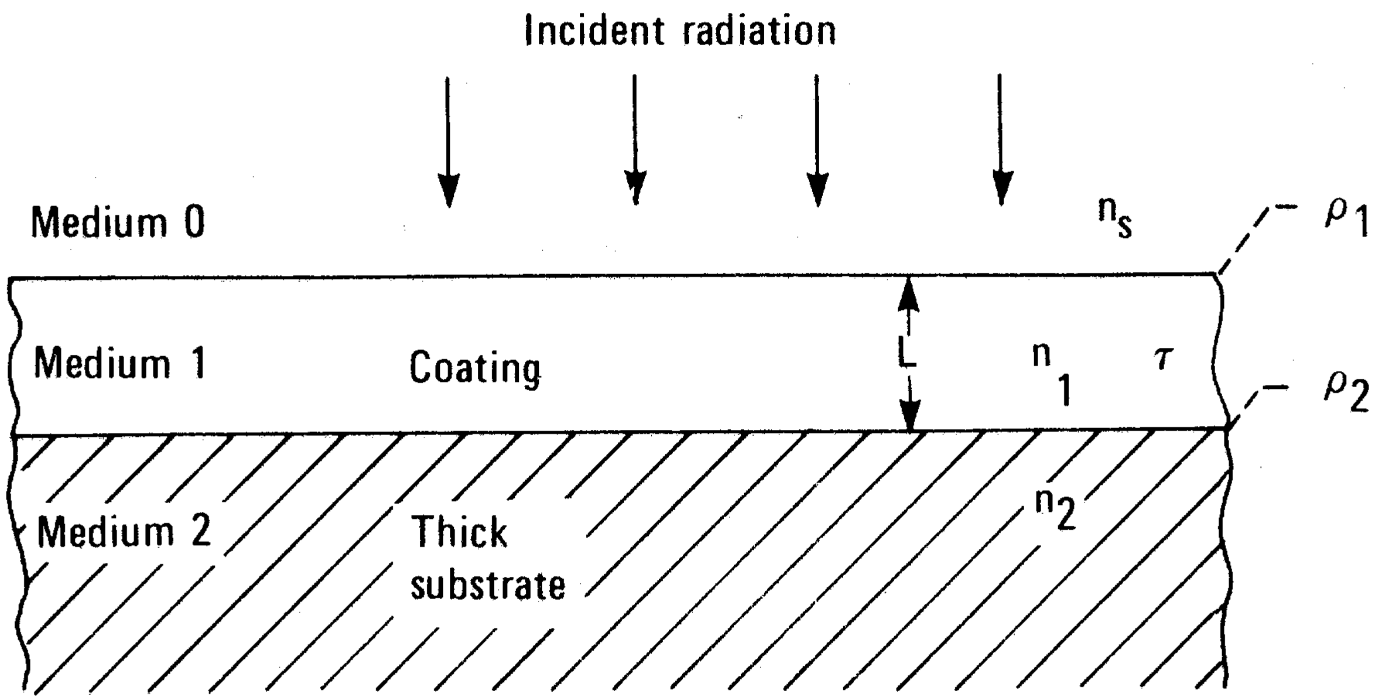
For n plates: $J_n = \bar{\tau}_n + H_n\bar{\rho}_n$

$$\bar{\alpha}_c = H_c - J_c = H_c - (1-\alpha_c)H_c$$
$$= \alpha_c H_c = \alpha_c(\bar{\tau}_n + H_n\bar{\rho}_n)$$
$$= \alpha_c\bar{\tau}_n + \alpha_c\bar{\rho}_n(1-\alpha_c)H_c$$
$$= \alpha_c\bar{\tau}_n + \bar{\rho}_n(1-\alpha_c)\bar{\alpha}_c$$

$$\bar{\alpha}_c = \frac{\alpha_c\bar{\tau}_n}{1-(1-\alpha_c)\bar{\rho}_n}$$

Coatings/Thin Films

- Assumption: No interference



Fraction of incident radiation reflected:

$$\bar{\rho} = \rho_1 + \rho_2 \frac{(1-\rho_1)^2 \tau^2}{1-\rho_1\rho_2\tau^2}$$

$$= \frac{\rho_1 + \rho_2(1-2\rho_1)\tau^2}{1-\rho_1\rho_2\tau^2}$$

Non-absorbing (dielectric) coating

$$\kappa_1 = \frac{4\pi k_1}{\lambda} \to 0 \longrightarrow \tau = \exp(-\kappa_1 s) \to 1 \longrightarrow \bar{\rho} = \frac{\rho_1 + \rho_2(1-2\rho_1)}{1-\rho_1\rho_2}$$

k_1: absorption index

Fresnel's equation for normal incidence:

$$\rho_1 = \left(\frac{n_1/n_s - 1}{n_1/n_s + 1}\right)^2$$

$$\rho_2 = \left(\frac{n_2/n_1 - 1}{n_2/n_1 + 1}\right)^2$$

$$\bar{\rho} = 1 - \frac{4 n_s n_1 n_2}{\left(n_1^2 + n_s n_2\right)\left(n_s + n_2\right)}$$

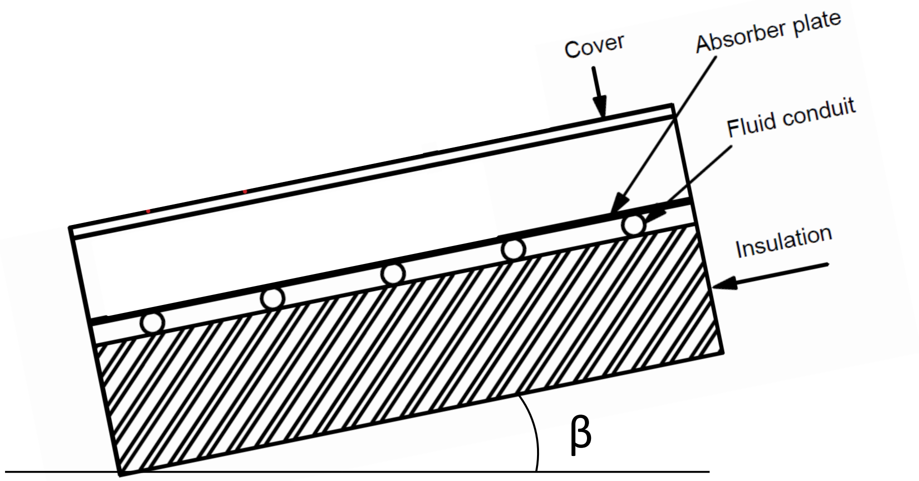
Minimize reflection:

$$\frac{d\bar{\rho}}{dn_1} = n_s n_2 - n_1^2 = 0 \longrightarrow n_1 = \sqrt{n_s n_2} \longrightarrow \bar{\rho}_{min} = 1 - \frac{2\sqrt{n_s n_2}}{n_s + n_2}$$

Substrate Reflectivity:

$$\rho_{sub} = \left(\frac{n_2/n_s - 1}{n_2/n_s + 1}\right)^2 \longrightarrow \frac{\bar{\rho}_{min}}{\rho_{sub}} = \frac{n_s + n_2}{n_s + 2\sqrt{n_s n_2} + n_2}$$

Energy balance on collector



- Radiation absorbed:

$$S = I_d R \bar{\alpha}_{c,d} + I_{dif} \bar{\alpha}_{c,dif} \left(\frac{1 + \cos(\beta)}{2} \right) + \rho_{ground} (I_d + I_{dif}) \bar{\alpha}_{c,ground} \left(\frac{1 - \cos(\beta)}{2} \right)$$

- With R: ratio of beam radiation on tilted surface to that on horizontal surface

$$R = \frac{\cos(\theta_{in})}{\cos(\theta)}$$

- With $\cos(\theta_{in}) \approx \cos(\theta)\cos(\beta) + \sin(\theta)\sin(\beta)$

Energy balance on collector

- Efficiency: $$\eta = \frac{\dot{Q}_c}{I_{tilted} A}$$

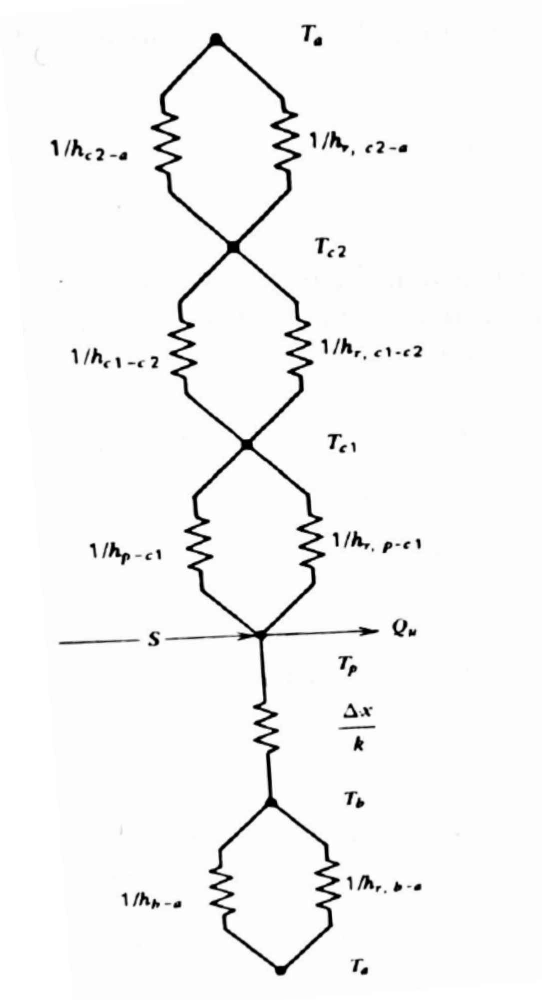
- Useful energy: $$\dot{Q}_\mathrm{c} = A_\mathrm{c}\left(S - U_\mathrm{L}(T_\mathrm{cm} - T_\mathrm{a})\right)$$

- But how to estimate the overall heat loss and the mean collector temperature?

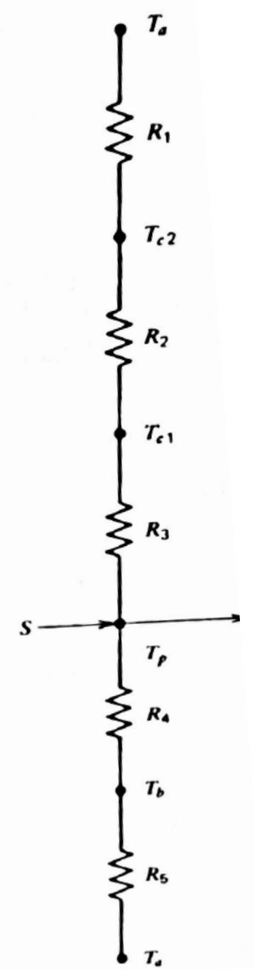
→ detailed energy balance of the collector

Energy balance on collector

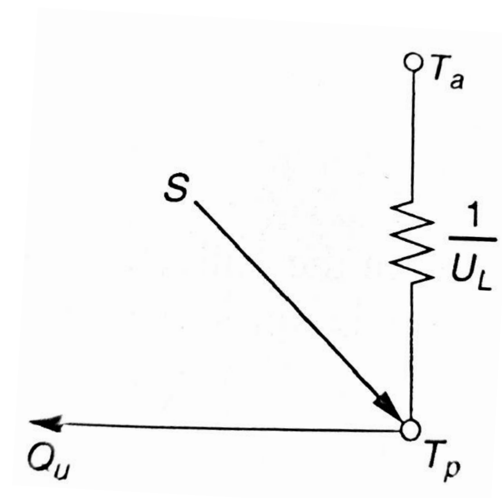
- Resistor approach (example for two-cover collector):



In terms of convection, conduction, radiation



In terms of resistances to heat transfer



Energy balance on collector

- Resistor approach (example for two-cover collector):
  - Plate-cover1:

$$\dot{q} = h_{conv,p-c1}(T_p - T_{c1}) + \frac{\sigma(T^4{}_p - T_{c1}{}^4)}{1/\varepsilon_p + 1/\varepsilon_{c1} - 1}$$

$$= (h_{conv,p-c1} + h_{rad,p-c1})(T_p - T_{c1})$$

$$= \frac{(T_p - T_{c1})}{R_3}$$

  - Cover1-conver2: equivalent to plate-cover1
  - Cover2-ambient:

$$\dot{q} = h_w(T_{c2} - T_a) + \sigma\varepsilon_{c2}(T^4{}_{c2} - T_{sky}{}^4)$$

$$= (h_w + h_{rad,c2-a})(T_{c2} - T_a)$$

$$= \frac{(T_{c2} - T_a)}{R_1}$$

Energy balance on collector

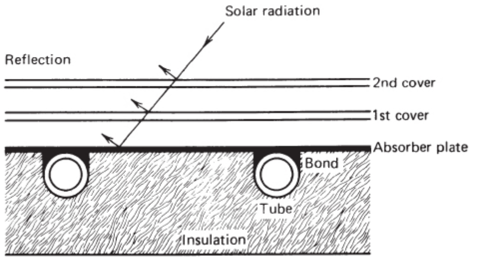
- Resistor approach (example for two-cover collector):
  - Overall top loss heat transfer coefficient:

$$U_t = \frac{1}{R_1 + R_2 + R_3}$$

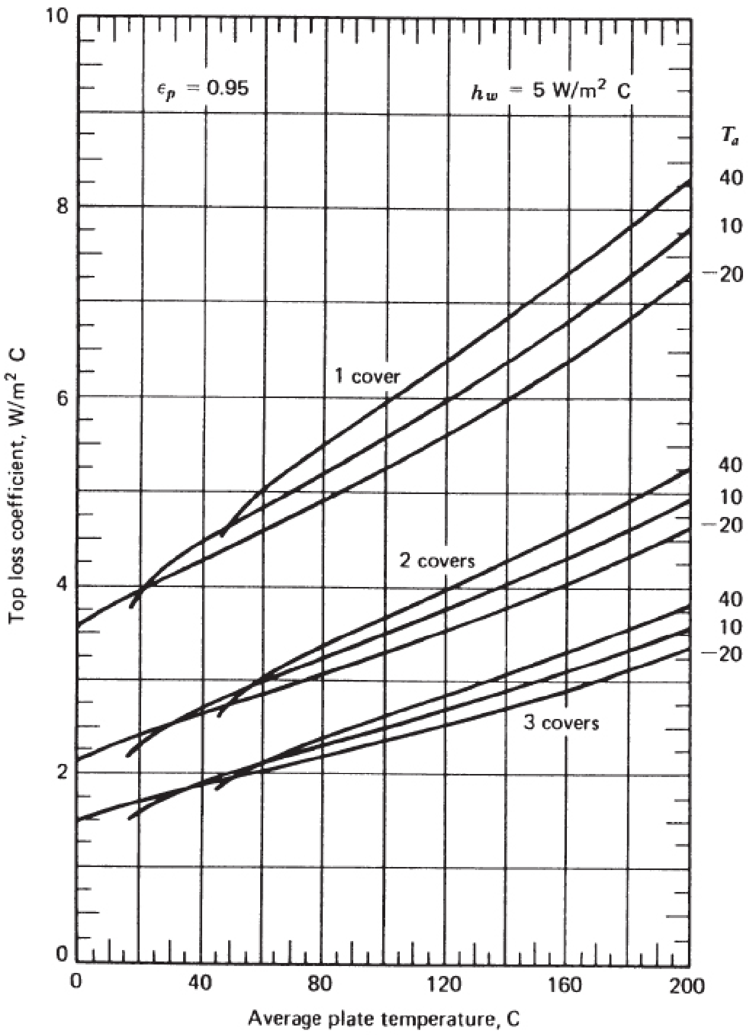
  - Since 1D problem:

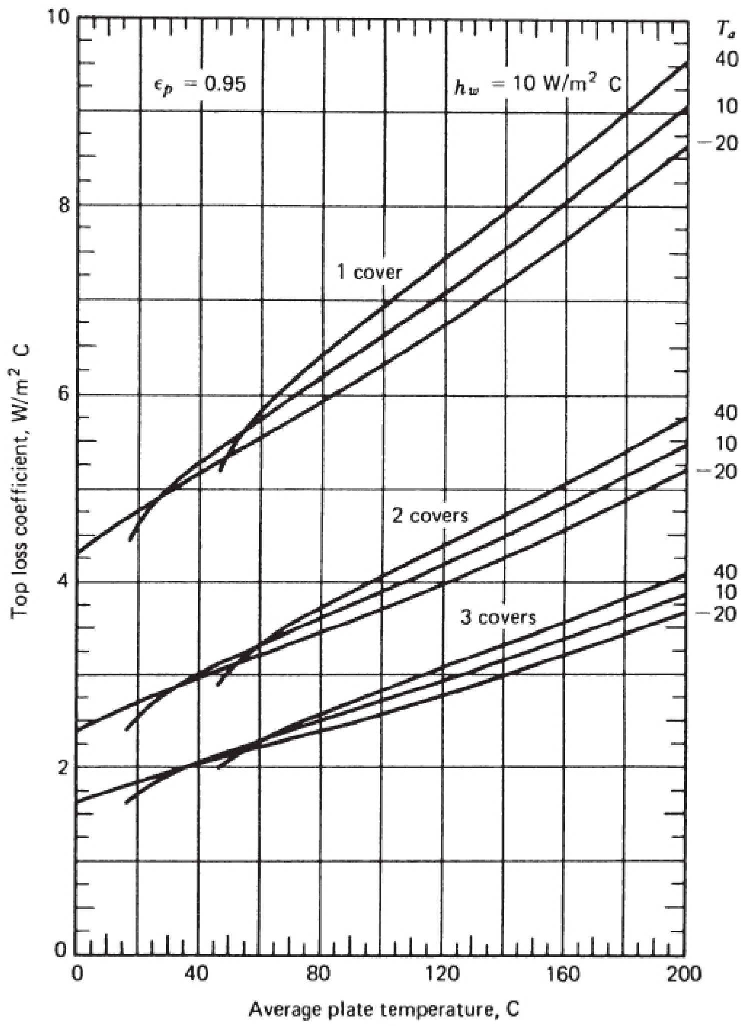
$$(T_i - T_j) / R_{ij} = (h_{conv,i-j} - h_{rad,i-j})(T_i - T_j) = U_t (T_p - T_a)$$

Flat plate collector



- Top heat loss coefficient, U_t ($U_L = U_t + U_b + U_{edge}$):





Energy balance on collector

- Resistor approach (example for two-cover collector):
  - Overall bottom loss heat transfer coefficient:

$$U_b = \frac{1}{R_4} = \frac{1}{l / k}$$

  - Overall edge loss heat transfer coefficient:

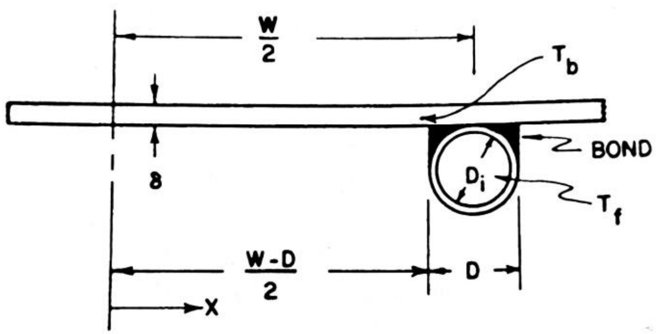
$$U_{edge} = \frac{(UA)_{edge}}{A_c}$$

  - Total heat loss: sum of top, edge and bottom

Energy balance on collector

- Mean plate temperature: Energy balance over elements

$$S\Delta x - U_L \Delta x (T - T_a) = \left(-k\delta \frac{dT}{dx}\right)_{x+\Delta x} - \left(-k\delta \frac{dT}{dx}\right)_{x}$$

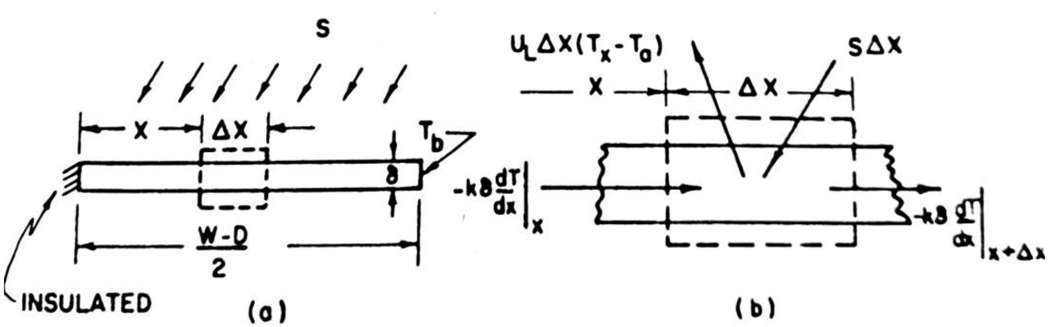


Sheet and tube dimensions.

$$\frac{d^2T}{dx^2} = \frac{U_L}{k\delta}\left(T - T_a - \frac{S}{U_L}\right)$$

BC:

$$\left.\frac{dT}{dx}\right|_{x=0} = 0, \left.T\right|_{x=(W-D)/2} = T_b,$$



Energy balance on collector

- Mean plate temperature: Analytical solution

$$\dot{q}'_{fin} = (W-D)\left(S - U_L(T_b - T_a)\right)\overbrace{\frac{\tanh\left(\sqrt{\frac{U_L}{k\delta}}(W-D)/2\right)}{\sqrt{\frac{U_L}{k\delta}}(W-D)/2}}^{=F}$$

- Using the fin-efficiency, *F*, and base temperature T_b

Energy balance on collector

- Mean plate temperature: Energy transfer to fluid

$$\dot{q}_u' = \dot{q}_{fin}' + \underbrace{\dot{q}_{tube}'}_{D\left(S - U_L(T_b - T_a)\right)} = \left((W - D)F + D\right)\left(S - U_L(T_b - T_a)\right)$$

$$\dot{q}_u' = \frac{T_b - T_f}{\dfrac{1}{h_{f,in}\pi D_{in}} + \dfrac{1}{C_b}}$$

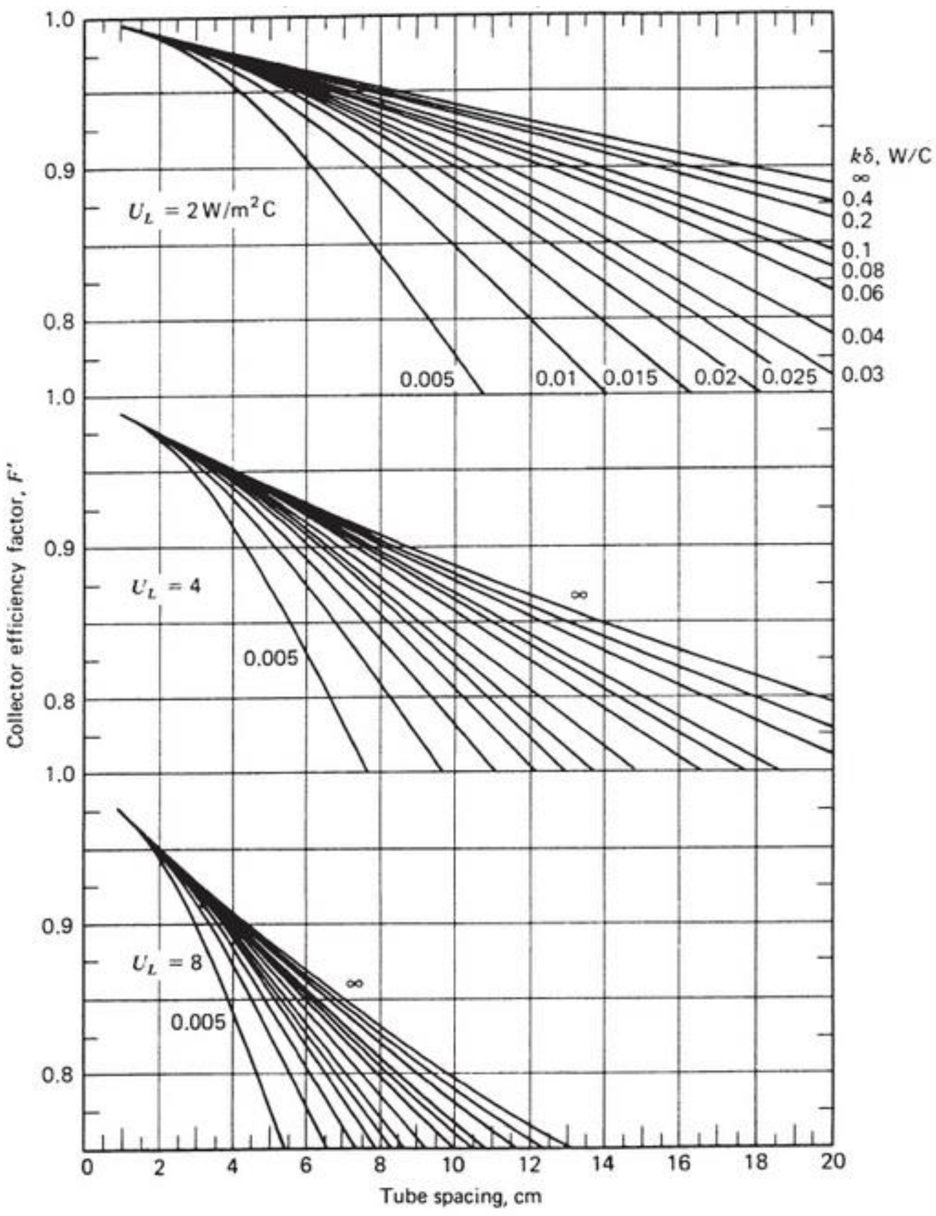
- With C_b, conductance of bond
- Replacing T_b gives $\dot{q}_u' = WF'\left(S - U_L(T_f - T_a)\right)$

- With F', collector efficiency factor:

$$F' = \frac{1/U_L}{W\left[\dfrac{1}{h_{f,in}\pi D_{in}} + \dfrac{1}{C_b} + \dfrac{1}{U_L\left[D + \left(W - D\right)F\right]}\right]}$$

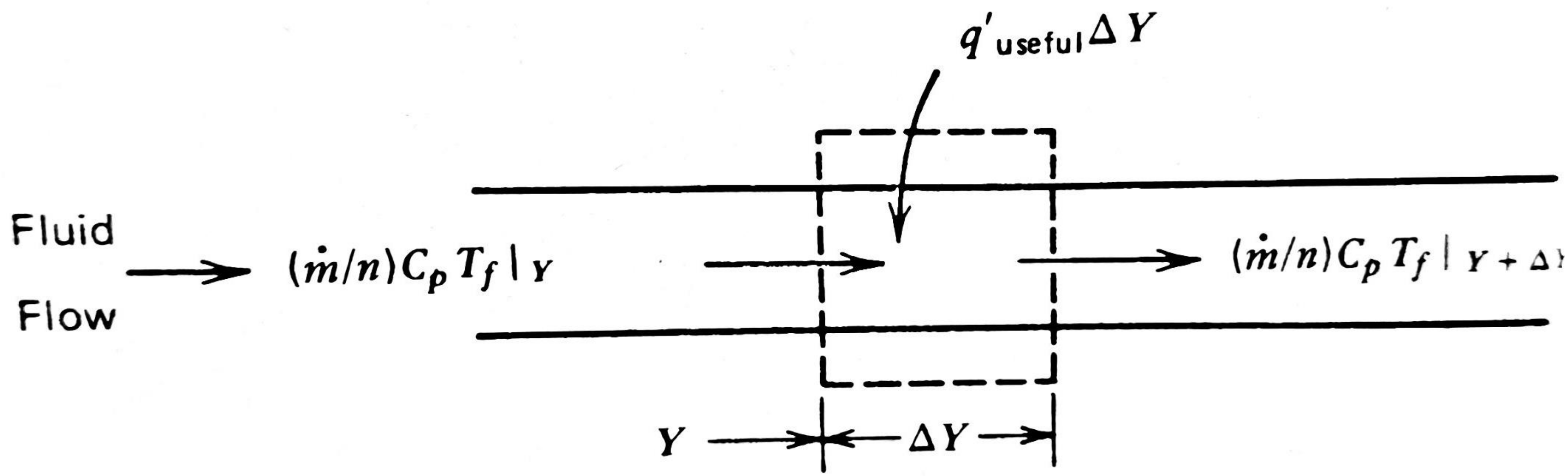
Conversion pathways: Solar to thermal

- Collector efficiency factor, *F*':



Energy balance on collector

- Temperature in flow direction: Energy balance



$$\frac{\dot{m}}{n} c_p T_f \Big|_y - \frac{\dot{m}}{n} c_p T_f \Big|_{y+\Delta y} + \Delta y q'_u = 0$$

$$\frac{\dot{m}}{n} c_p \frac{dT_f}{dy} - nWF'\left[S - U_L (T_f - T_a)\right] = 0$$

n: number of parallel tubes

Energy balance on collector

- Temperature in flow direction: Analytical solution

$$\frac{T_{f,out} - T_a - S/U_L}{T_{f,in} - T_a - S/U_L} = \exp\left(-\frac{U_L A_c F'}{\dot{m} c_p} \right)$$

- With collector heat removal factor:

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

- Now I can relate everything to fluid inlet temperature

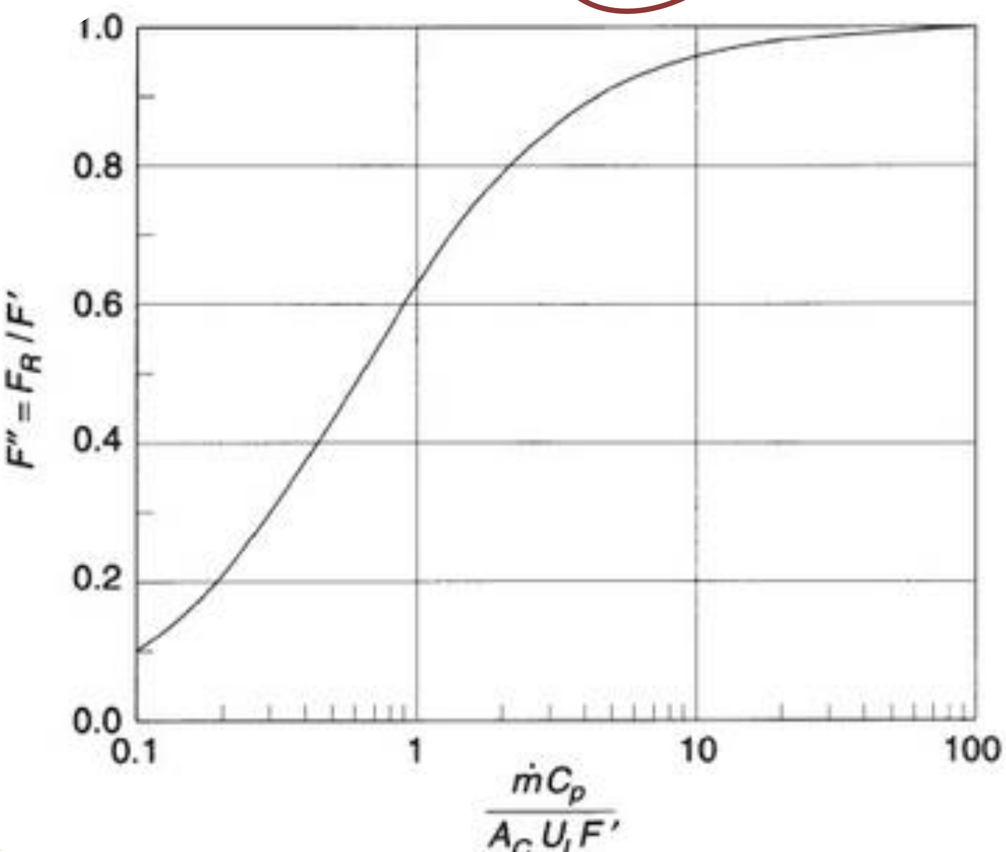
Energy balance on collector

- Temperature in flow direction: Analytical solution

Collector capacitance rate

- Rearranging:

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

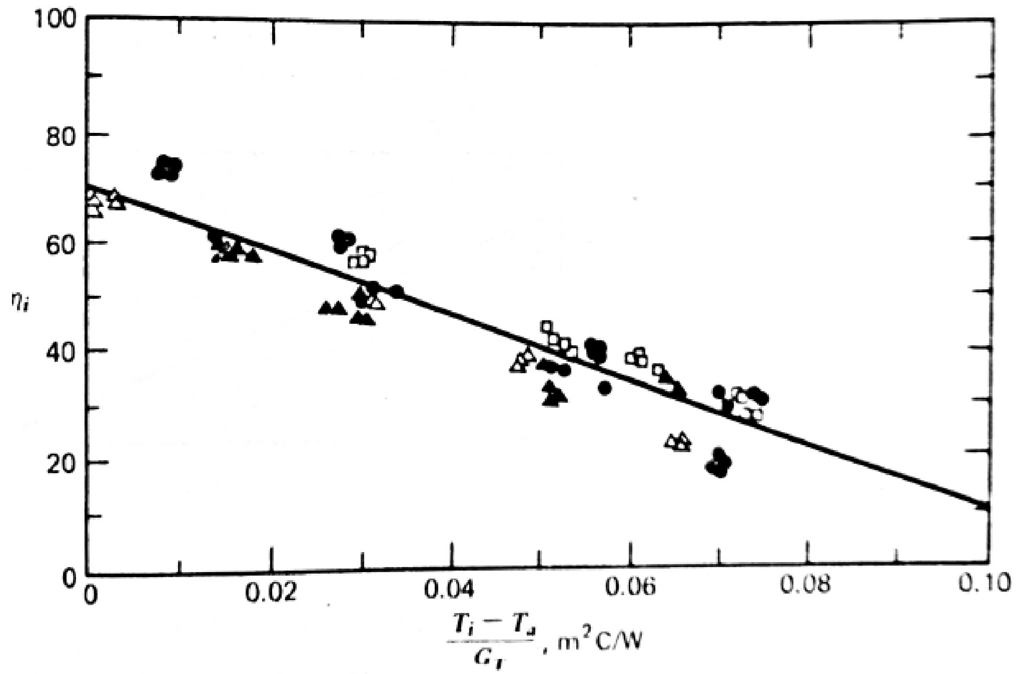


Energy balance on collector

- Flat-plate solar collectors: Using inlet collector temperature, Hottel-Whillier-Bliss equation: $$Q_c = A_c F_R \left(S - U_L (T_{f,in} - T_a) \right)$$

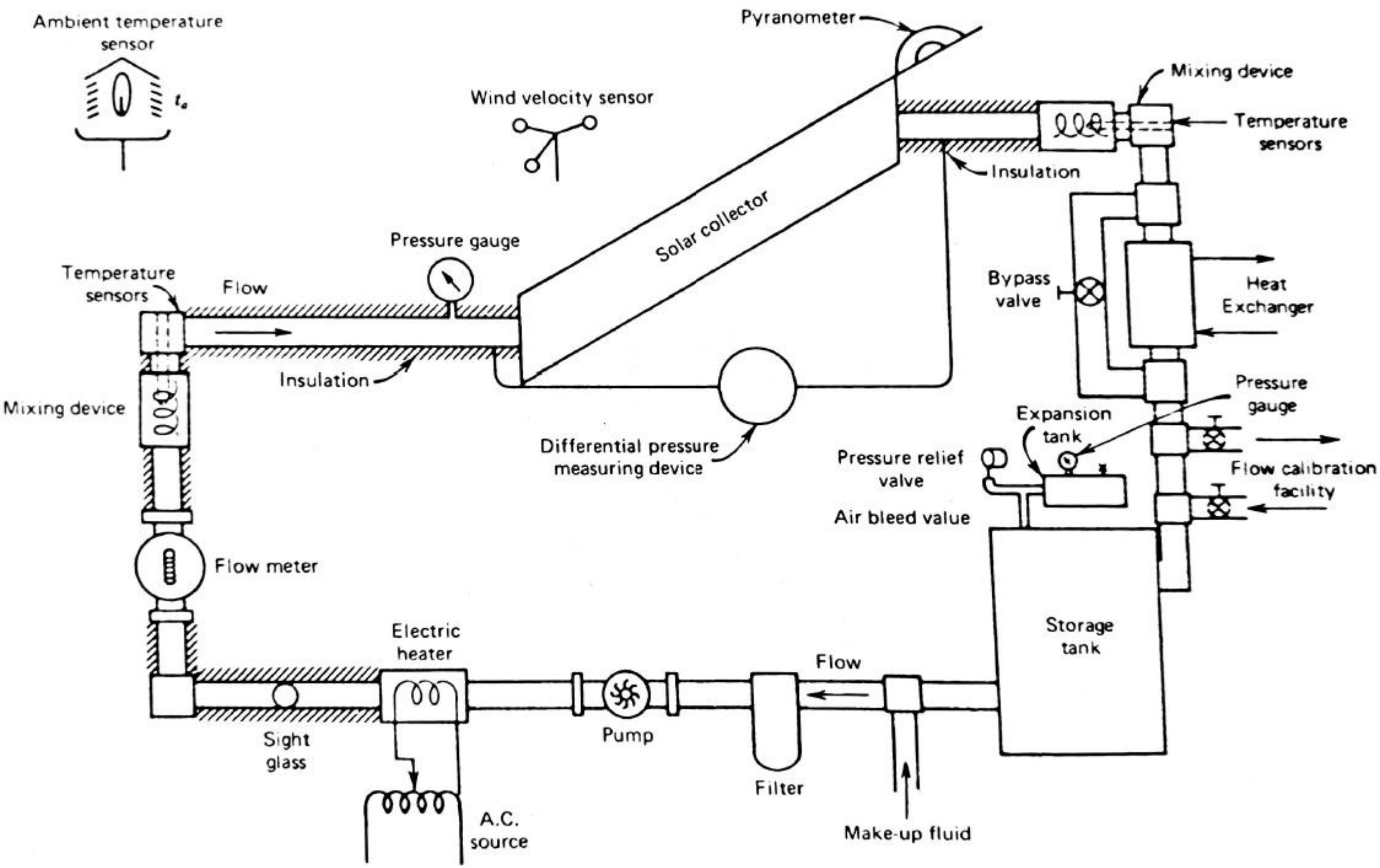
  - Efficiency:

$$\eta = \frac{Q_u}{IA_c} = \frac{mc_p (T_{f,out} - T_{f,in})}{IA_c} = \frac{A_c F_R \left(\overset{I\eta_{opt}}{S} - U_L (T_{f,in} - T_a) \right)}{IA_c} = F_R \eta_{opt} - F_R U_L \left(\frac{T_{f,in} - T_a}{I} \right)$$



Energy balance on collector

- Flat-plate solar collectors: Measurements



Energy balance on collector

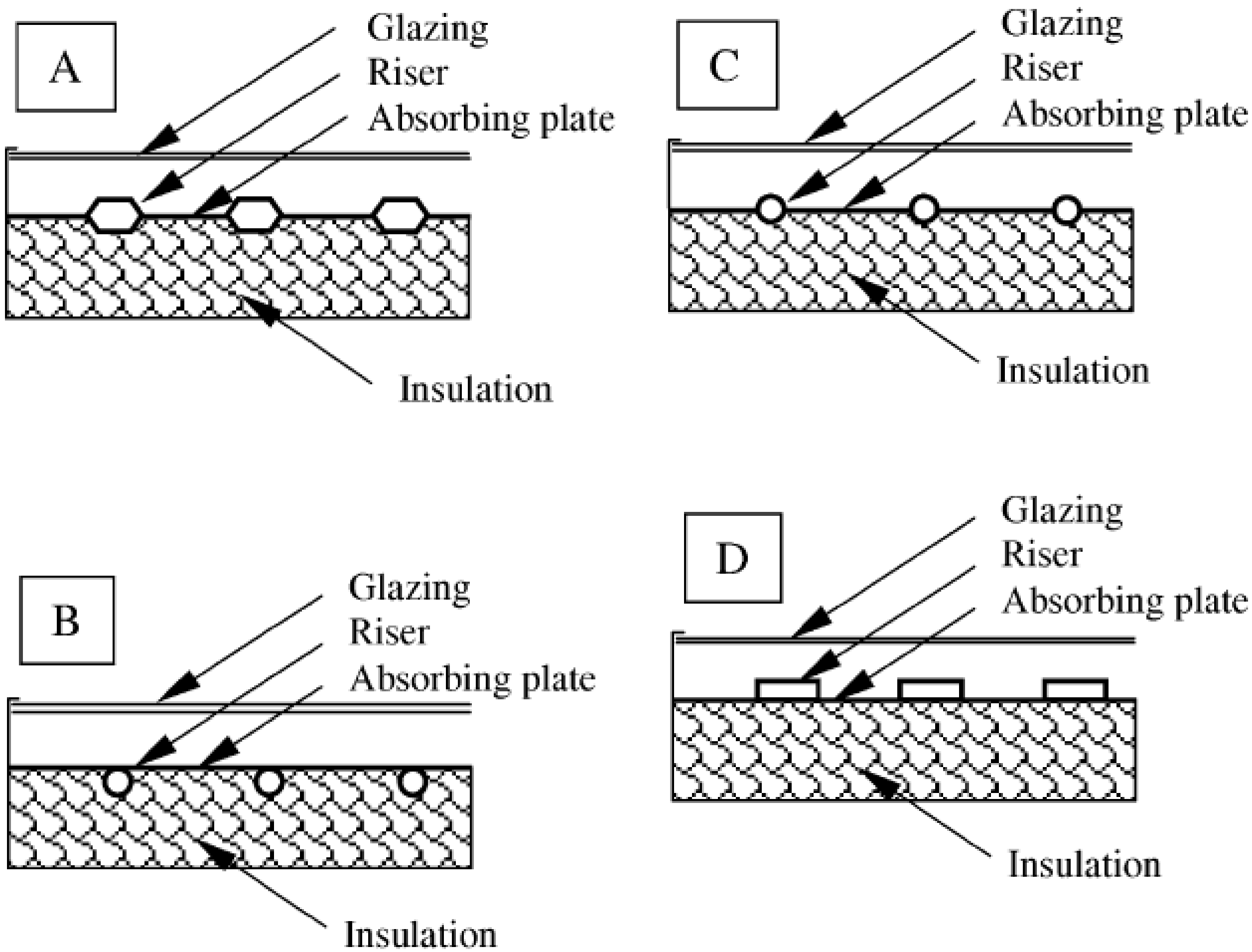
- Solar to thermal: non or low-concentrating
  - Flat-plate solar collectors: Other characteristics
    - Collector time constant: $$\frac{T_{f,t} - T_{\mathrm{f,in}}}{T_{\mathrm{f,ini}} - T_{f,in}} = \frac{1}{e} = 0.368$$
    - Stagnation temperature: $q_{\mathrm{c}} = 0$ $$T_{\mathrm{f,in}} = T_{\mathrm{a}} + \frac{I\eta_{\mathrm{opt}}}{U_{\mathrm{L}}}$$
    - Pressure drop for active systems: keep parasitic energy consumption low (electricity for pumps and blowers)
  - Improving performance:
    - selective window and absorber coating
    - two glass cover
    - improved absorber and heat transfer fluid tube connections (e.g. high quality welding)

Energy balance on collector

- Flat-plate solar collectors:
  - Practical performance reduction
    - Effect of dust: difficult to quantify, orders of magnitude 1-2% reduction in absorbed radiation
    - Effect of shading: due to non-normal irradiance and typically in the range of 1% of absorption is lost

Design options

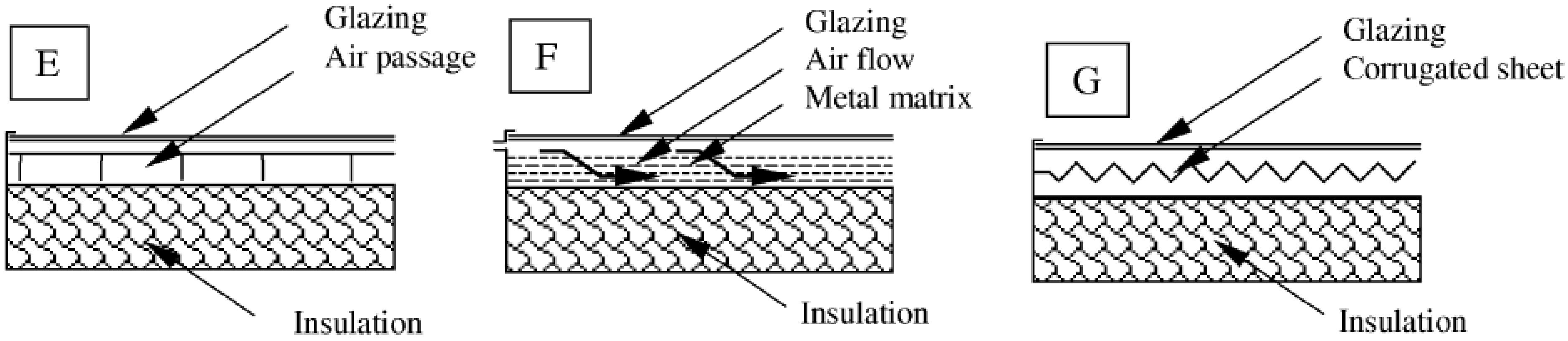
- Flat-plate solar collectors: typical absorber configurations
  - Liquid working fluid



Kalogirou, 2004

Design options

- Flat-plate solar collectors: typical absorber configurations
  - Air as working fluid
    - Lower specific heat capacity (larger volume flow rates, larger pumping power)
    - Lower heat transfer coefficients between air and absorber
    - Open loop or closed loop



Kalogirou, 2004

Applications

- Flat-plate solar collectors:

Source: wksolar

Glazed flat plate collectors integrated in building, Architect Philippon

Kaidun solar energy

12m^2 air collectors for Bettelwürfhütte, Austria (source: Grammer Solar)

Improving performance

- Collector configuration

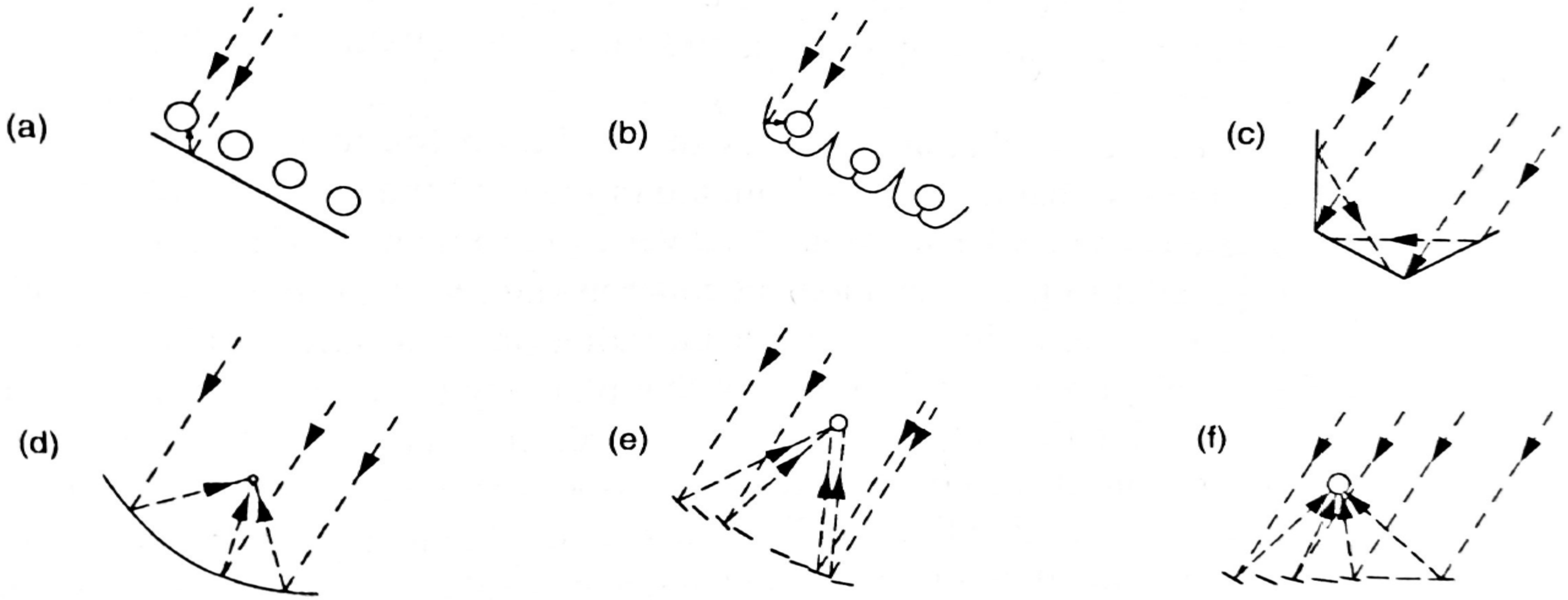
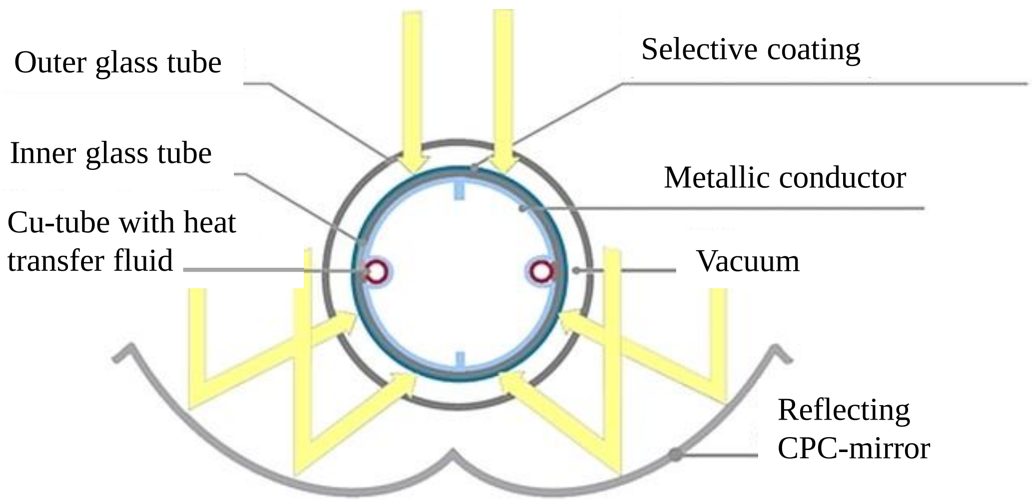


Figure 7.1.1 Possible concentrating collector configurations: (a) tubular absorbers with diffuse back reflector; (b) tubular absorbers with specular cusp reflectors; (c) plane receiver with plane reflectors; (d) parabolic concentrator; (e) Fresnel reflector; (f) array of heliostats with central receiver.

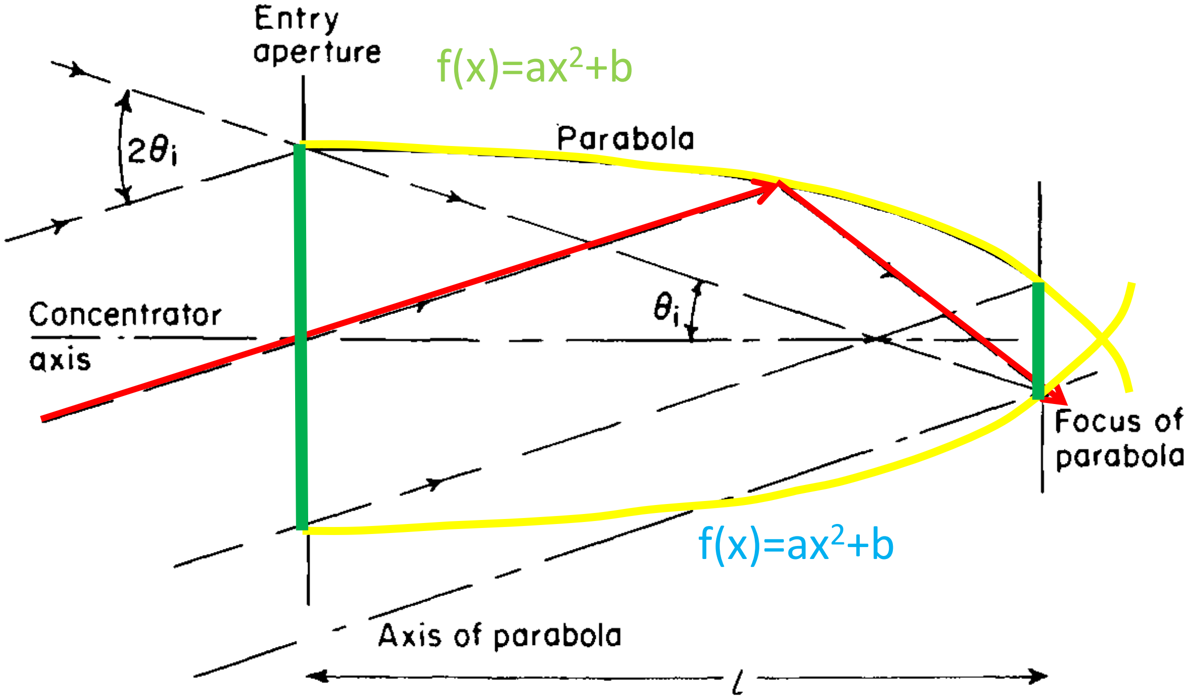
Low-concentration

- Using non-imaging optics
  - 2D compound parabolic concentrator (CPC)
    - Direct and some diffuse radiation
    - Advantage:
      - Higher performance
      - Higher temperatures
    - Temperature range: 60-240°C
    - Concentration: 1-5



Low-concentration

- Using non-imaging optics
  - 2D compound parabolic concentrator



  - All radiation within CPC incidence angle will be concentrated

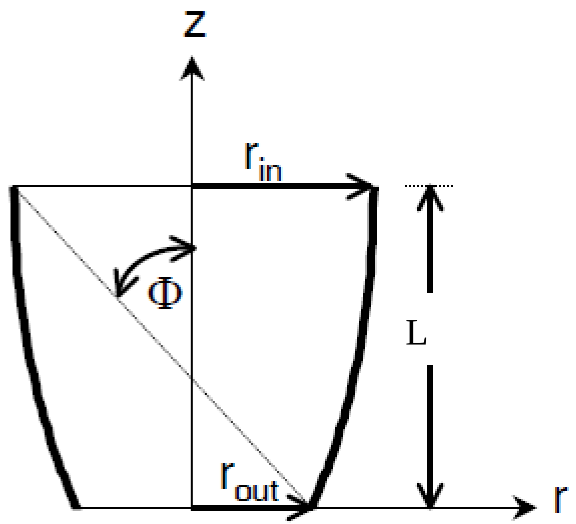
Low-concentration

- Using non-imaging optics
  - 2D compound parabolic concentrator
    - Acceptance angle Φ
    - Concentration, $C = 1/\sin(\Phi)$
    - Outlet radius, $r_{out} = r_{in} \cdot \sin(\Phi)$
    - Length, $L = (r_{in}+r_{out}) \cdot \cot(\Phi)$
    - r and z coordinates

$$r = \frac{2r_{out}(1+\sin(\Phi))\sin(\varphi+\Phi)}{1-\cos(\varphi)} - r_{out}$$

$$z = \frac{2r_{out}(1+\sin(\Phi))\cos(\varphi+\Phi)}{1-\cos(\varphi)}$$

with $2\Phi < \varphi < \Phi + \pi/2$

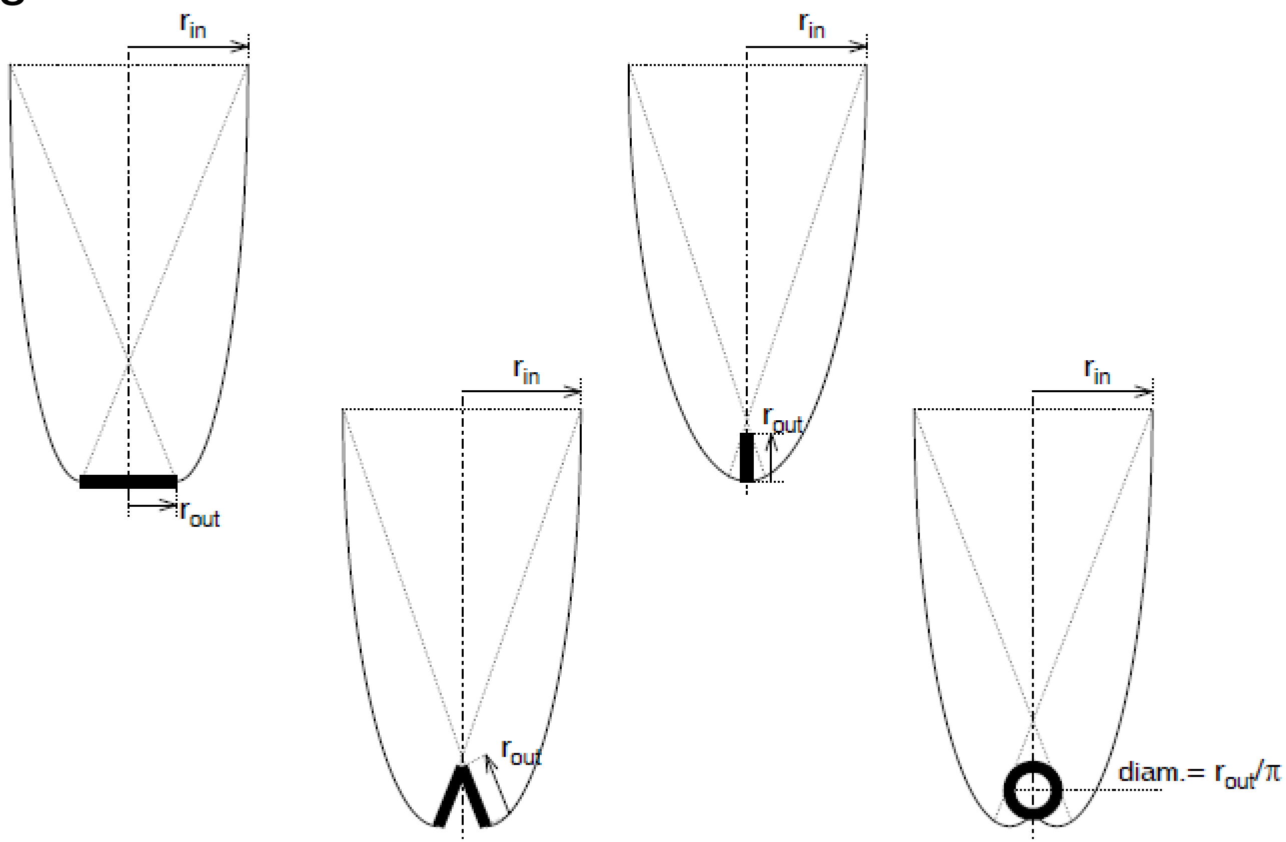


Low-concentration

```
%-----------------------------------------------------
% Matlab file to plot a CPC
% -----------------------------------------------------

% 3D CPC input parameters
phi_a=50;                        % half acceptance angle in degree
r_out=0.05/2;                    % exit radius of CPC in m
deltaz=0.0001;                   % discrete steps for length

% Calculations - 3D CPC
conc=sin(phi_a/180*pi)^(-2);               % concentration factor
r_in=r_out*sqrt(conc);                     % entrance radius of CPC in m
length=(r_out+r_in)/tan(phi_a/180*pi);     % length of CPC in m

phi=[2*phi_a:0.01:90+phi_a]/180*pi;
f=r_out*(1+sin(phi_a/180*pi));
r=2*f*sin(phi-phi_a/180*pi)./(1-cos(phi))-r_out;
z=2*f*cos(phi-phi_a/180*pi)./(1-cos(phi));

plot(r,z,'-k'); hold on;
plot(-r,z,'-k');
axis([-0.08 0.08 0 0.2]);

disp(['Phi [°]: ', num2str(phi_a)]);
disp(['r_out [m]: ', num2str(r_out)]);
disp(['r_in [m]: ', num2str(r_in)]);
disp(['l [m]: ', num2str(length)]);
```

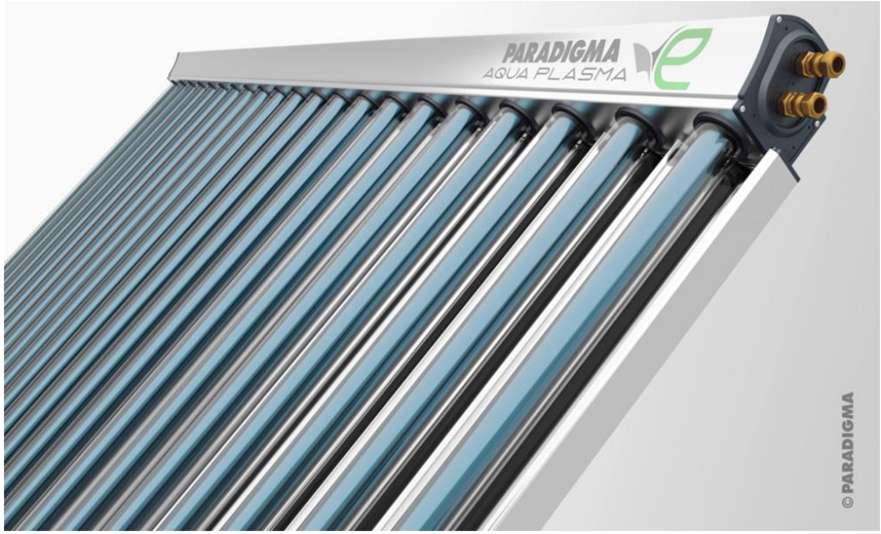
Low-concentration

- Using non-imaging optics
  - 2D compound parabolic concentrator: typical absorber configurations



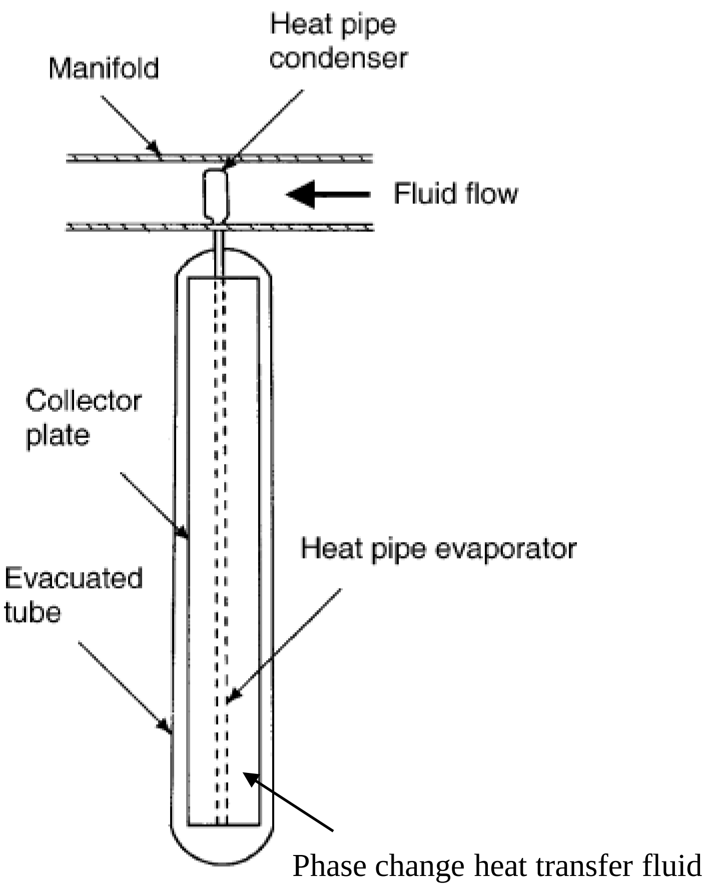
Low-concentration

- Compound parabolic concentrator:




Performance improvements

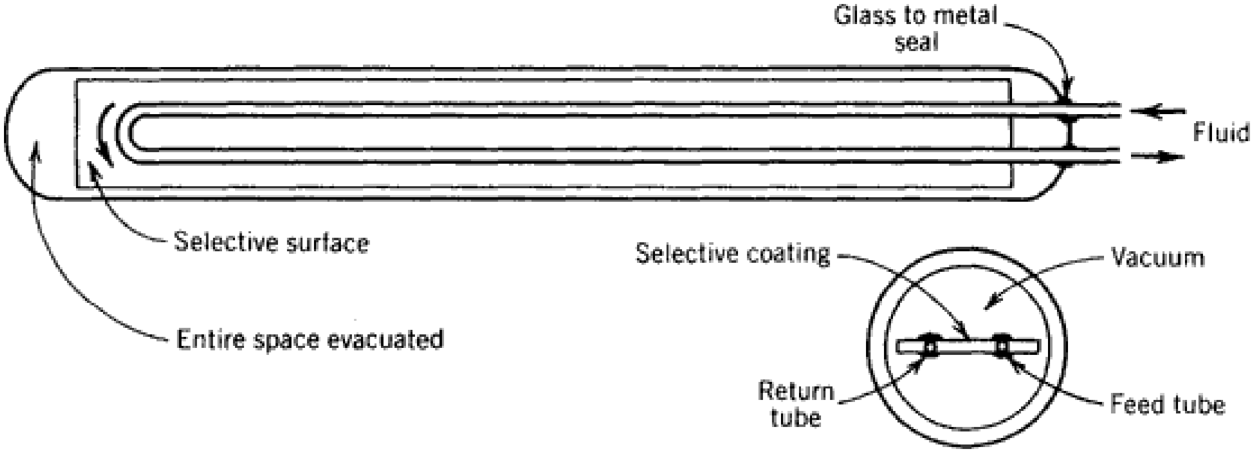
- Evacuated tubular collector
  - Diffuse and direct radiation
  - Advantage:
    - Convection losses reduced
    - More flexible to weather variations as condensation and moisture is avoided
    - Inherent freezing/overheating protection
  - Temperature range: 50-200°C
  - Concentration: 1
  - Use liquid-vapor phase change heat transfer fluids in evacuated tubes



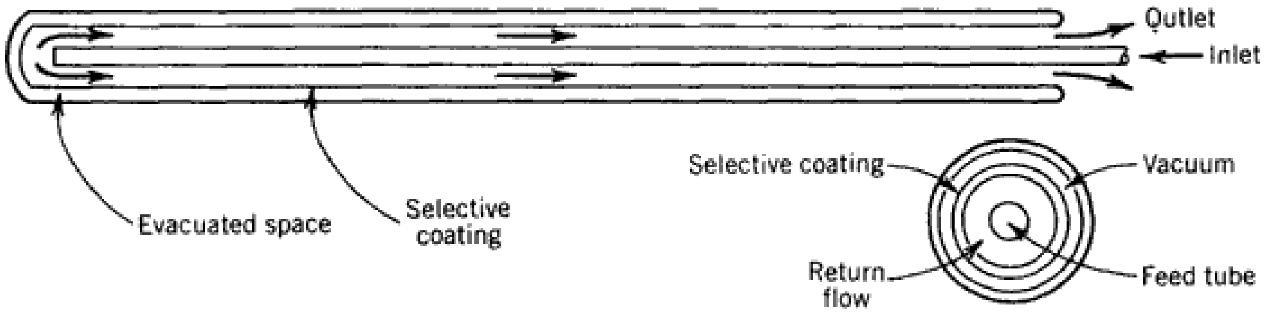
Performance improvements

- Evacuated tubular collector: typical absorber configurations
  – Metal-fin-in-vacuum tubes

    Requires glass-metal seal

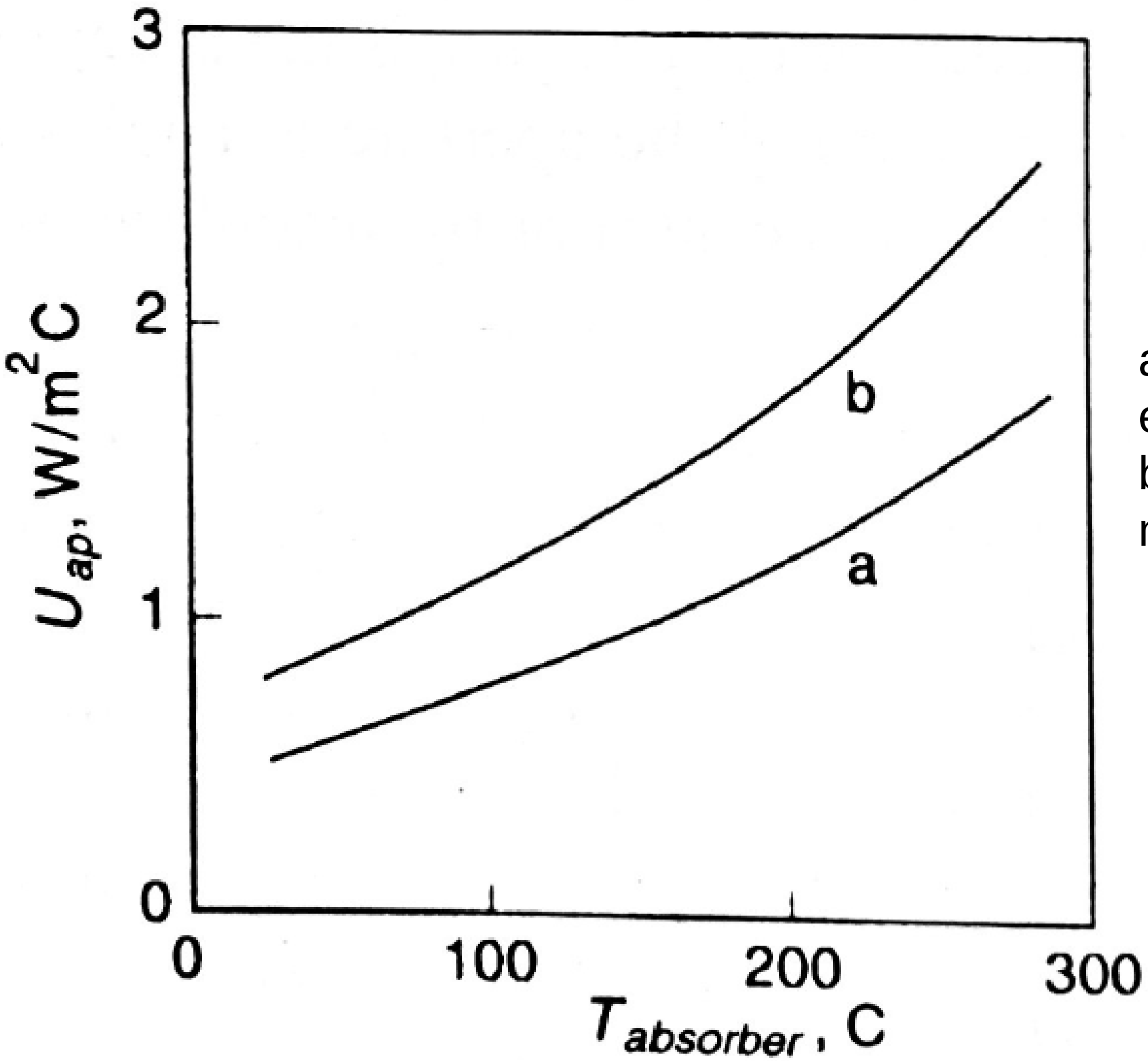


  - Dewar tubes



Performance improvements

- Evacuated tubular collector: Calcualted loss, U_L



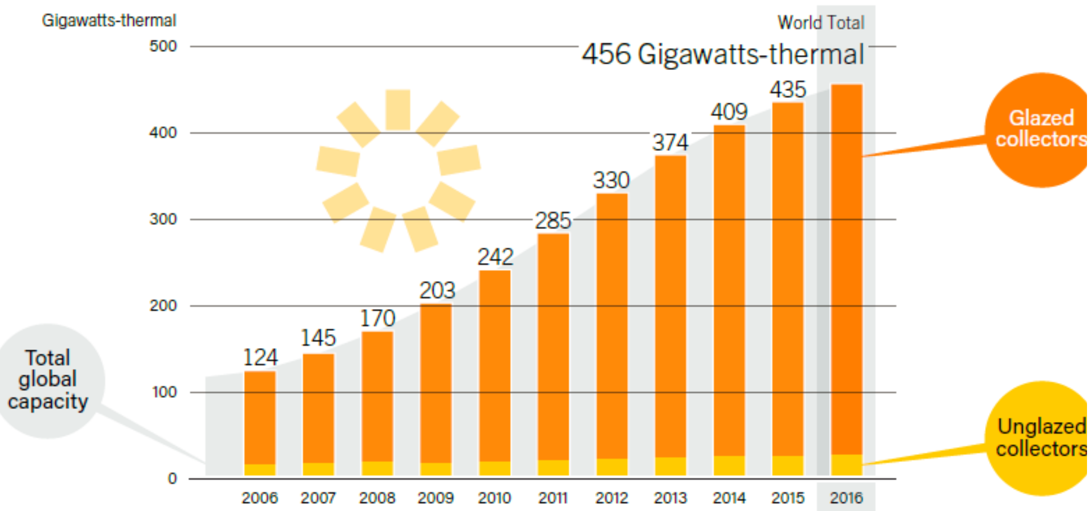
a: radiation only across evacuated space
b: adding 50% loss through manifolds

Examples

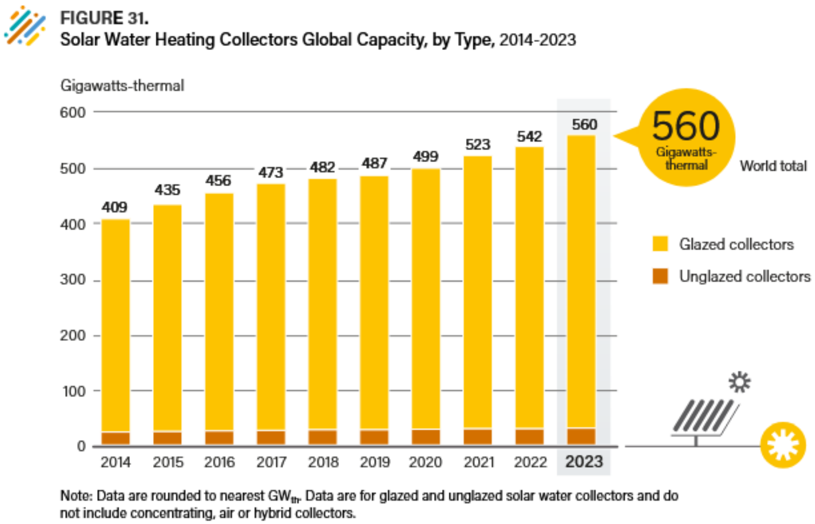
- Evacuated tubular collector:

Solar collectors

- Global installed capacity of water and air collectors by 2016 (456 GW):

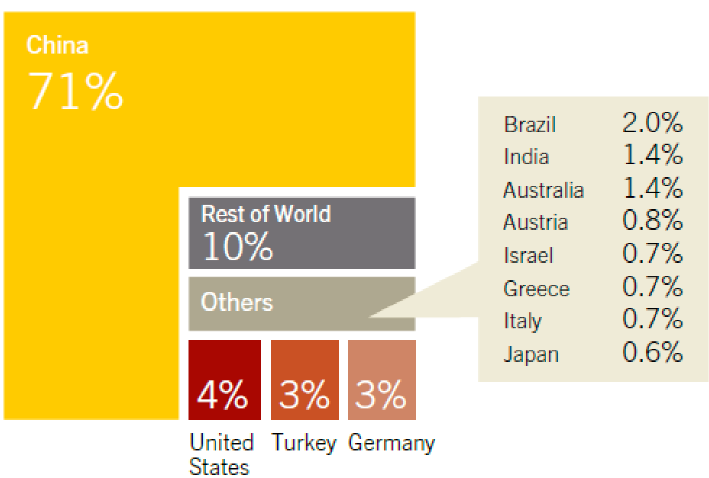


REN21, Renewable 2017 Global Status Report



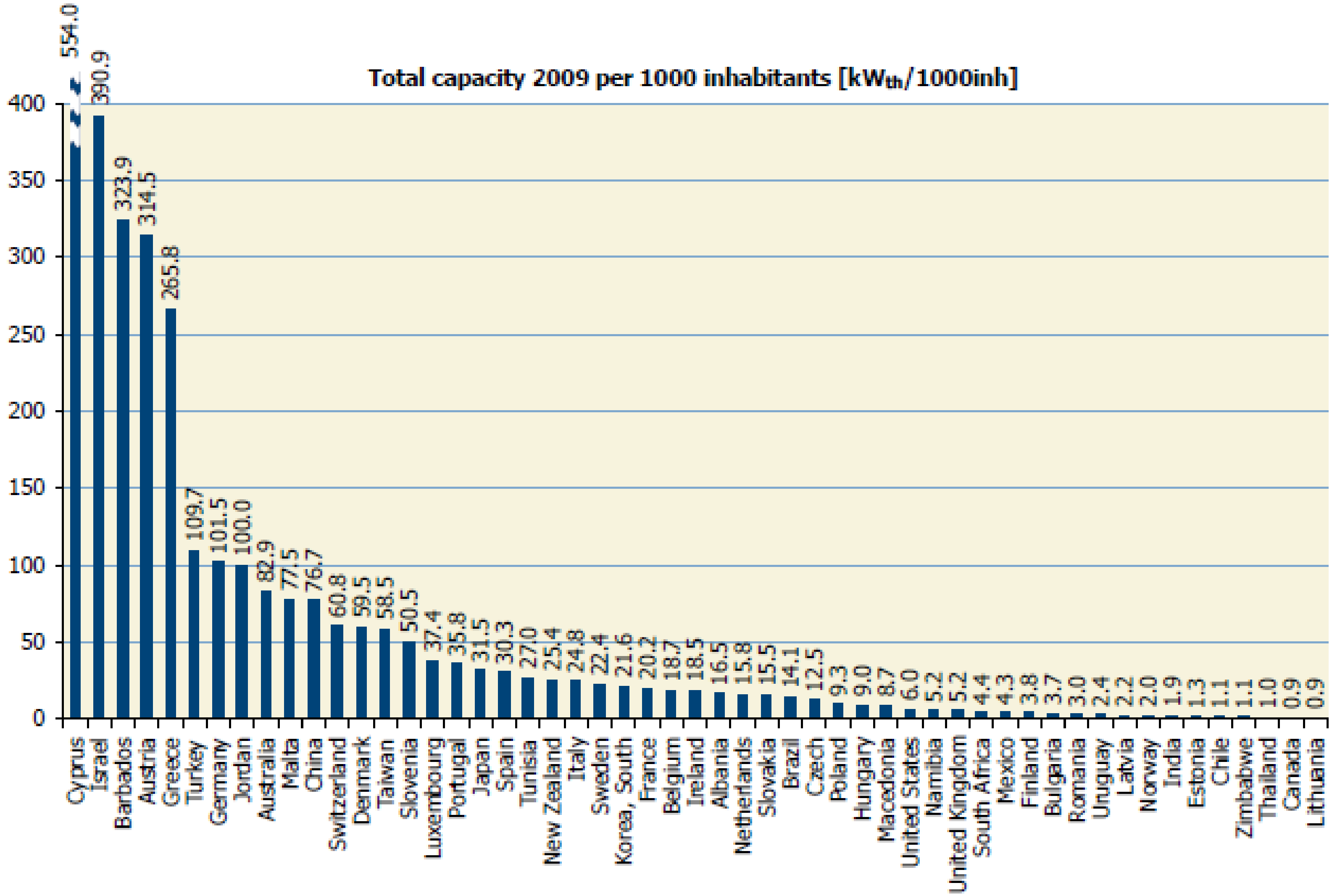
REN21, Renewable 2024 Global Status Report

Where (2016):



Solar collectors

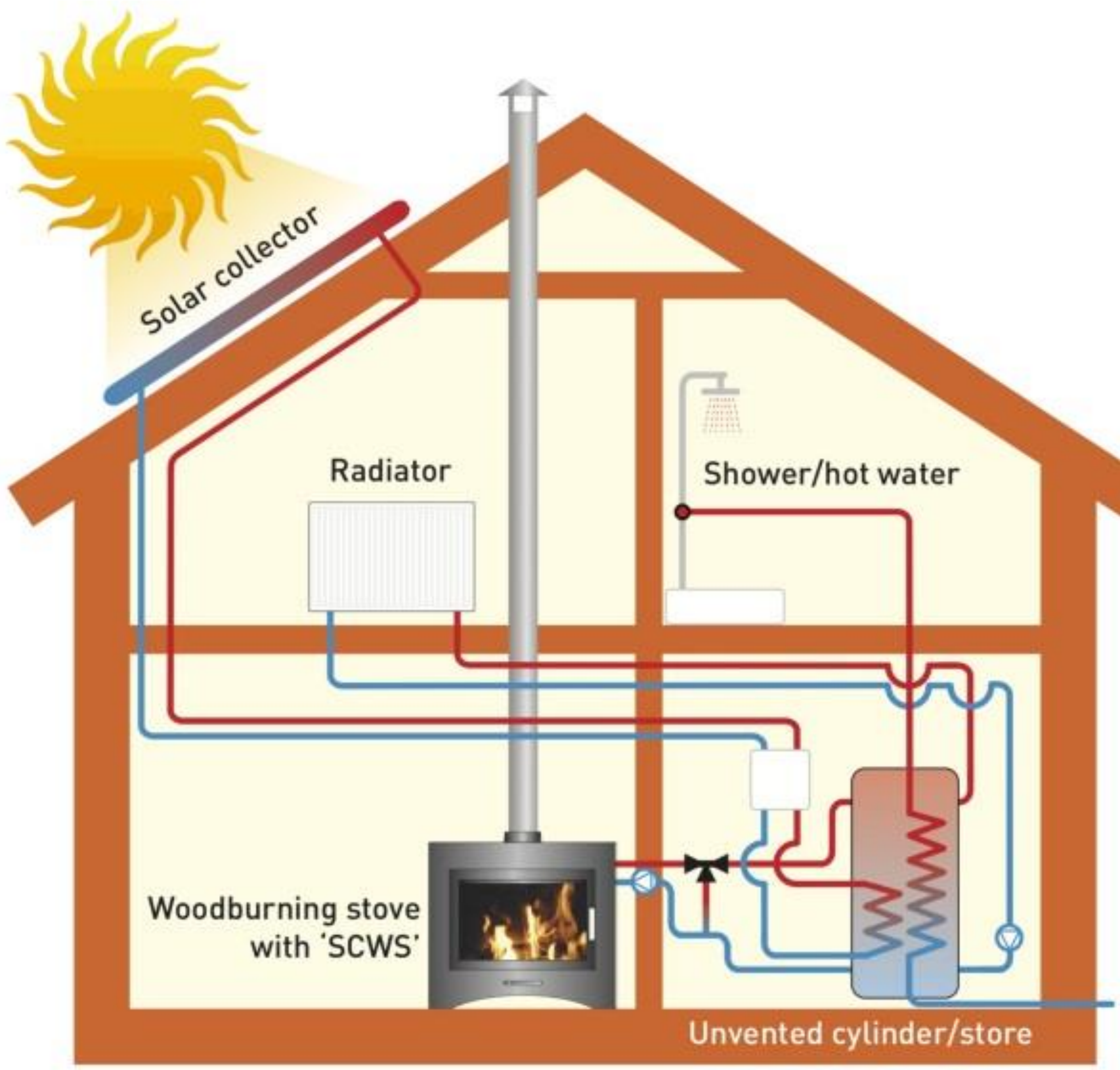
- Installed capacity of glazed and evacuated tubes per capita by 2009:



Weiss and Mauthner, Solar Heat Worldwide, Solar heating and cooling, IEW, 2011

Solar collectors

- For residential applications – often together with heat storage



Source: Brosley