Karlsruher Institut für Technologie

"Solar Energy" WS 2014/2015

Lecture 19: Solar Thermal

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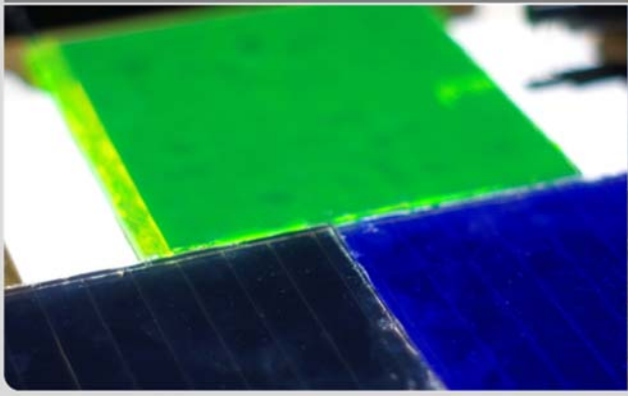
KIT Focus Optics & Photonics



Solar Thermal Market in Germany

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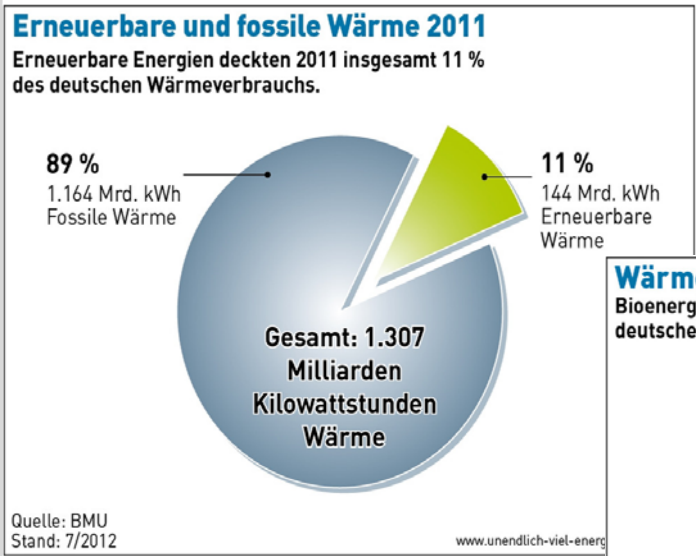
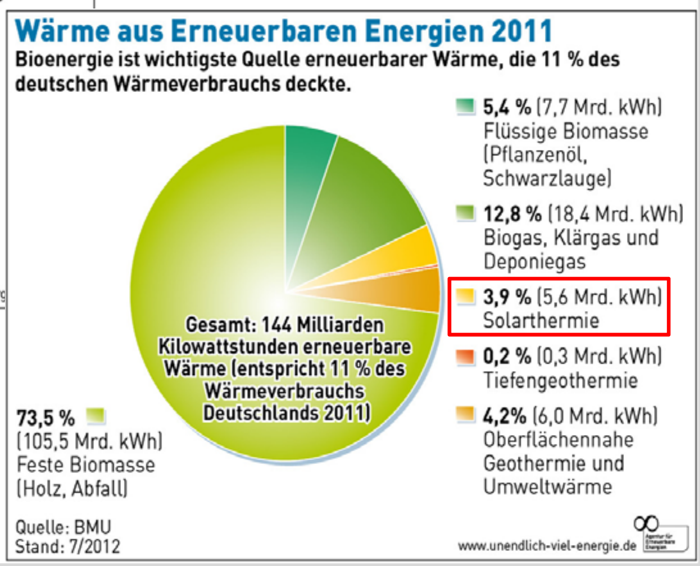
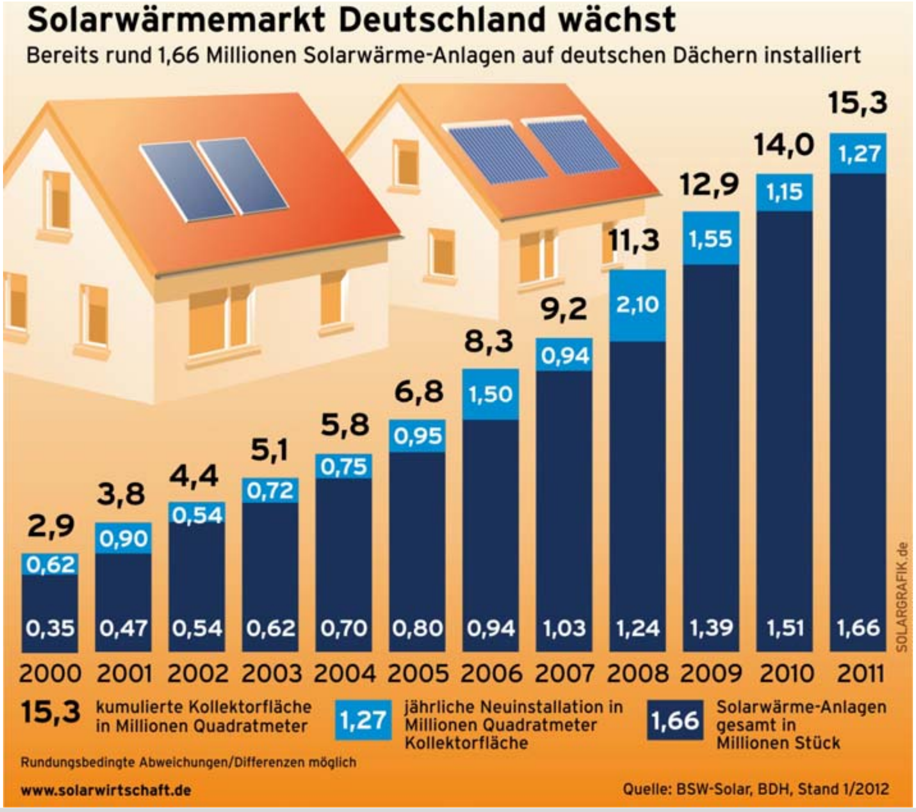




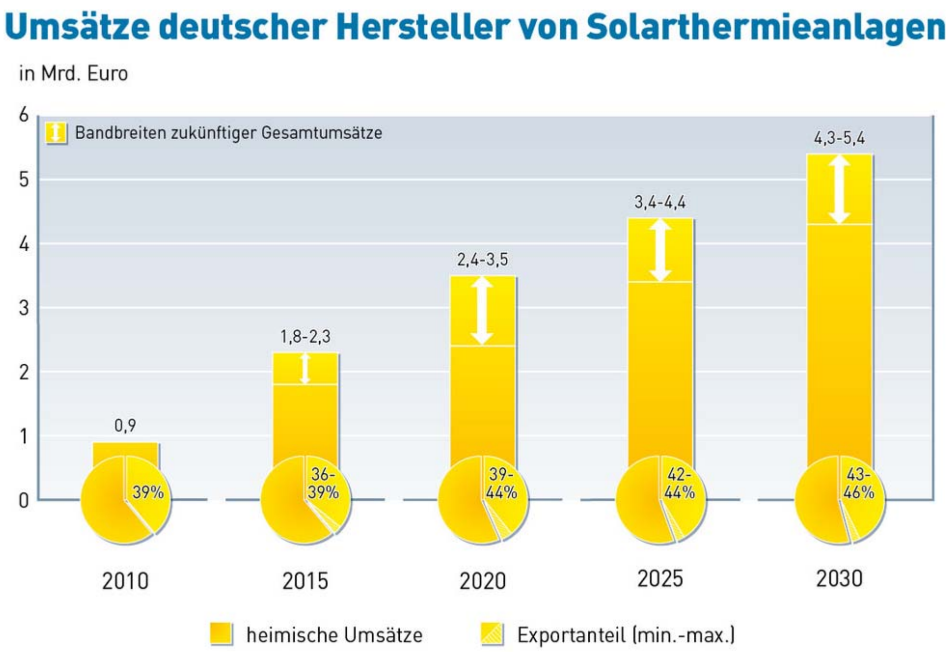
Solar Thermal Market in Germany



10.7 GW_{th}
End 2011

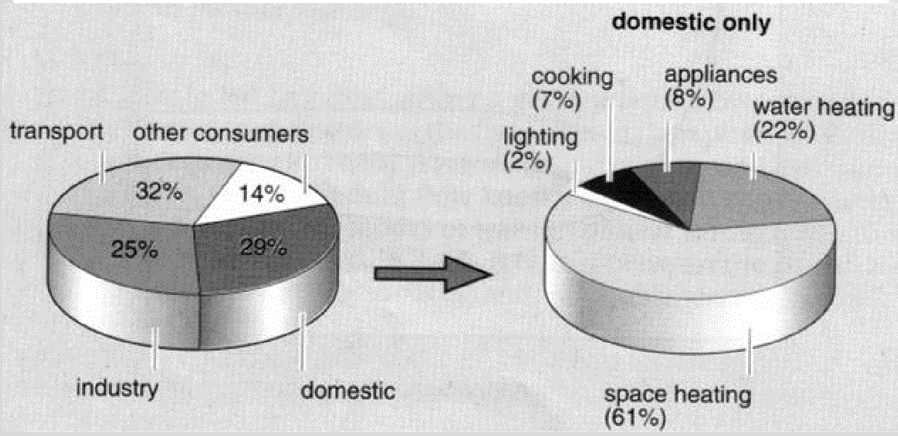
Solar Thermal Market in Germany

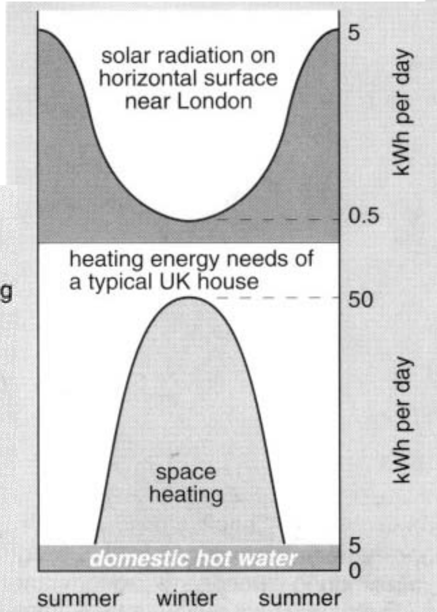
- Steady growth predicted for German manufacturers
- Domestic sales expected to shrink but exports to grow



Solar Thermal End Uses

- Large fraction (~80%) of energy use in EU domestic sector is low-temperature heating – space heating and water heating
- Resource not so well matched to demand



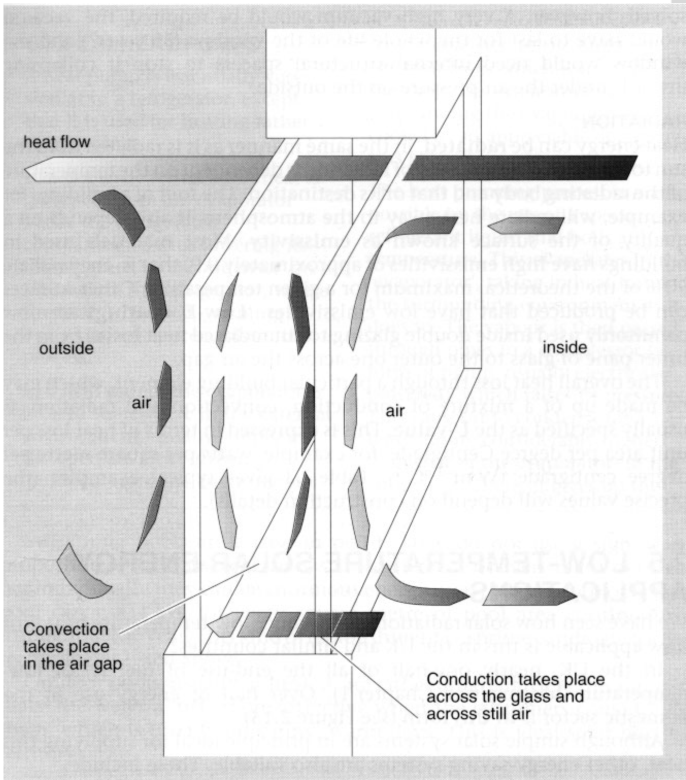


Heat Transport Through Glass

Windows:

An example to illustrate mechanisms for transport of heat through materials:

1. Radiation
2. Conduction
3. Convection



Heat Transport Through Glass

1. **Radiation** – glass radiates electromagnetic energy depending on its temperature

$$\dot{Q} = \varepsilon \cdot \sigma \cdot T_g^4$$

- $\sigma = 5.67 \cdot 10^{-8}$ W/m^2.K^4 (Stefan Boltzmann constant)
- ε is the emissivity ($0 < \varepsilon < 1$), a property of the glass material or its coatings
- ε is typically ~0.9, although special "Low-E" coatings can be employed in double-glazed windows to reduce radiative heat losses

Heat Transport Through Glass

2. **Conduction** – heat flows through glass (and framing materials) due to temp. difference between one side and the other

$$\dot{Q} = \frac{k \cdot A}{L} \cdot \Delta T = U \cdot A \cdot \Delta T$$

- *k* is thermal conductivity (W.m^{-1}.°C^{-1})
- *A* and *L* are the area and thickness of the glass, respectively
- ΔT is the temperature difference between the two surfaces
- *U* is the thermal transmittance, often called the "U-value" (W.m^{-2}.°C^{-1}) incorporates thickness with *k,* since glazing materials are often made to a standard thickness
  e.g. single glazing *U* = 6, double glazing *U* = 3
- conduction through framing materials often larger than through glass materials, especially for double-glazing

Heat Transport Through Glass

3. **Convection** – heat flows due to physical transport of the medium containing the heat
   - natural convection occurs with air
     - » air in contact with surface warms due to conduction
     - » warm air expands and rises, carrying away heat
     - » cooler air replaces warm air warming due to conduction
   - natural convection occurs on both surfaces, as well as within the space between double-glazed windows
     - » fill space with heavy gas molecules (argon or carbon dioxide) that circulate more slowly
     - » evacuate space to eliminate conduction and convection

Solar Thermal Systems

Four classes of solar thermal systems:

1. Active Solar Heating – involves the use of a discrete *solar collector* designed to gather and store solar radiation
   - Solar hot water (SHW) systems for domestic heating, T < 100°C

2. Solar Thermal Engines – systems that employ a secondary engine (e.g. steam or vapour turbine) to produce higher-grade energy (e.g. electricity)
   - concentrator systems increase temperatures upwards of 1000°C
   - low-temperature vapour-liquid systems work with small temperature differences (< 50°C)

Solar Thermal Systems

Four classes of solar thermal systems:

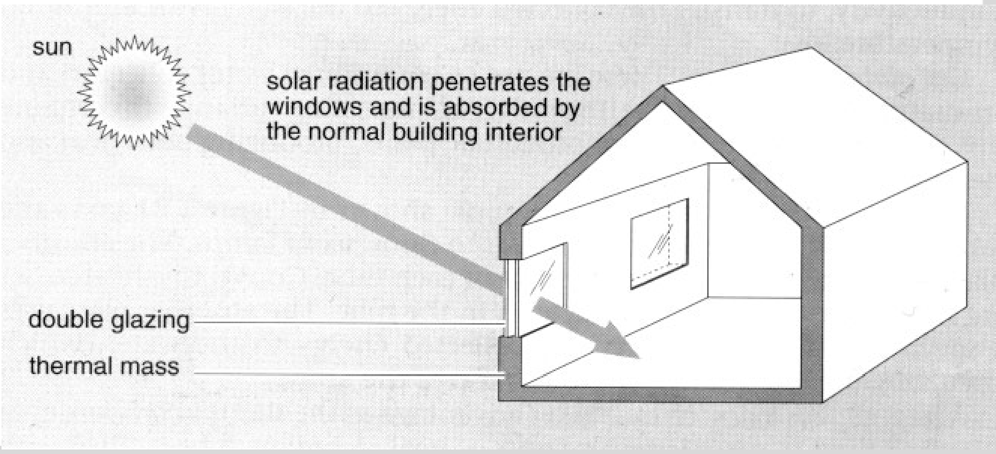
3. Passive Solar Heating – involves the use of a building to collect and store solar energy for its own space heating needs

4. Daylighting – involves the use of architectural design features that provide natural sunlight to displace a building's electrical lighting needs

Passive Solar Thermal

- Passive Solar Energy – absorption of solar energy directly into a building for space heating

- Called "passive" as the energy "collector" is the building itself and "active" delivery of heat (e.g. pumps or fans) are not required



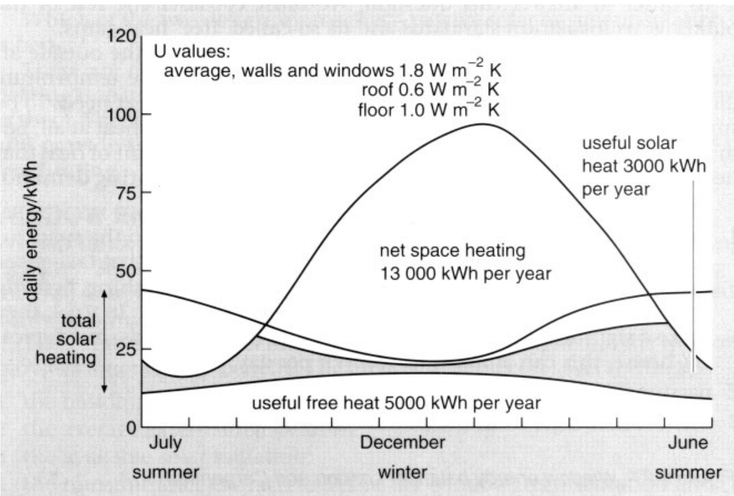
Passive Solar Thermal

- Usually integrated with low-energy building design to reduce peak heating / cooling demand (i.e. winter space heating / summer air conditioning)

- All buildings with glazing are passive solar collectors by direct gain, however some are better designed for the climate than others

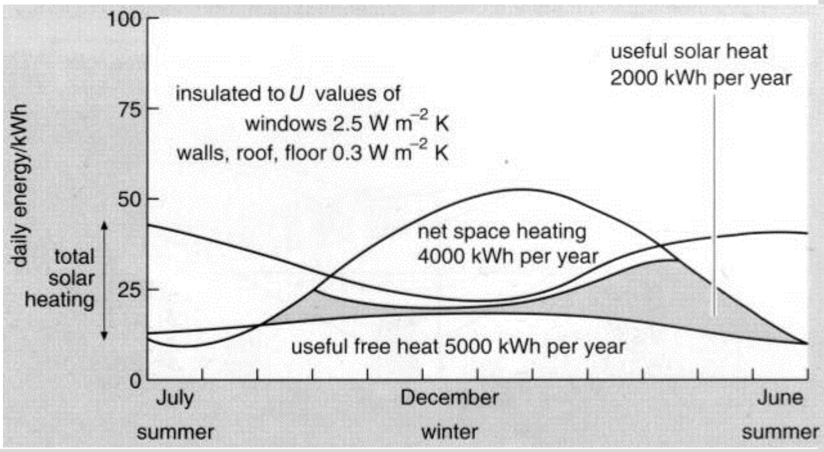
Passive Solar Thermal

- Heating load – must balance radiative, convective and conductive heat losses to maintain interior temperature
- e.g. poor insulated house in London
  - About 5000 kWh/yr is "free" – cooking, etc., people
  - About 3000 kWh/yr from passive solar heating (14%)
  - About 13000 kWh/yr net space heating loads



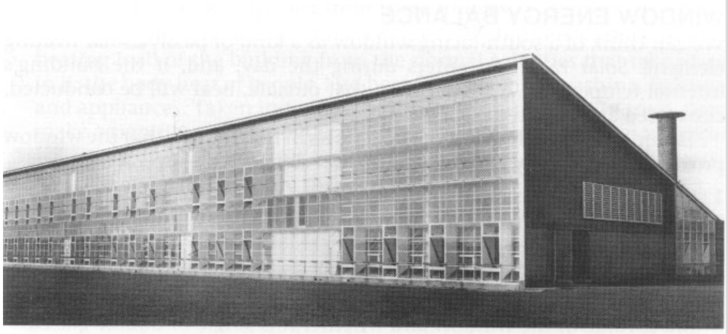
Passive Solar Thermal

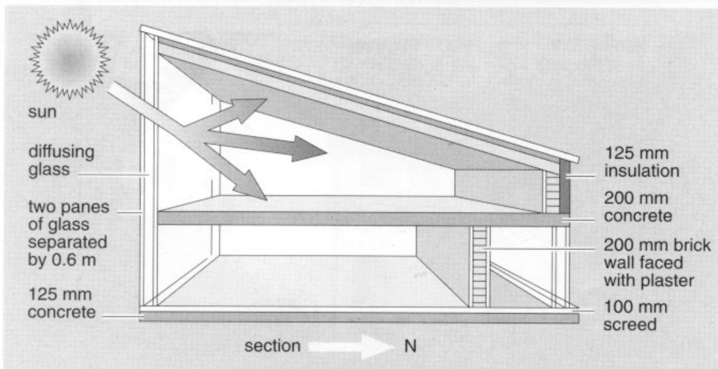
- Standard wall, roof and window insulation – will decrease heat losses and shorten heating season
    - Heating season about 2 months shorter
    - Net heating load reduced to 4000 kWh/yr (by 66%)
    - Passive solar heating contribution is smaller 2000 kWh/yr (18%)
- Further savings possible, but not always clear which approach is better… insulation or insolation?



Passive Solar Thermal

- Insolation – early example, school in Cheshire, England (1961)
- Large-area, south-facing glazing to collect light
- Large thermal mass to store heat energy in winter, reduce cooling load in summer
- Double glazing and thick insulation to minimise heat transfer with outside





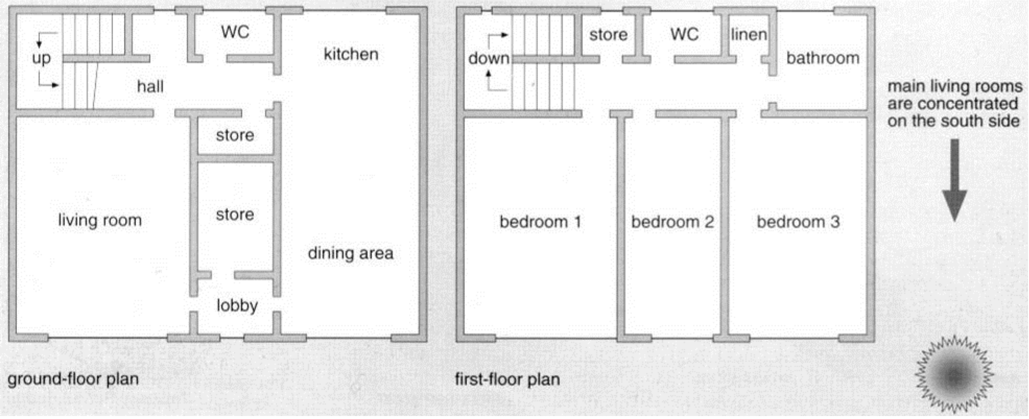
Passive Solar Thermal

- Super Insulation – house in Machynlleth, Wales (1975)
- 450-mm thick wall insulation
- Small-area, quadruple-glazed windows

- Insolation vs. Insulation ⇒ spectrum of good designs depending on
  - Climate, insolation
  - Available materials, cost
  - Needs and preferences of occupants

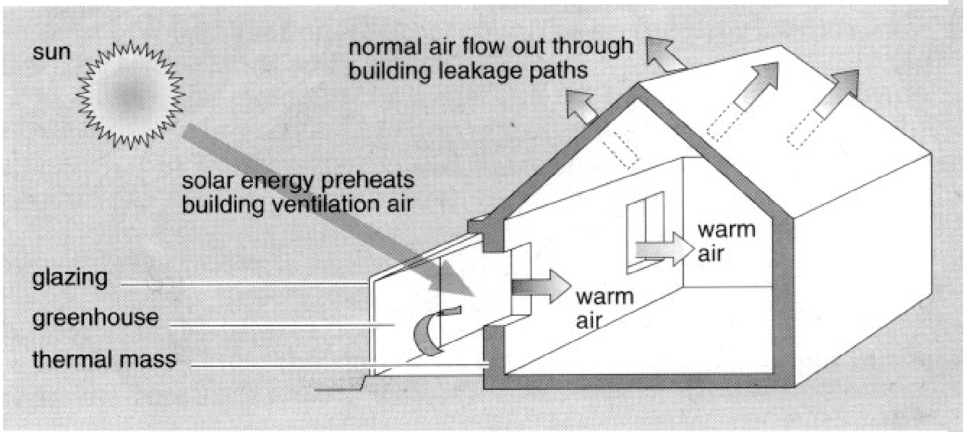
Passive Solar Thermal

- Passive Solar Design Principles
  1. Insulate to minimise overall heating load
  2. Use an efficient, responsive backup heating system
  3. Concentrate glazing and main living (bedrooms, living/dining rooms) areas on the south side, less-used rooms on north side
  4. Avoid overshadowing by other buildings, esp. in mid winter.
  5. Use thermally massive construction to store heat overnight and minimise summer cooling load.



Passive Solar Thermal

- Conservatories, greenhouses, atria – can be used to add passive solar features to an existing house
  - 800 kWh/yr of heating energy could be saved
  - Expensive feature (per energy savings), but liveable space
  - If otherwise heated, however, passive solar gains will be negated!!!

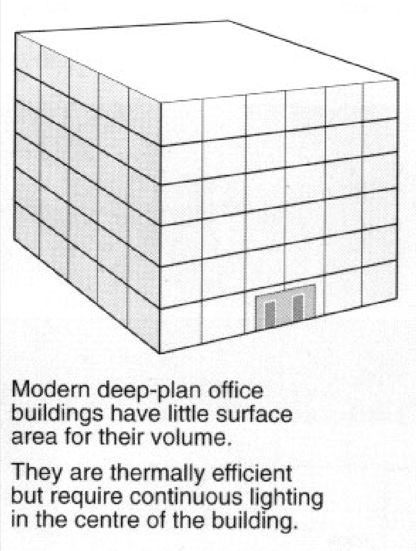


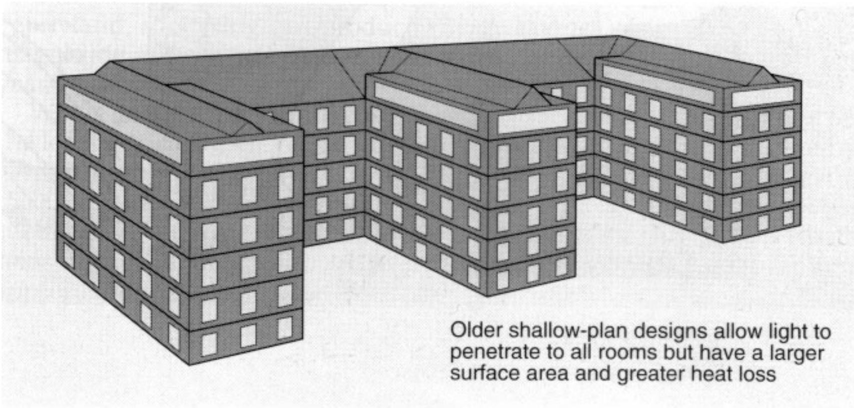
Daylighting

- Lighting: ~2% of domestic energy use
- Office buildings often don’t take advantage of natural lighting
- Daylighting: combines energy conservation and passive lighting design (c.f. solar thermal)
  - Shallow-plan design: light can reach all rooms
  - Light wells and roof lights bring light to centrally located windows
  - Tall windows allow light to reach deep into rooms
  - Light coloured surfaces: distribute light, reduce glare
  - Efficient task lighting rather than whole-building lighting conserves energy
  - Switch off artificial light sources when not needed

Daylighting

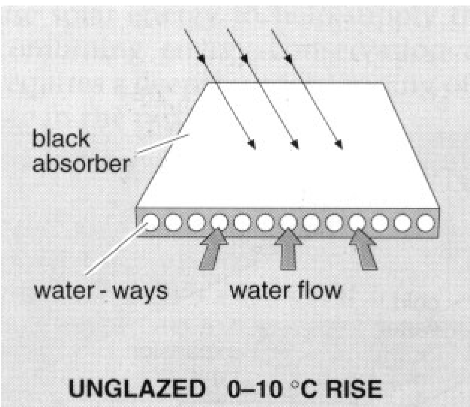
Daylighting and passive solar thermal design have an inherent trade-off…





Active Solar Heating

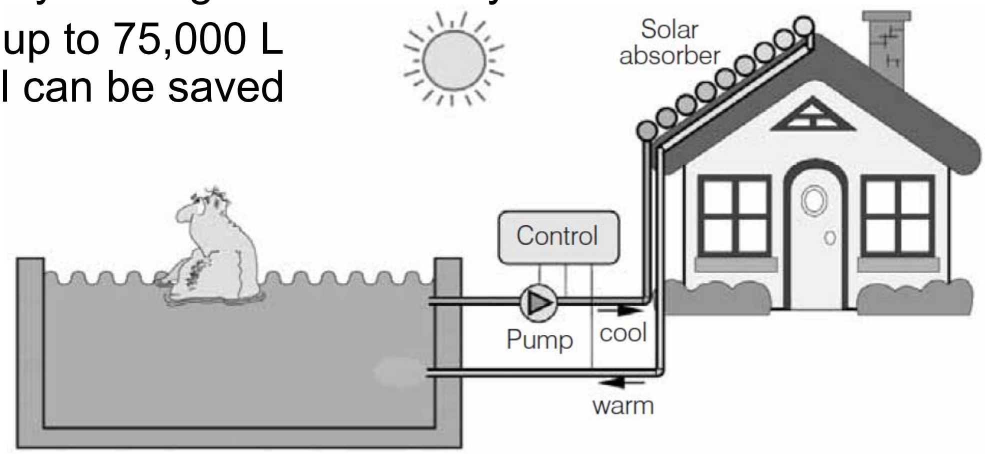
- Use of discrete *solar collector* designed to gather and store solar radiation



- Unglazed – e.g. swimming pool water heaters
  - heating requirements are only a few degrees, so losses are unimportant

Active Solar Heating

- Water flowing through blackened pipes made of polyethylene (PE), polypropylene (PP) or stable ethylene-propylene-diene monomer (EPDM) designed to cover a large area
- Absorber surface ~ 50 – 80% of the pool surface
- For water T = 23°C the heat demand is 150 to 450 kWh/m^2
- Supplementary heating can be usually omitted
- For 2000m^2 up to 75,000 L of heating oil can be saved per season

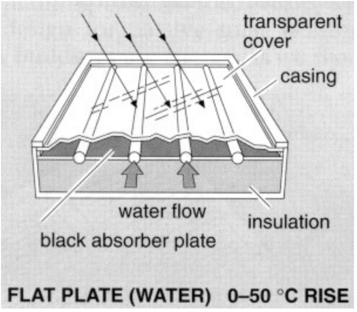


Active Solar Heating

Abb. 1: Unverglaster Kollektor im Freibad in Berlin-Pankow Source: DGS

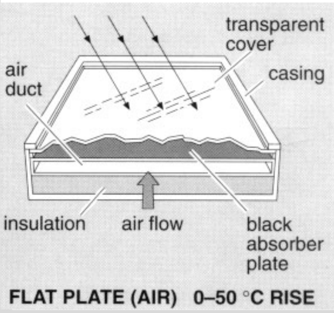
Active Solar Heating

- Glazed flat plate (water) – SHW heating



- black absorber plate only reflects ~10% of incident light and conducts heat readily
- selective surfaces (high absorptivity in visible and low emissivity in infrared) reduce heat loss

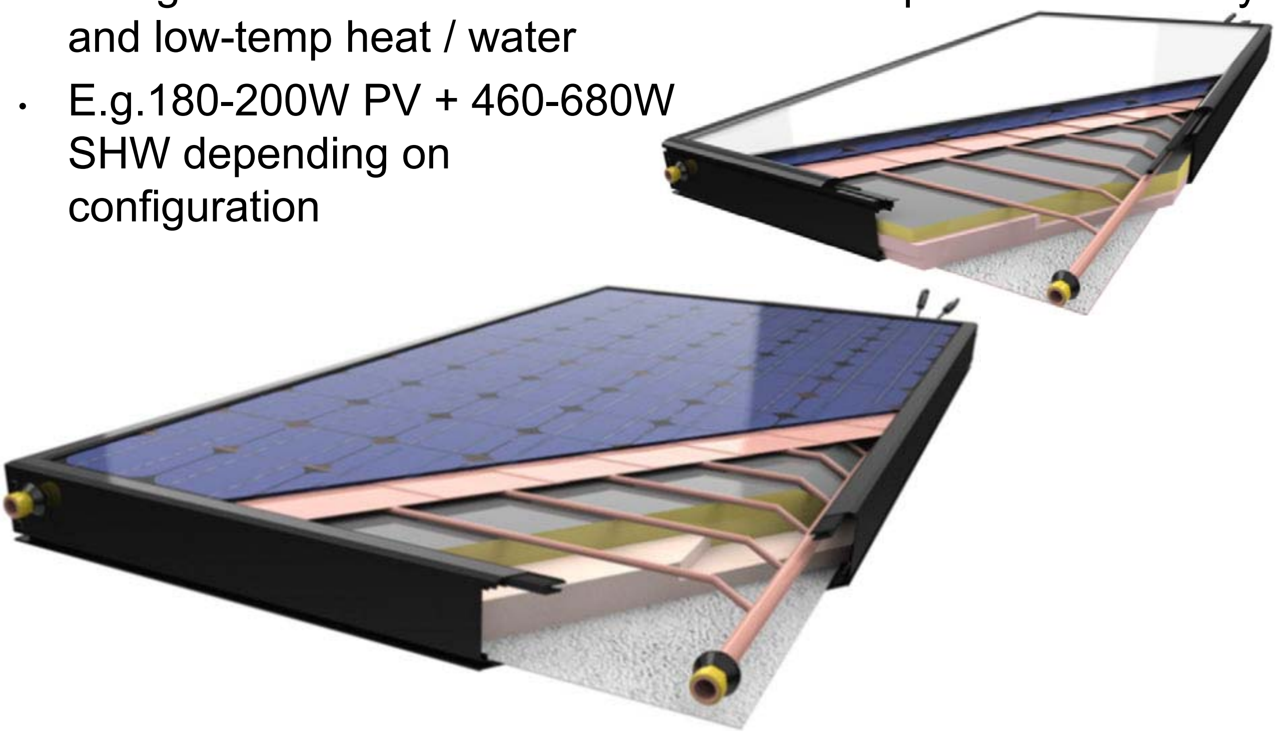
- Glazed flat plate (air) – used for space heating



- less common than SHW collectors
- N.B. Designs available that combine with PV to produce electricity and low-temp heat / water

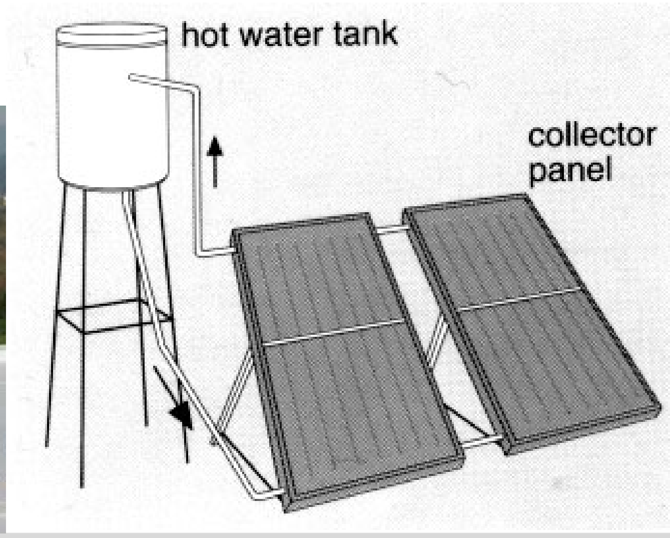
Active Solar Heating

- Designs available that combine with PV to produce electricity and low-temp heat / water
- E.g.180-200W PV + 460-680W SHW depending on configuration



Active Solar Heating

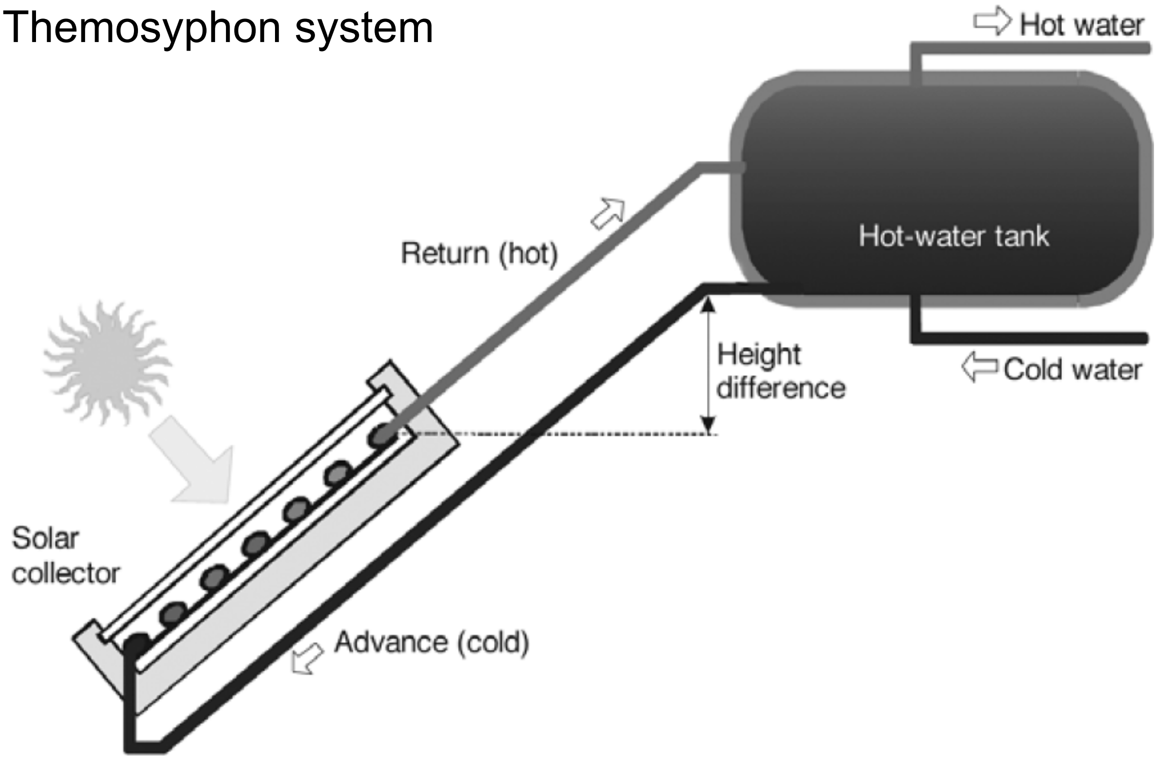
- Themosyphon effect – Hot water is less dense than cold water. If a storage tank is higher than a collector, water will circulate naturally
- Otherwise, e.g. in the case of swimming pool heaters ⇒ a pump is needed



Active Solar Heating

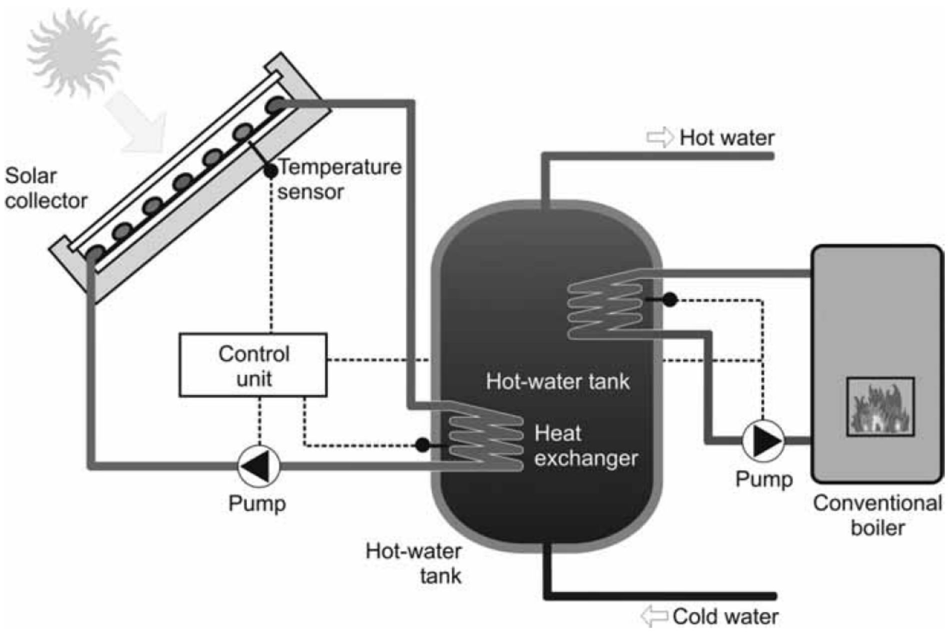
Active Solar Heating

- Themosyphon system



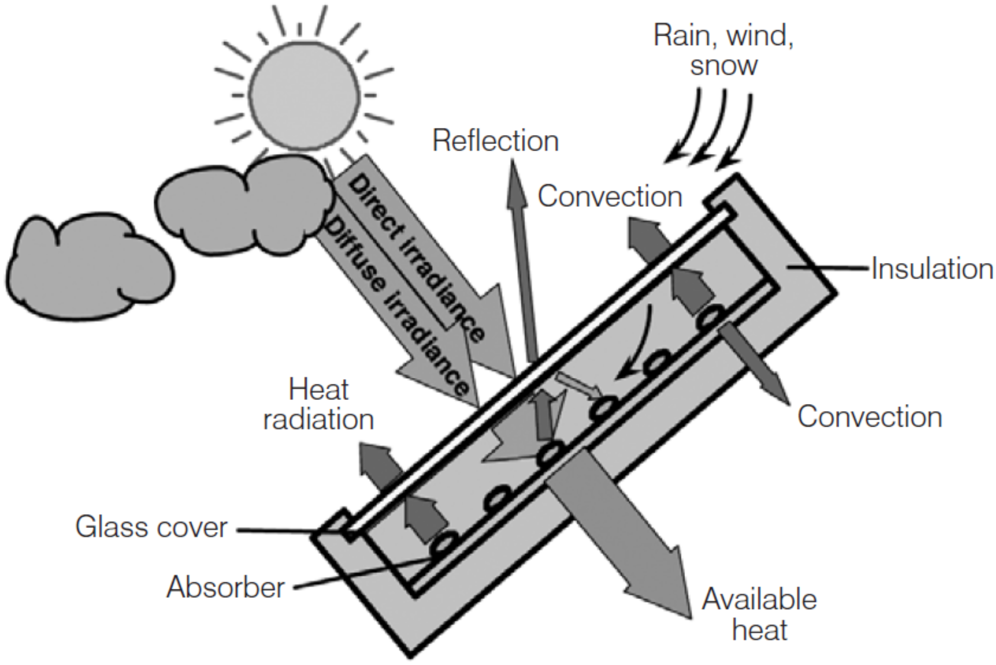
Active Solar Heating

- Forced circulation - N.B. no longer purely thermal system given electricity requirements of pump



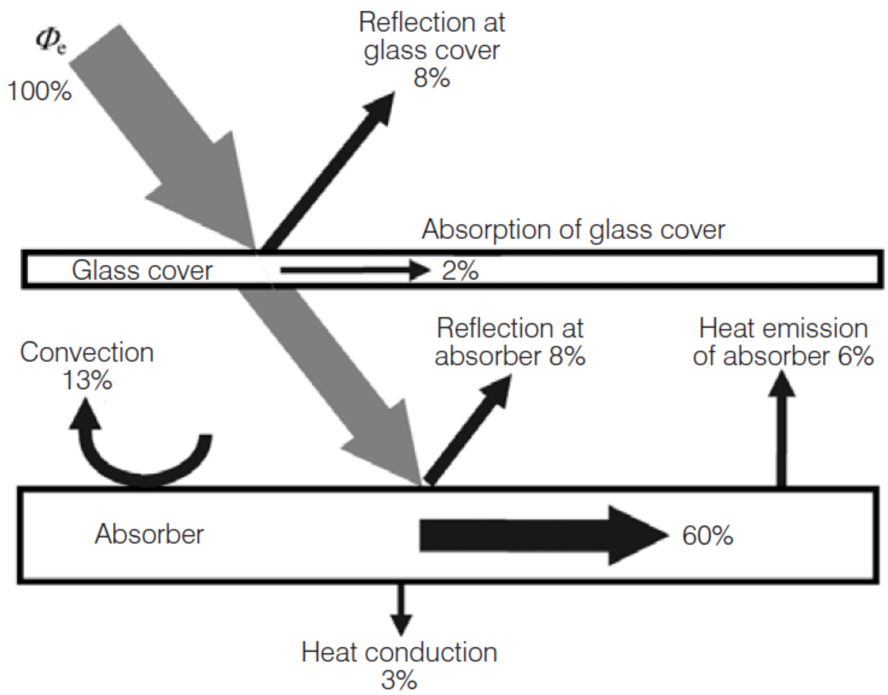
Active Solar Heating

- Thermal processes in a solar thermal flat plate collector



Active Solar Heating

- Energy conversion and possible losses in a solar thermal flat plate collector



Active Solar Heating

- Optical properties of materials:

Table 3.5 *Absorption, Transmission and Reflection Factors for IR Glass In_2O_3 and ZnO_2 Compared with Ordinary Window Glass*

	Visible			Infrared		
Material	$\alpha = \varepsilon$	τ	ρ	$\alpha = \varepsilon$	τ	ρ
Window glass	0.02	0.97	0.01	0.94	0	0.06
In_2O_3	0.10	0.85	0.05	0.15	0	0.85
ZnO_2	0.20	0.79	0.01	0.16	0	0.84

Source: Kleemann and Meliß, 1993

Active Solar Heating

- Majority of solar spectrum is in range λ < 2 µm $\therefore$ absorber needs to have very high absorptance in this range
- Sun heats up absorber to ~350 K $\Rightarrow$ maximum of the corresponding emittance spectrum is higher than >2 µm
- Since absorptance α is identical to emittance ε (according to Kirchhoff's law of emission of radiation) $\Rightarrow$ absorptance should be as low as possible for λ > 2 µm so that heated absorber emits only a little heat radiation to the environment

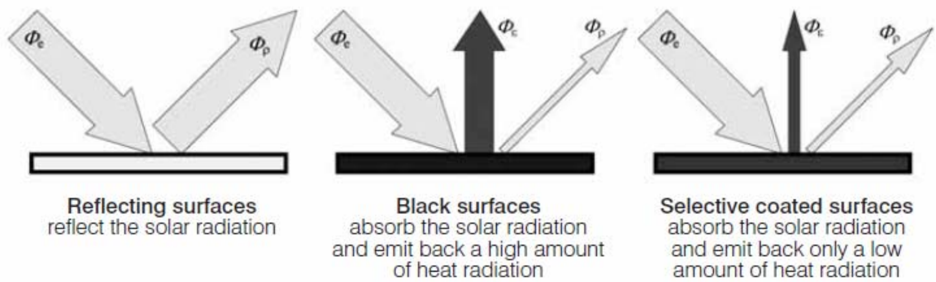


Figure 3.10 *Losses at Absorber Surfaces with Different Types of Coating*

Active Solar Heating

Table 3.6 *Absorptance α, Transmittance τ and Reflectance ρ for Different Absorber Materials*

	Visible			Infrared		
Material	α = ε	τ	ρ	α = ε	τ	ρ
Non-selective absorber	0.97	0	0.03	0.97	0	0.03
Black chrome	0.87	0	0.13	0.09	0	0.91
Black nickel	0.88	0	0.12	0.07	0	0.93
TiNOX (TiN + TiO + TiO_2)	0.95	0	0.05	0.05	0	0.95

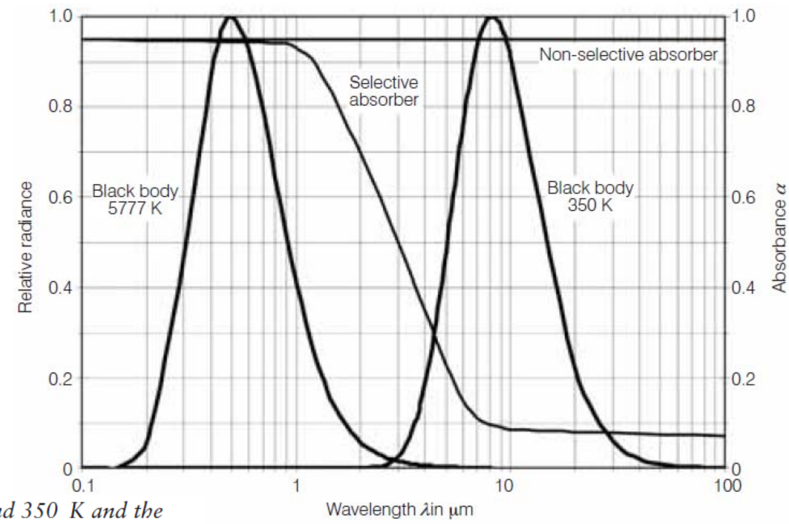
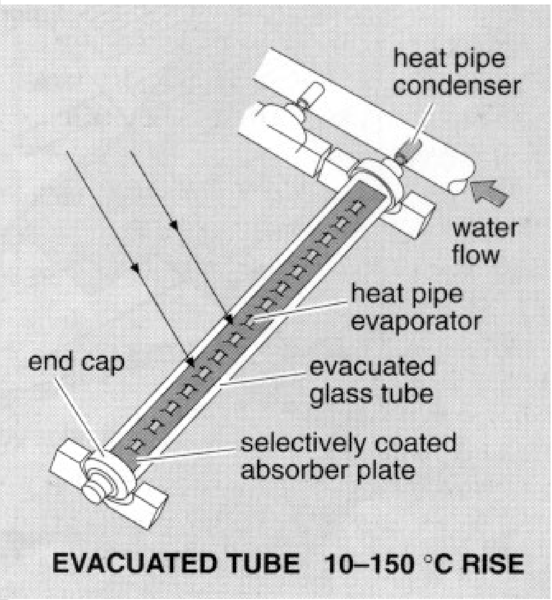


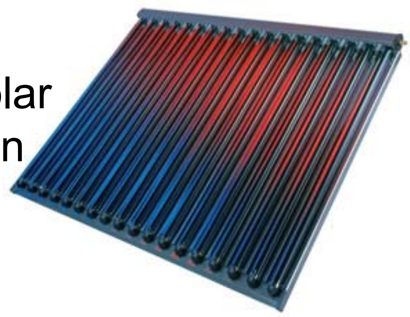
Figure 3.11 *Spectra of Black Bodies at 5777 K and 350 K and the Absorptance of Selective and Non-selective Absorbers*

Active Solar Heating

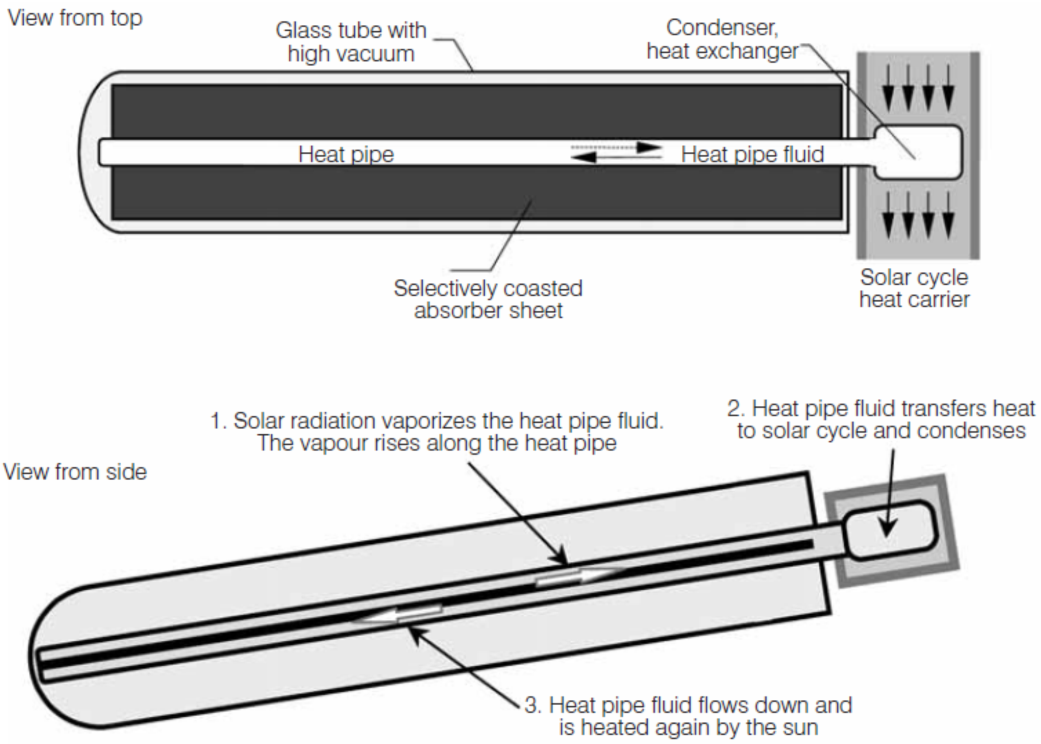
- Evacuated Tube – vacuum between absorber strips and glass minimises conduction and convection losses



- heat pipe uses evaporation / vapour transport / condensation to give high lateral conduction of heat
- vapour condenses inside header, heating water in header pipe
- E.g. Ritter Solar near Tübingen



Active Solar Heating



Active Solar Heating

- Efficiency calculations: collector converts solar irradiance E that is transmitted through front glass cover with transmittance τ onto the collector surface A_C, directly to heat
- Power output of solar collector $\dot{Q}_{out}$ is reduced by losses due to reflection $\dot{Q}_{ref}$, convection $\dot{Q}_{conv}$, and heat radiation $\dot{Q}_{rad}$

$$\dot{Q}_{out} = \tau \cdot E \cdot A_C - \dot{Q}_{ref} - \dot{Q}_{conv} - \dot{Q}_{rad}$$

- Note, convection losses $\dot{Q}_{conv}$ and heat radiation losses $\dot{Q}_{rad}$ can be combined as $\dot{Q}_{RC}$
- Heat radiation losses $\dot{Q}_{rad}$ of selective absorbers much less than that of non-selective absorbers
- Vacuum between the front cover and absorber can reduce convection losses $\dot{Q}_{conv}$ significantly
- Reflection losses $\dot{Q}_{ref}$ estimated using the reflectance ρ from the irradiance passing glass front cover

Active Solar Heating

- So, now substituting

$$\dot{Q}_{RC} = \dot{Q}_{conv} + \dot{Q}_{rad} \quad \text{and} \quad \dot{Q}_{ref} = \tau \cdot \rho \cdot E \cdot A_C$$

the collector power output becomes:

$$\dot{Q}_{out} = \tau \cdot E \cdot A_C \cdot (1 - \rho) - \dot{Q}_{RC}$$

- Simplified further by defining the absorptance $\alpha = 1 - \rho$ and optical efficiency $\eta_0 = \alpha \cdot \tau$ (collector efficiency without losses due to convection or heat radiation ⇒ strictly only case if $T_{abs} = T_{amb}$)

$$\dot{Q}_{out} = \tau \cdot \alpha \cdot E \cdot A_C - \dot{Q}_{RC} = \eta_0 \cdot E \cdot A_C - \dot{Q}_{RC}$$

Active Solar Heating

- Thermal losses $\dot{Q}_{RC}$ depend on collector temperature ϑ_C and ambient temperature ϑ_A and on loss coefficients a_1 and a_2:

$$\dot{Q}_{RC} = a_1 \cdot A_C \cdot (\vartheta_C - \vartheta_A) + a_2 \cdot A_C \cdot (\vartheta_C - \vartheta_A)^2 \approx a \cdot A_C \cdot (\vartheta_C - \vartheta_A)$$

- Loss coefficients measured in practice ⇒ much lower for evacuated tube collectors than flat-plate collectors ⇒ higher efficiency at low ambient temperatures or low irradiances

Table 3.7 *Optical Efficiencies η_0 and Loss Coefficients a_1 and a_2 of Real Collectors with the Collector Absorber Area A_C as Reference*

Name	*Type*	η_0	a_1 in *W/(m² K)*	a_2 in *W/(m² K²)*	A_C in *m²*
Paradigma Solar 500	Flat-plate	0.805	3.79	0.009	4.7
Solahart M	Flat-plate	0.746	4.16	0.0084	1.815
Solahart OYSTER Ko	Flat-plate	0.803	2.49	0.0230	1.703
Sonnenkraft SK 500	Flat-plate	0.800	3.02	0.0013	2.215
Wagner Euro C18	Flat-plate	0.789	3.69	0.007	2.305
Microtherm Sydney SK-6	Evacuated tube	0.735	0.65	0.0021	0.984
Thermolux 2000-6R	Evacuated tube	0.801	1.13	0.008	1.05
Ritter CPC 12 OEM	Evacuated tube	0.617	1.04	0.0013	2.01
Sunda SEIDO 5-16	Evacuated tube	0.736	1.78	0.0130	2.592

Active Solar Heating

- Finally, collector efficiency η_C calculated using power output of solar collector $\dot{Q}_{out}$ and solar irradiance E that reaches the collector surface A_C
- Using

$$\eta_C = \frac{\dot{Q}_{out}}{E \cdot A_C} = \eta_0 - \frac{\dot{Q}_{RC}}{E \cdot A_C}$$

  the collector efficiency becomes

$$\eta_C = \eta_0 - \frac{a_1 \cdot (\vartheta_C - \vartheta_A) + a_2 \cdot (\vartheta_C - \vartheta_A)^2}{E} \approx \eta_0 - \frac{a \cdot (\vartheta_C - \vartheta_A)}{E}$$

Active Solar Heating

- Typical collector efficiencies of a flat-plate collector shown

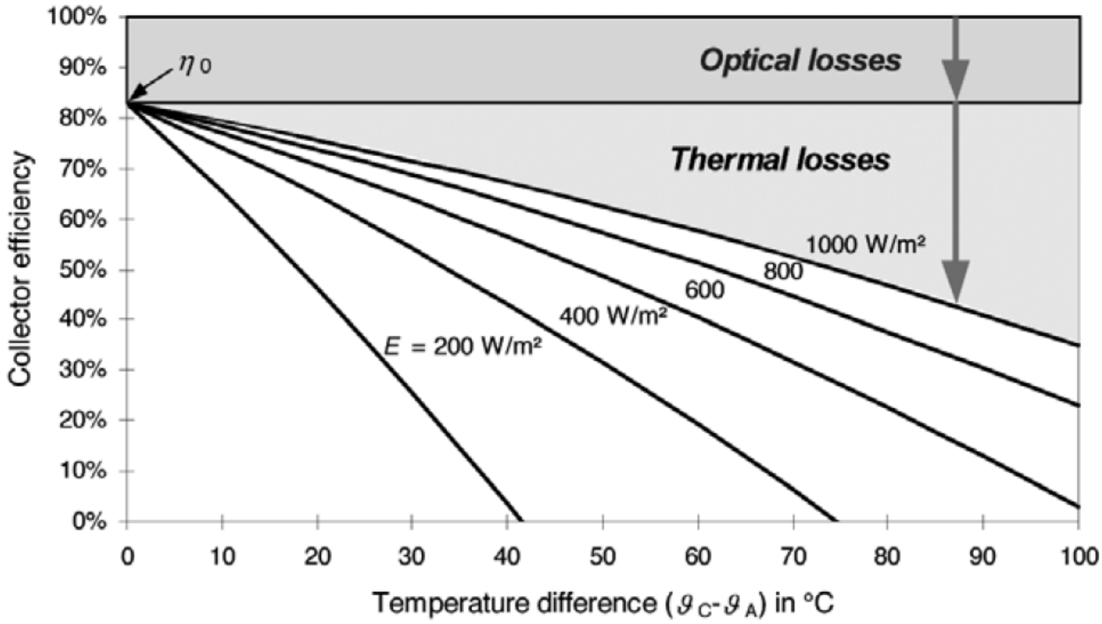


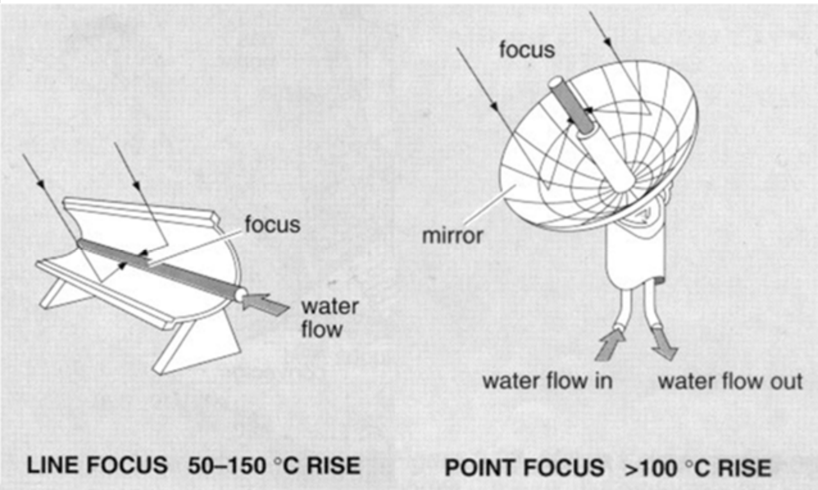
Figure 3.14 *Collector Efficiencies* η_C *at Different Irradiances* E *and Temperature Differences* $\Delta\vartheta$

Active Solar Heating

- Thermal losses increase with rising temperature differences between the collector and ambient air
- At low solar irradiances the efficiency decreases faster, e.g. at E = 200 W/m^2 the output of collector is zero at a temperature difference of about 40°C
- *Stagnation temperature* ≡ temperature at which collector power output and collector efficiency are equal to zero
- At E = 400 W/m^2, stagnation temperature of collector is ~75°C above ambient temperature, but can rise to >200°C at E = 1000 W/m^2
- Therefore, collector materials must be carefully chosen to resist relatively high temperatures over a long period of time
- N.B. calculation of collector efficiency above only valid if there is no wind; otherwise convective thermal losses will increase

Active Solar Heating

- Line/Point focus concentrator – parabolic trough or dish concentrates sunlight on the absorber
  - higher temperatures
  - commonly used with secondary turbine *to generate electricity*



- must actively track the sun – in 1D for line concentrators and in 2D for point concentrators

Active Solar Heating

- Daily, point-of-use SHW remains the dominant application, although other approaches have been tried
- E.g. Active solar thermal space heating in England:
    - large collector areas needed to meet winter demand – much of the heat supply is wasted in the summer
    - Concluded that the capital investment should be put into better insulation first

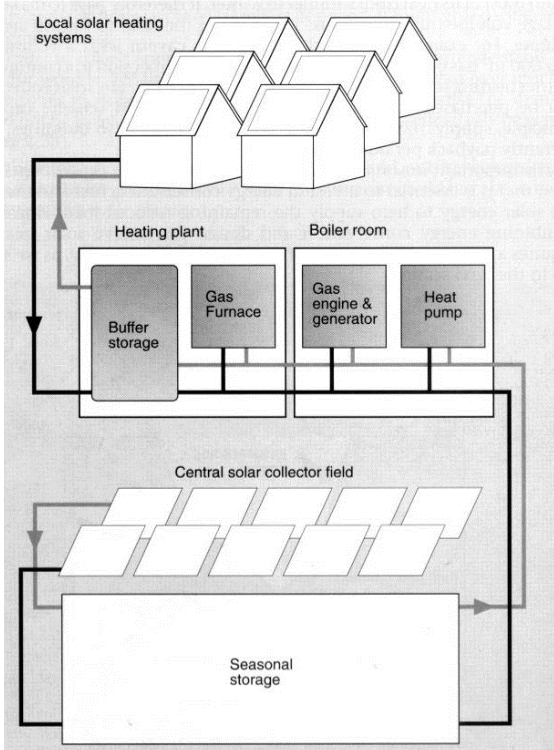
Active Solar Heating

- Inter-seasonal district solar thermal hot water $\Rightarrow$ 1025 m^2 of collectors heats water to 80°C during summer, which is stored underground in a large tank for use in winter
    - Inter-seasonal storage for point-of-use systems would require ~4m thick insulation!
    - Inter-seasonal storage is more reasonable for large storage, where there is a smaller surface area to volume ratio

District SHW project serving 92 homes in Herlev (DK)

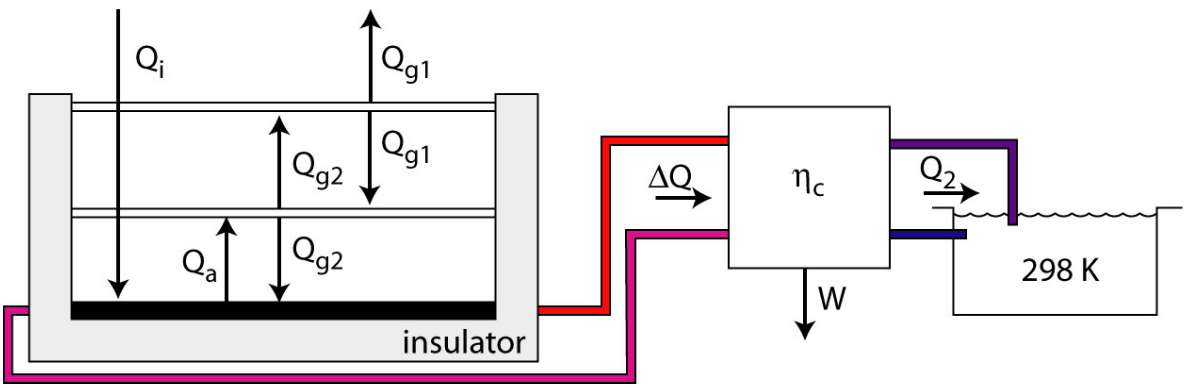
Active Solar Heating

- Summer – hot water provided by individual daily point-of-use systems on each house
- Winter – shortfall at end of winter is boosted by additional heaters
- Losses are large and energy payback times (EPT) are long ~34 years for this prototype system (too long for any investor)



Solar Thermal Engines

- Solar thermal energy ⇒ electricity using a secondary steam/vapour cycle can be done if the temperature is high enough
  - extra glazings – temperature gains are relatively small
  - Large numbers of glazings are not practical



Solar Thermal Engines

- Remember, a body radiates electromagnetic energy depending on its temperature

$$\dot{Q} = \varepsilon \cdot \sigma \cdot T_g^4$$

$\sigma = 5.67 \cdot 10^{-8}$ W/m^2.K^4 (Stefan Boltzmann constant)

ε is emissivity ($0 < \varepsilon < 1$)

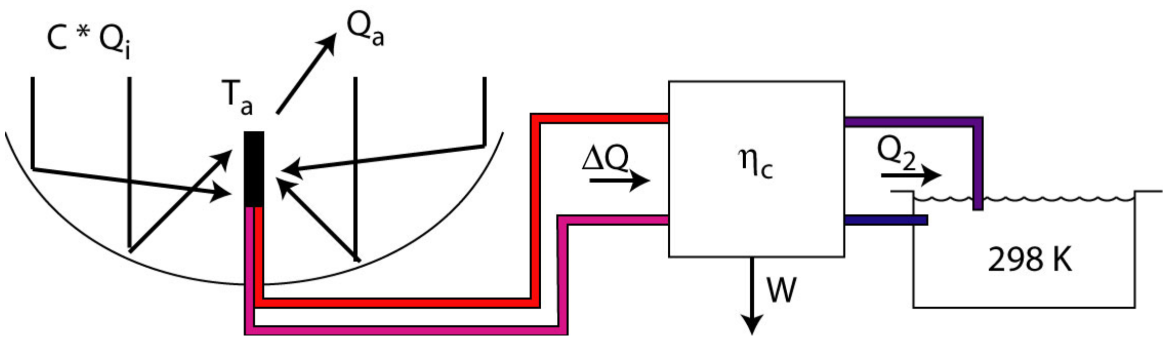
- Rearranging to find the absorber temperature, we can then also determine the Carnot efficiency (often assume $\varepsilon = 1$):

$$T_a = \sqrt[4]{\left(Q_i - \Delta Q\right)/\sigma}$$

$$\eta_c = 1 - T_{sink}/T_a = 1 - 298/T_a$$

Solar Thermal Engines

- Solar thermal energy $\Rightarrow$ electricity using a secondary steam/vapour cycle can be done if the temperature is high enough
  - **concentration C times – temperature gains are relatively large**
  - **C ~ 1000 in practical systems**



$$T_a = \sqrt[4]{\left(C \cdot Q_i - \Delta Q\right)/\sigma}$$

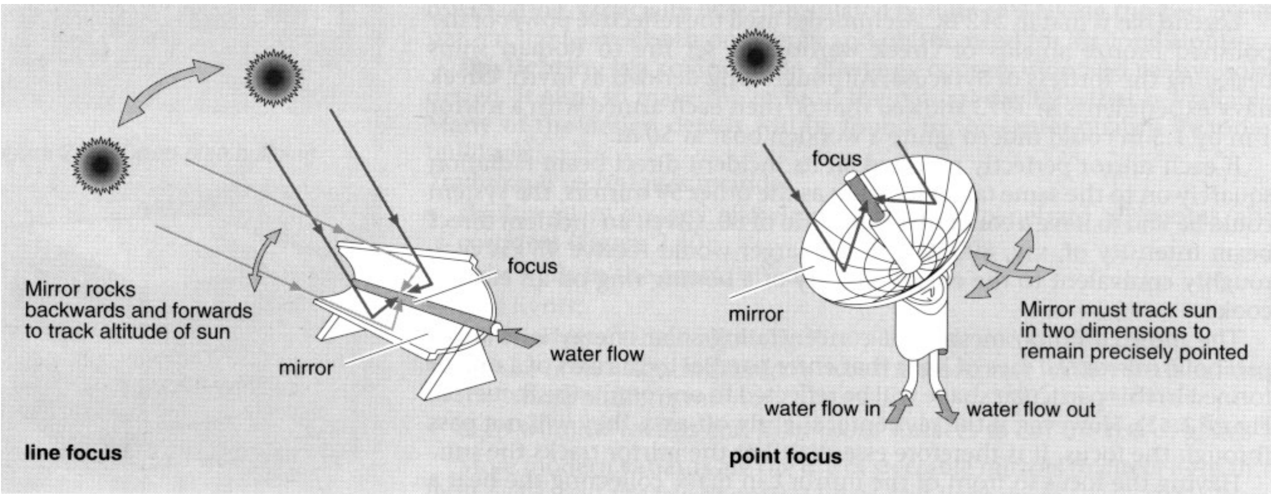
$$\eta_c = 1 - T_{sink}/T_a = 1 - 298/T_a$$

Solar Thermal Engines

Ideal System	*Carnot Engine Efficiency (to 298 K)*
Non-glazed, flat plate	**18%**
Single-glazed, flat plate	**31%**
Double-glazed, flat plate	**38%**
N-glazed, flat plate	$1-298/T_a$
10X linear concentrator	**53%**
100X point concentrator	**73%**
N X point concentrator	$1-298/T_a$

Solar Thermal Engines

- Concentrator solar thermal systems employ (usually) mirrors to focus light on the absorber
  - only direct component of sunlight can be focused
  - mirrors must be made to "track" the sun's position

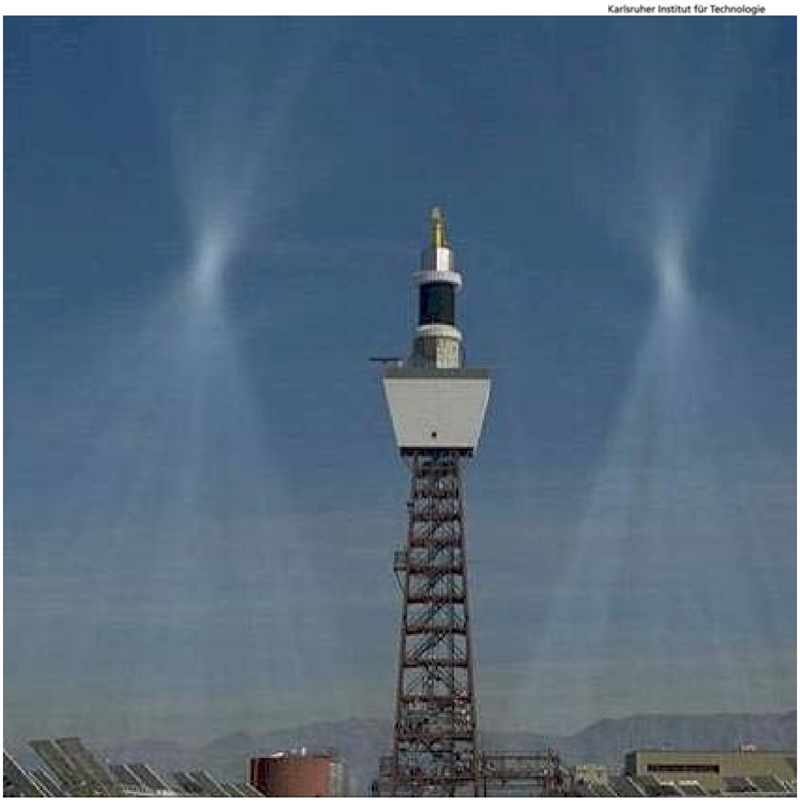


Up to about 50X, 200–400°C
Up to about 1000X, 1500°C

Solar Thermal Engines

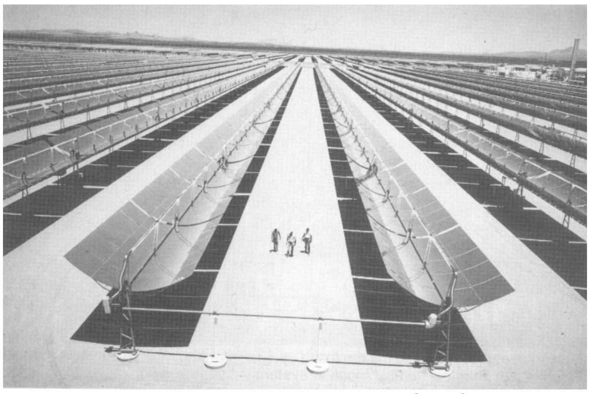
- Power Towers – large no. of mirrors focus light onto a central receiver, e.g. 10 MW “Solar One” in California (early-mid ‘80s)
  - Tracking heliostats reflect light onto the central absorber
  - Molten salt (high thermal capacity and thermal conductivity) carries heat away from the absorber to a boiler, where steam at >500°C is generated
  - The steam turns a turbine

Solar Thermal Engines

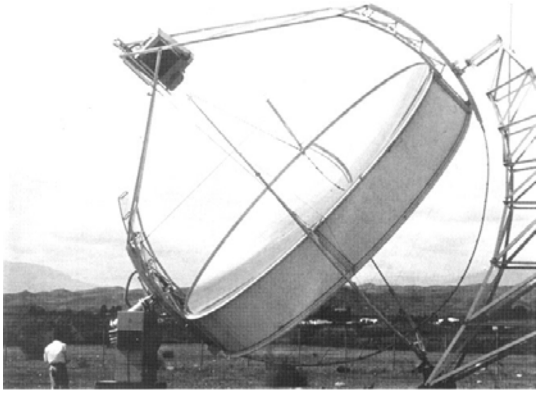


Solar Thermal Engines

- Parabolic Trough and Dish Systems – tracking mirrors fixed to the absorber
  - Large scale systems can be cost competitive with conventional energy sources (estimated at US$0.10 / kWh)
  - However, they require large tracts of land – competing use?



Luz solar collector southern California



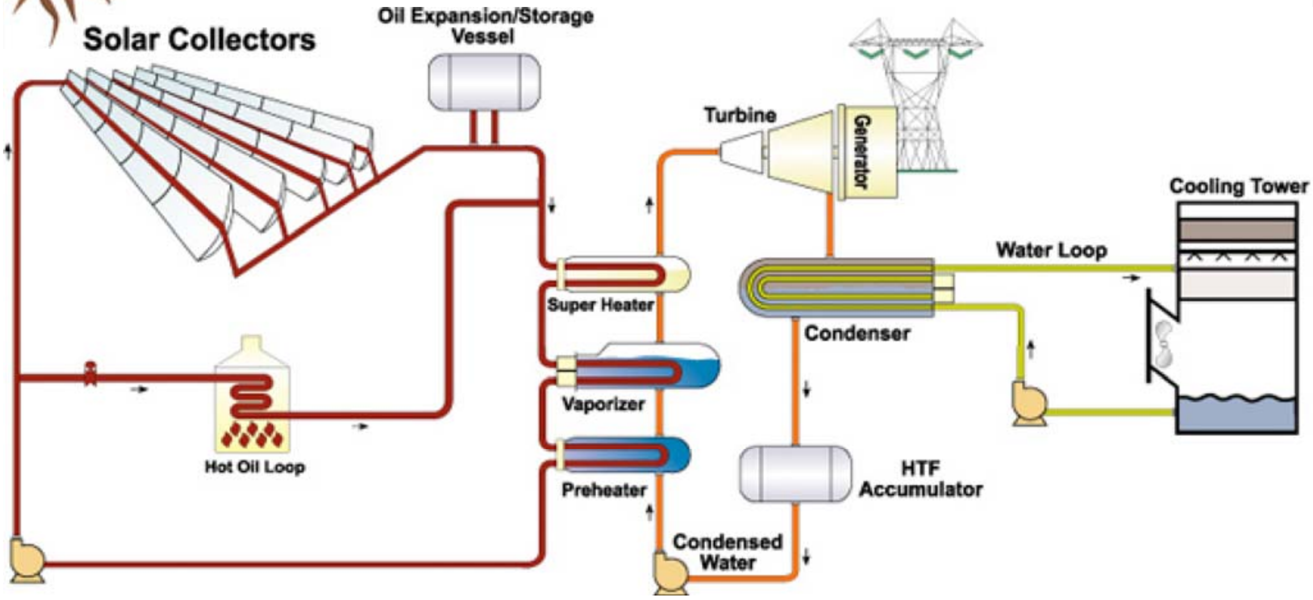
Parabolic dish

Solar Thermal Engines

- Solar Energy Generating Systems (SEGS) series of plants in California ⇒ world's first *commercial* parabolic trough plants (commissioned 1984 – 1990) ⇒ still running today with a capacity of 354MW
- 2 million m^2 parabolic trough collectors
- Low materials usage: 18kg steel + 11kg glass per m^2
- 30-50 % lower land usage as dish / tower systems
- Lowest cost solar power 10-15 €ct/kWh
- Good modularity
- Parabolic reflector and absorber tube production in Germany

Solar Thermal Engines

- Overall thermal efficiency: < 50%
- Efficiency of electricity production in steam turbine: < 45%
- Solar electricity generating efficiency SEGS VIII: 14%



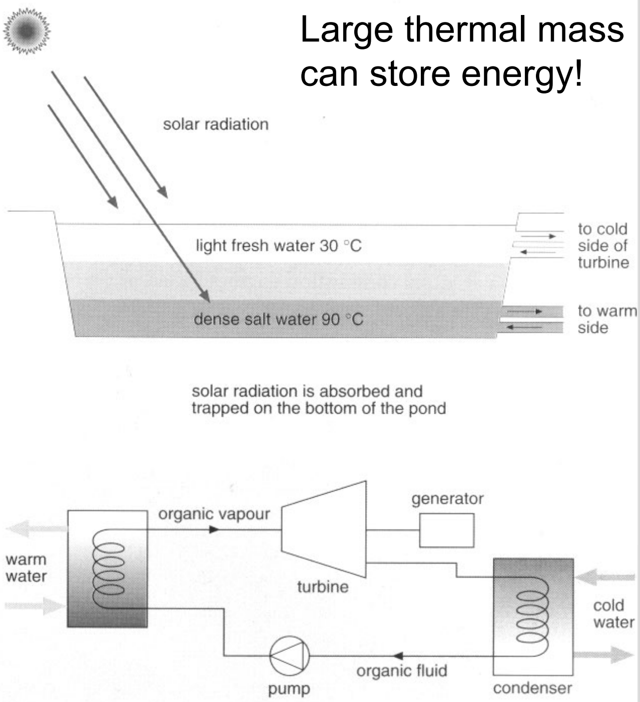
Solar Thermal Engines

- Ivanpah Solar Electric Generating System in California now largest (completed 2014, 392MW)
- Heliostat design focuses solar energy onto boilers located in three centralised solar power towers
- Cost $2.2 billion with Google putting in $168 million
- Project was scaled back from original 440MW design in 2010 to avoid building on the habitat of the desert tortoise

Solar Thermal Engines

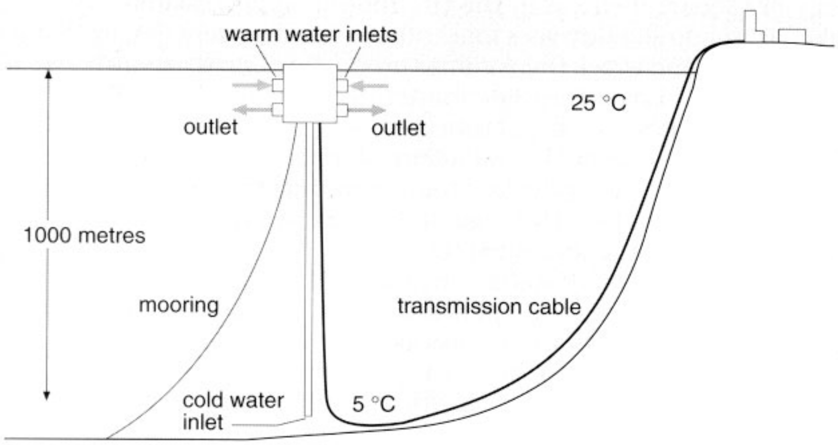
- Solar Ponds – use salt gradient in a large pond to collect solar thermal energy
  - dense salty water at the bottom of the pond absorbs solar radiation with T ~ 90°C
  - salty water is more dense, stays at the bottom
  - ΔT between top and bottom layers can drive a vapor cycle engine
  - requires large areas of land and lots of fresh water

Large thermal mass can store energy!



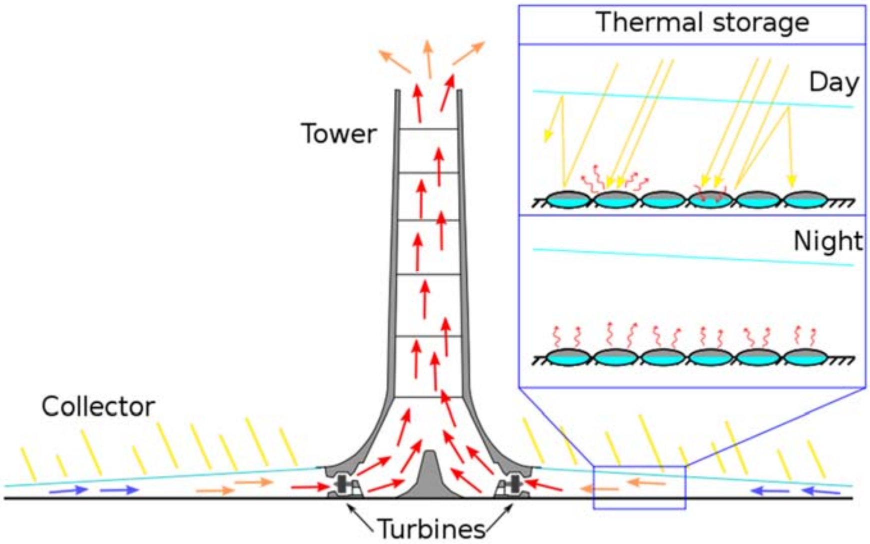
Solar Thermal Engines

- Ocean thermal energy conversion (OTEC) – conceptually similar to solar ponds, except they use the natural temperature gradient of heat with depth in the ocean
  - seawater is about 20°C colder at 1000 m depth
  - efficiency is low, but the volume of water is enormous
  - engineering challenges are large:
    100 MW would require 500 m^3 per second



Solar Thermal Engines

- Solar updraft tower (a.k.a. solar chimney)
- Sunshine heats the air beneath a very wide greenhouse-like roofed collector structure surrounding the central base of a very tall chimney tower ⇒ resulting convection causes a hot air updraft in the tower ⇒ airflow drives wind turbines placed in the chimney to produce electricity



Solar Thermal Engines

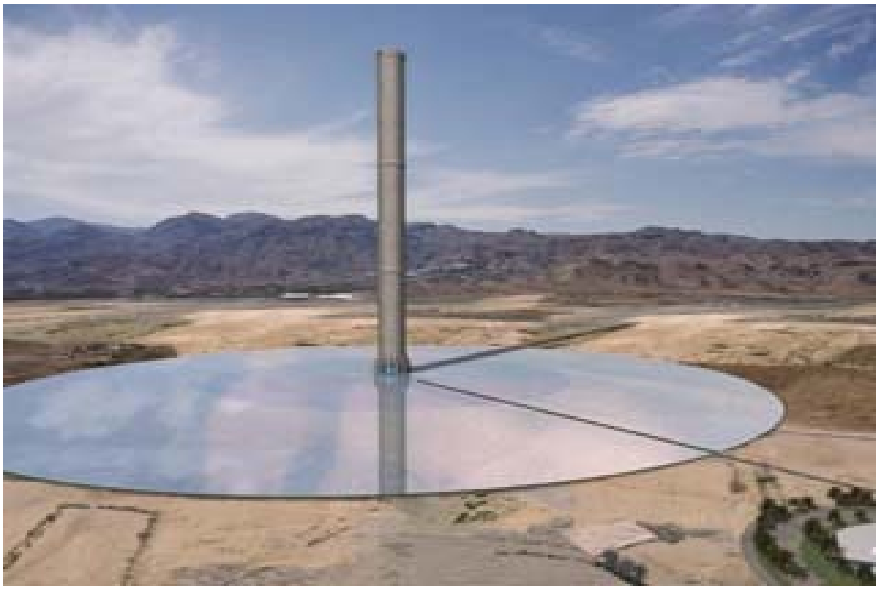
- Until now an experimental plant in Spain with 100kW
- 250m collecter diameter
- 2m chimney diameter
- 200m height
- Wind speeds 9 – 15 m/s
- Low efficiency (0.2 %)
- Low investment costs
- Dismantled in 1988 after chimney collapsed

Abbildung 3
Prototyp für ein Aufwindkraftwerk in Manzanares Spanien

- New designs being proposed with heights up to 1000m…

Solar Thermal Engines

- New designs being proposed with heights up to 1000m…
- In planning with German engineers….? Location Mildura, Australia



Solar Thermal Perspectives

- Domestic active solar water heating
  - If 50% of UK homes were fitted with solar hot water systems, the savings would be 9.6 TWhr/yr (gas), 2.4 TWhr/yr (electrical) and 5.6 million t/yr of CO_2 emission (~1% of UK emissions)
  - SHW systems are significantly cheaper where production volumes (and insolation levels) are higher
  - Good application where summer loads peak (eg. air conditioning)
  - Small environmental impact – uses common materials and covers existing rooftops.
- Active solar space heating
  - Technically feasible on individual homes, but more economical to invest in better insulation or passive solar features
  - Inter-seasonal storage also possible in district applications, but marginally economical (long payback times)

Solar Thermal Perspectives

- Passive solar thermal and daylighting
  - Passive solar heating is highly economical, although most easily applied to new construction
  - Energy conservation is an integral part of passive solar thermal and daylighting design
  - In Denmark, for example, national space heating energy consumption fell by 30% between 1972 and 1985 while total heated floor space rose by 30% over same period
- Solar thermal engines/electricity generation
  - Plenty of *direct* insolation is required for high temperatures and efficient heat-to-electricity conversion
  - Trough (Luz)-type schemes can be cost competitive
  - Environmental impact
    - 80 MW of Luz-type collectors occupies more than 2.5 sq km
    - Solar ponds require more area as conversion efficiencies are lower
    - OTEC systems can bring deep dissolved CO_2 back to the surface, negating any abatement advantages