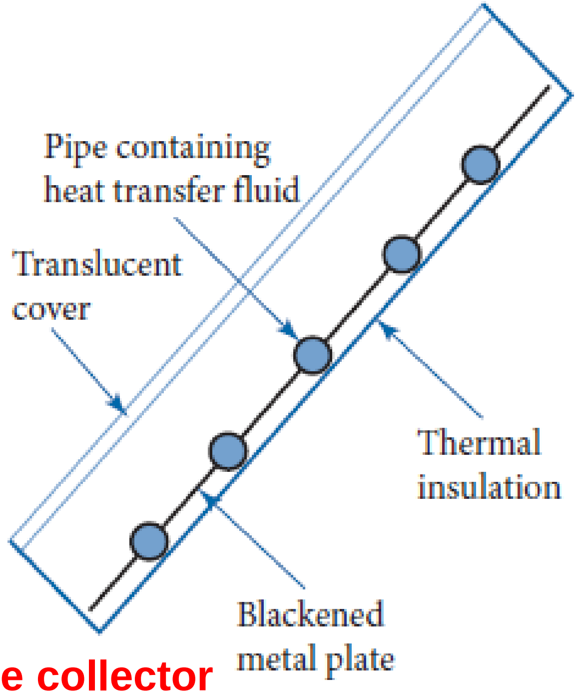
John Andrews & Nick Jelley

Lecture 5:

Solar thermal and geothermal energy

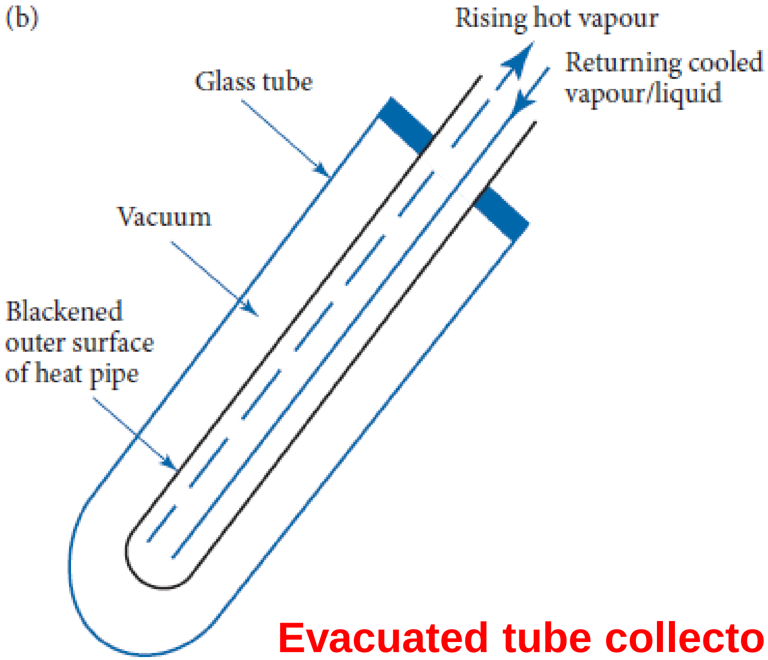
Solar thermal energy

Solar thermal energy = direct conversion of radiation from Sun into heat, via a **solar thermal collector**.



Flat plate collector

Radiation absorbed on blackened surface. Heat transported by fluid (e.g. antifreeze) to insulated thermal tank. Prone to heat loss in cold and windy conditions.



Evacuated tube collector

Radiation absorbed on blackened outer surface of heat pipe (vacuum barrier reduces heat loss). Fluid in heat pipe evaporates and the vapour rises due to buoyancy, Heat is transferred to heat exchanger and condensed fluid returns to heat pipe.

Andrews & Jelley: Energy Science, 3rd edition

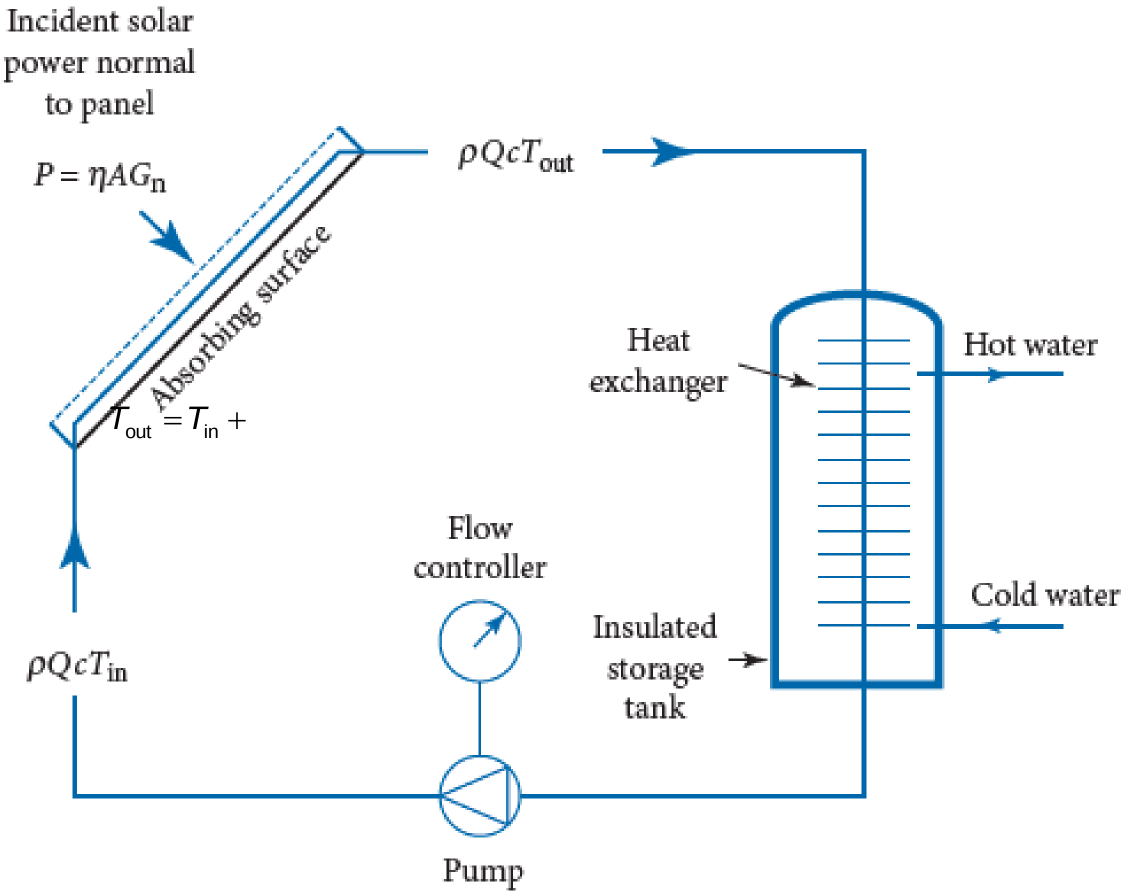
Domestic Solar Thermal Energy System

By energy conservation, power absorbed by collector = rate of heat transfer to fluid, so

$$P_{\mathrm{solar}} = \eta A G_{\mathrm{n}} = \rho Q c T_{\mathrm{out}} - \rho Q c T_{\mathrm{in}}$$

or

$$T_{\mathrm{out}} = T_{\mathrm{in}} + \frac{\eta A G_{\mathrm{n}}}{\rho Q c}$$



In warmer climates, circulation is usually via natural convection without a pump: **thermosyphon** system.

Solar thermal potential

Global capacity around 406 GWth by end of 2014, mostly for domestic use
80% in China, new markets in Asa, Africa, Latin America.

Fig. 5.3 Solar water heaters mounted on rooftops in China.

Other applications:

Solar air thermal collectors (especially in North America, in buildings with existing ducting system)
Evaporation ponds, e.g. for salt
Transpired collectors, for drying food, wood, etc.
Solar cookers, for cooking, drying and pasteurizing milk

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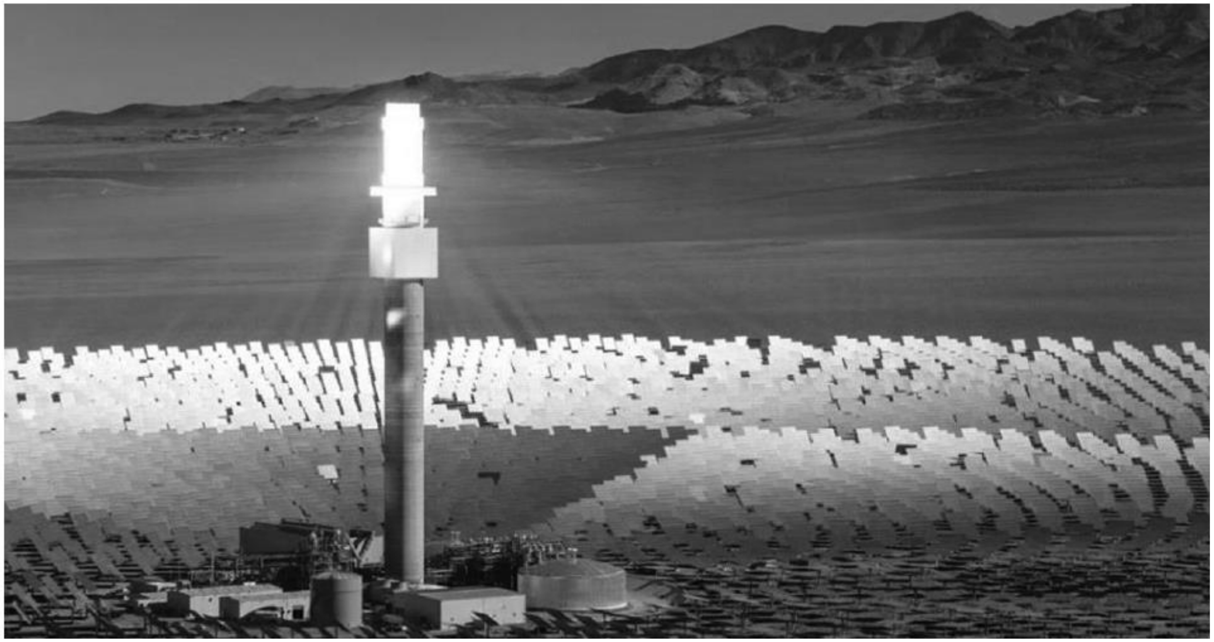
Concentrated solar thermal power (CSP) plants

CSP requires **direct sunlight**, concentrated on small areas by mirrors or lenses. Typically in hot, semi-arid regions between latitudes 15^o-40^o N or S of equator, where 80-90% of solar radiation impinges directly on Earth’s surface, without significant scattering.



Cresecent Dunes 110 MW USA

Flexibility when combined with **thermal storage** a considerable advantage.

Crescent Dunes 110 MW 10 h storage using molten Salt at ~550 ^oC

Typical efficiency for a tower plant ~18%

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Concentrating optical systems

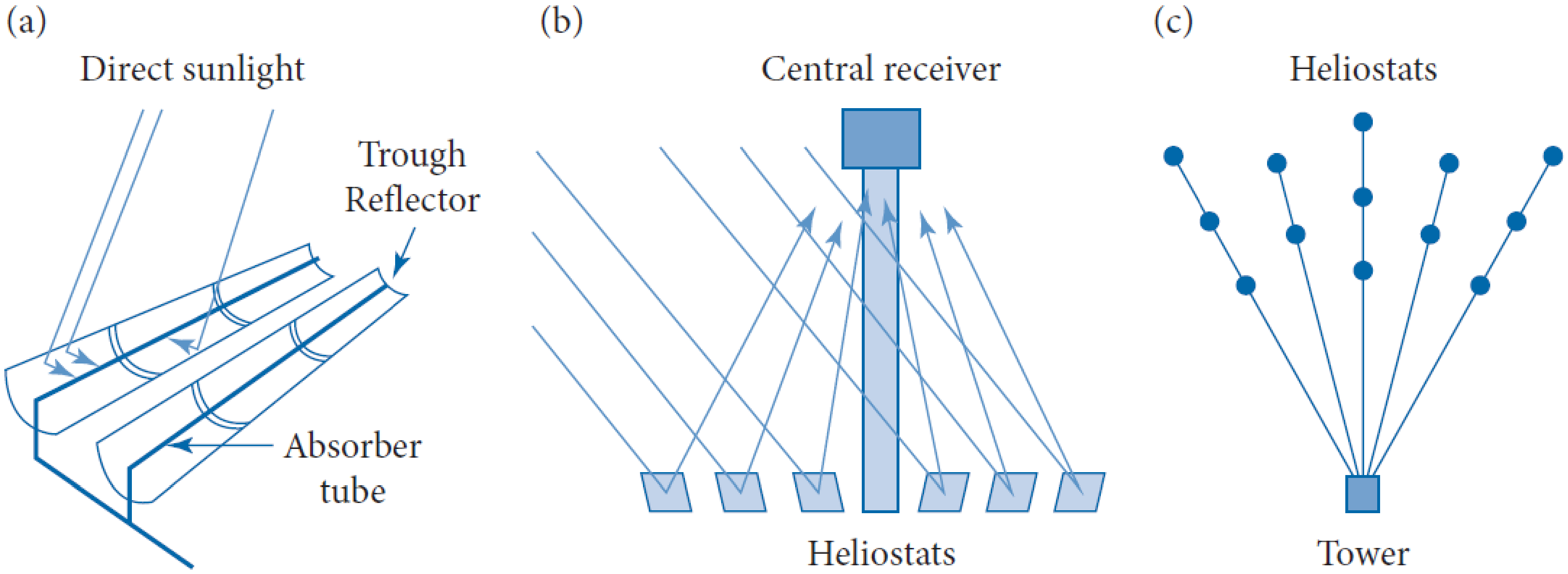
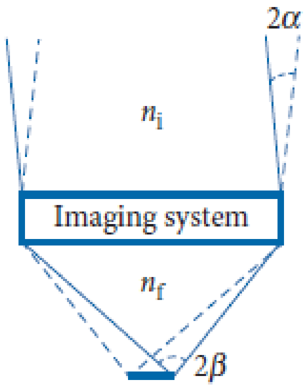


Fig. 5.7 Parabolic trough and solar tower/central receiver plants and heliostat layout (CSP2015).



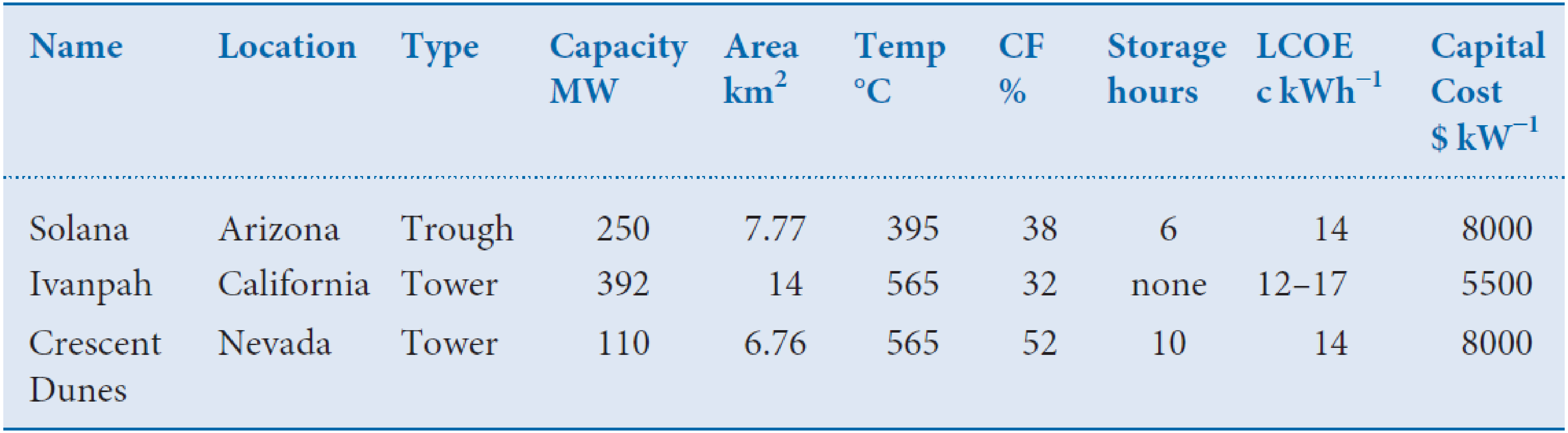
Light is captured within a solid angle *α* (entrance aperture) and transmitted into a larger solid angle *β* (exit aperture).

$$\text{Concentration Factor} = \frac{\text{area of entrance aperture}}{\text{area of exit aperture}} = \frac{n_f \sin^2 \beta}{n_i \sin^2 \alpha}$$

where n_f and n_i = refractive indices

Economics of CSP

Table 5.1 Costs and parameters for some recent US CSP plants (2015)



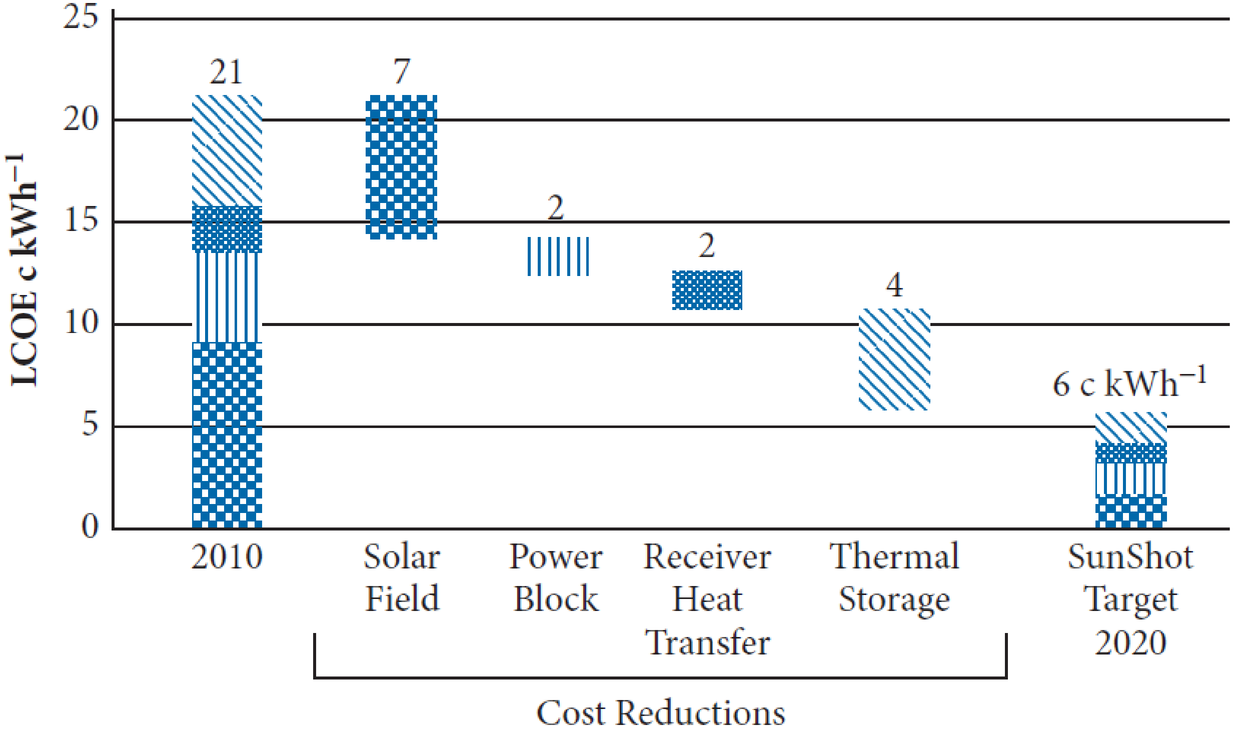
Name	Location	Type	Capacity MW	Area km^2	Temp °C	CF %	Storage hours	LCOE c kWh^{-1}	Capital Cost \$ kW^{-1}
Solana	Arizona	Trough	250	7.77	395	38	6	14	8000
Ivanpah	California	Tower	392	14	565	32	none	12–17	5500
Crescent Dunes	Nevada	Tower	110	6.76	565	52	10	14	8000

(Capital cost of nuclear = \$5500 kW^{-1}, onshore wind = \$2200 kW^{-1}, CCGT = \$1000 kW^{-1})

The operational and capacity benefits of CSP-TES, compared with variable generation PV when the penetration of the renewable generation is 40%, is an increase in the relative value of CSP-TES by up to 6 cents per kWh.

But still CSP currently generally not competitive with solar photovoltaic (PV) farms

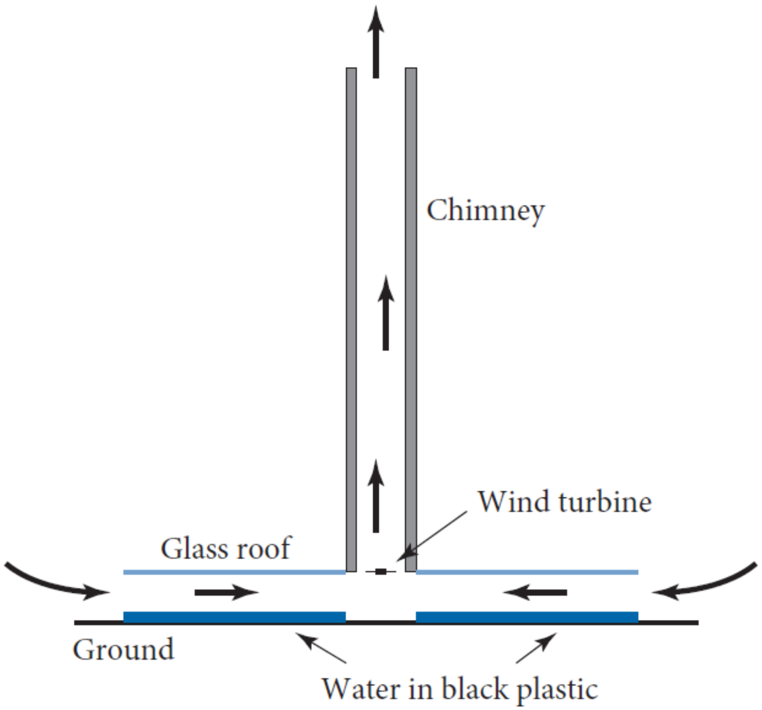
CSP cost reductions



USA Sunshot program aims to make CSP cost competitive with other sources without subsidies by 2020.

Since ~2012, CSP plants have faced stiff competition from cheaper silicon PV plants. However, CSP projects planned or under construction in several countries where there is good Sun and clear skies e.g. South Africa, Morocco, and Chile, but global market share small.

Solar Chimney



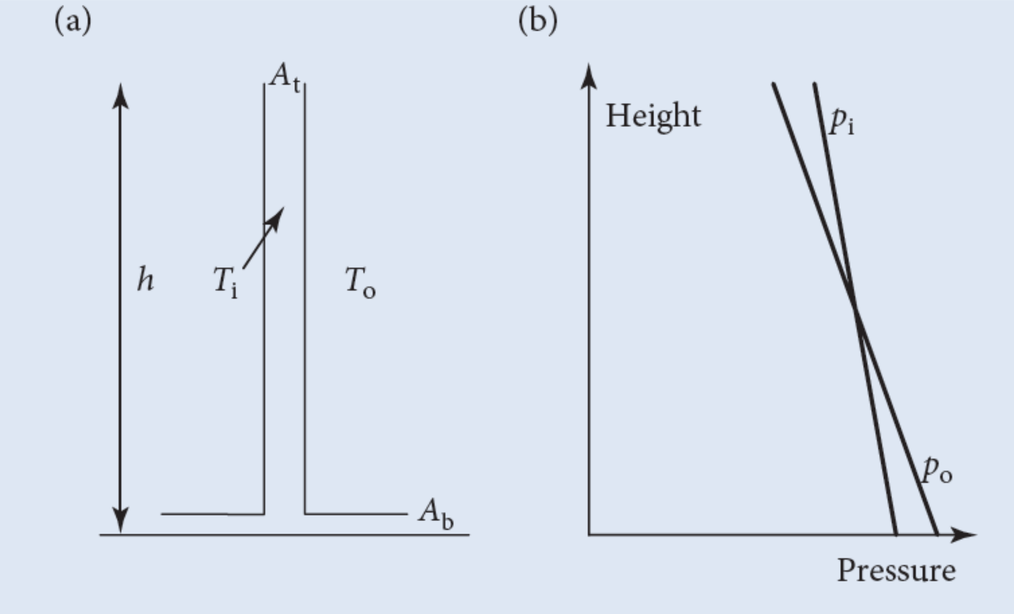


Fig. 5.15 (a) Solar chimney schematic. (b) Pressure variation in solar chimney.

Air is heated under glass and rise up high chimney. Prototype in Spain in 1980s produced 50 kW by solar chimney of height 195 m and diameter 10 m, with a collector of diameter 240 m. But currently not cost-effective.

Ocean thermal energy conversion

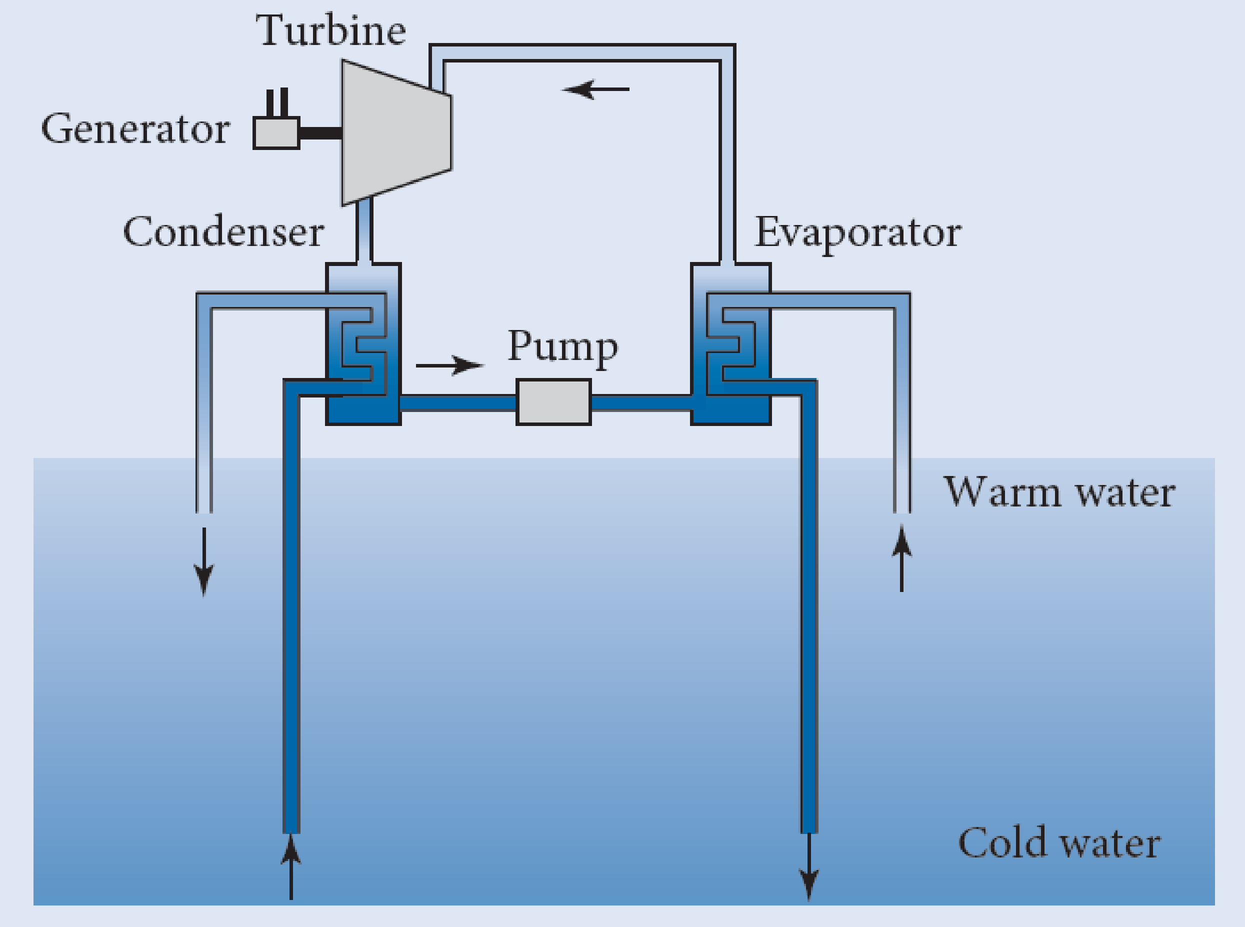


Fig. 5.16 Schematic of a possible OTEC system.

In the tropics, the top 100m of the oceans is 20-25 ^{o}C higher than at much greater depths. **Ocean thermal energy conversion** (OTEC) exploits this temperature difference, e.g. 100 kW plant off Hawaii uses ammonia as the thermal transfer fluid.

However, the efficiency is low, and there are only a few plants worldwide and significant technical challenges to overcome.

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Heat pumps

Heat pumps exploit fact that the ground at depth of around 10 m depth, and to a lesser extent the air, is maintained at a fairly constant temperature by the Sun. A **ground-source heat pump** draws heat from the ground during the winter which can be replaced when the heat pump is used to air-condition the building.

There has been a shift to the cheaper **air-source heat pumps** as their efficiency has improved, but ground-source heat pumps are well suited for large buildings.

Principle of heat pump is same at that of a refrigerator. For ideal pump, heat transferred is given by

$Q_1 = W \dfrac{T_1}{T_1 - T_2}$, so with $T_1 - T_2 = 31^{o}\text{C}$ and a ground temperature $T_2 = 6^{o}\text{C} = 279$ K

the work needed to pump heat across temperature difference of 31 ^{o}C is 10 times less than the heat extracted. In practice for temperature differences of 20-40 ^{o}C, 3-5 times (the **coefficient of performance**) less is required.

Heat pumps could make a significant contribution to low-carbon space heating and cooling of buildings.

Geothermal energy

Earth's interior is around 4000 °C - a vast and largely untapped energy resource of ~ 300 EJ y^{-1} from heat flow to surface.

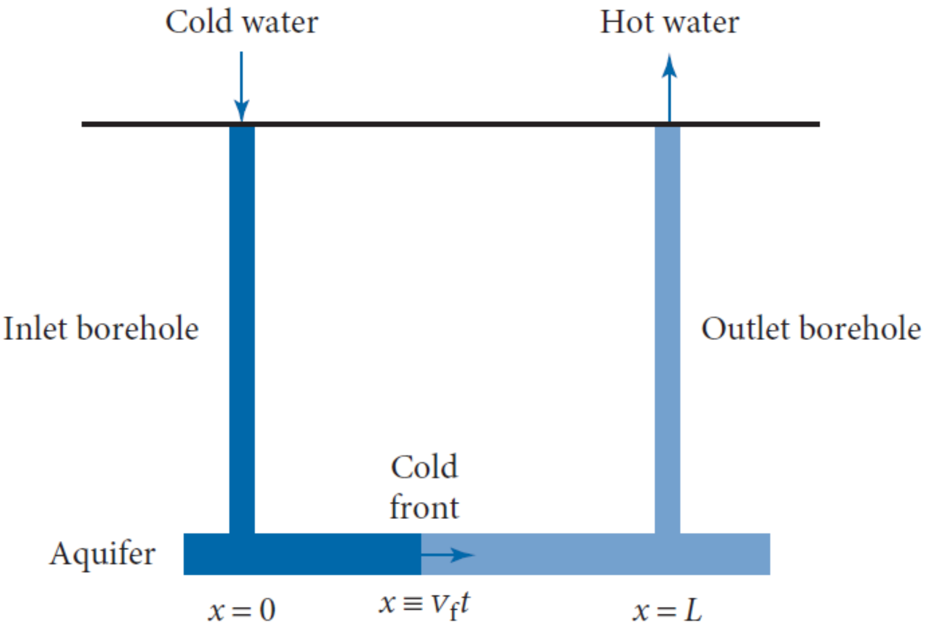
Cracks in Earth's crust arise at interfaces in tectonic plates, e.g. Iceland, California, Italy, New Zealand. Water seeps into cracks and boils, producing high pressure steam jets (**geysers**).

Credit: Ásgeir Eggertsson-own work CC BY SA 3.0

Krafla geothermal plant in Iceland has 300 MW electricity generating capacity and 130 MW hot water capacity.

Aquifer systems

Aquifers are layers of porous rock (e.g. sandstone) trapped between strata of impermeable rock. Aquifers at depths of 2-3 km are typically at 60-90 °C. Heat can be extracted in a two borehole system by pumping cold water through the inlet borehole, which is heated in the aquifer and is extracted through the outlet borehole.



In simple 1D model, **power output** is given by energy conservation as

$$P = \rho_w c_w \left(T_1 - T_0\right) Q$$

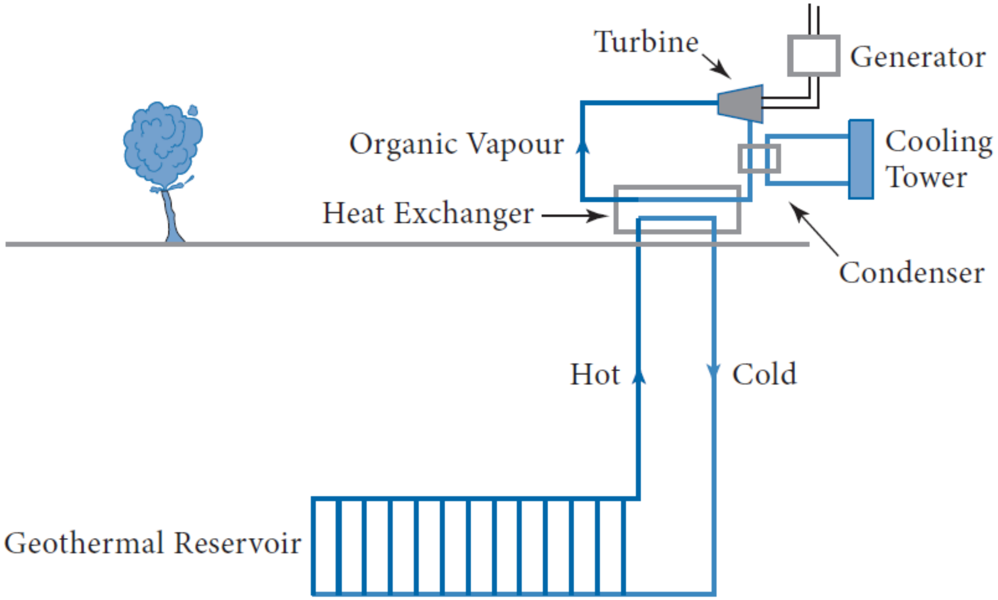
Cold front moves through aquifer with speed

$$v_{\text{front}} = \frac{\rho_w c_w}{\left(1-\varphi\right)\rho_r c_r} v_w$$

where φ = porosity of aquifer rock.

Lifetime of system $= \dfrac{L}{v_{\text{front}}}$

Hot dry rock extraction (enhanced geothermal systems)



Enhanced geothermal systems mine heat at depths of around 5 km, where the temperature is of order 250 °C. Water is pumped at high pressure through systems of cracks in the rock. Heat diffuses from the hot rock and is transferred to the water flowing through the crack.

In a time interval *t*, an isotherm moves a distance of order $(\kappa_r t)^{\frac{1}{2}}$

Energy extracted per unit length of crack is of order $\pi\kappa_r C_r \Delta T$

Typically $\kappa_r \approx 10^{-6}\,\mathrm{m}^2\mathrm{s}^{-1}, C_r \approx 2.5\,10^6\ \mathrm{Jm}^{-3}\mathrm{K}^{-1}, \Delta T \approx 10^2\ {}^{\mathrm{o}}\mathrm{C}$

yielding $\approx\ 0.75\mathrm{MW}_{\mathrm{th}}$ per kilometre of crack. Separation of cracks ~ $2(\kappa_r t)^{\frac{1}{2}}$

After 10 years ~ 36 m, so ~1000 cracks within 1 km^3 giving a power density of ~750 MWth km^{-2}

Outlook for geothermal energy

Geothermal energy now generates 12.8 GWe and is used in 78 countries, predominantly China, Turkey, Japan, Iceland.

Estimated economic potential is 140 GWe by 2050 (half from enhanced geothermal systems). Capacity factor is around 70%, so accessible potential is around 100 GWe.

Outlook dependent on economics of fossil fuels and alternative energy, and progress in drilling and fracturing rock basins.

Development of low temperature binary cycle plants has increased potential of geothermal energy.

Reliability of supply makes geothermal attractive in volatile markets.

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Key Points

- Solar thermal hot water heating could save ~0.6 $GtCO_2$ per year by 2050, providing approximately 10 EJ y^{-1} of low-carbon heat. Solar coolers and solar fuels could also make savings.

- Concentrated solar thermal power (CSP) with storage has considerable potential but will need support to make its LCOE competitive. Currently, an accessible potential for electricity generation of 300 GWe by 2050.

- Heat pumps are expected to be deployed more and more, and could supply ~8 EJ y^{-1} by 2050.

- Geothermal energy could supply about 100 GWe, with ~50% from EGS, and about 6 EJ y^{-1} of heat by 2050.