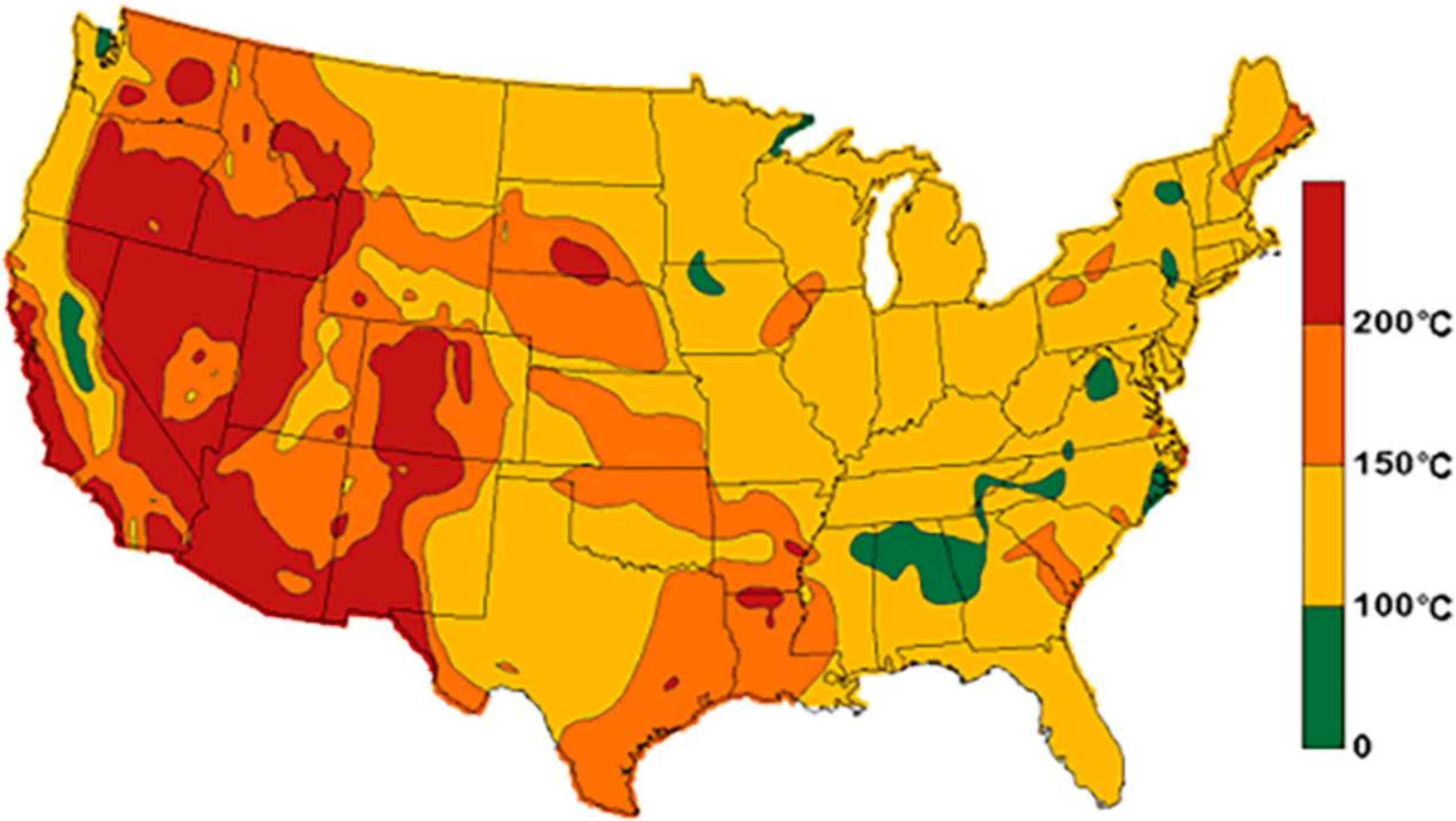
Geothermal Power

Agenda

Energy conservation, conversion, and transformation

- Transfer of thermal energy (heat)
  - Conduction, convection, radiation (cooling)
  - Internal energy, equivalence of work and heat
  - Basic (First Law & Second) Laws of Thermodynamics,
  - Entropy and spontaneous processes, examples.
- Thermal work and energy
  - Ideal Carnot processes
  - Geothermal energy production
- Thermal power plants
  - Real gases/substances
  - Steam and gas turbines
  - Fossil fuel combustion
  - Carbon capture & sequestration

U.S. Geothermal Resources



Most of the geothermal power plants in the United States are in western states and Hawaii, where geothermal energy resources are close to the earth's surface. California generates the most electricity from geothermal energy. The Geysers dry steam reservoir in Northern California is the largest known dry steam field in the world and has been producing electricity since 1960.

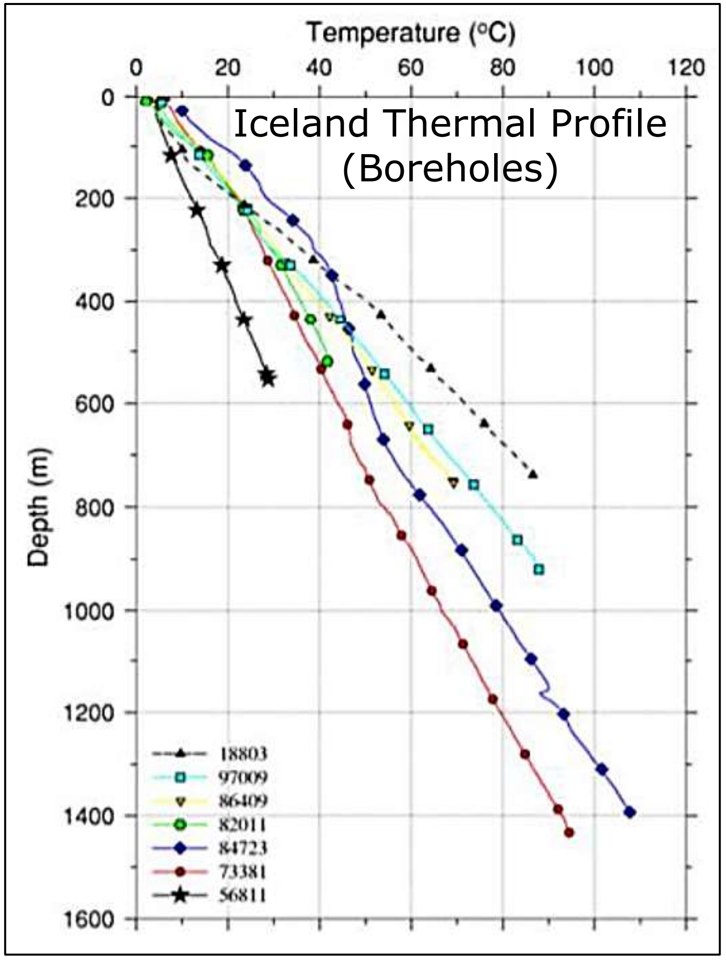
U.S. Geothermal Power Electricity Generation 2022

	State share of total U.S. geothermal electricity generation	Geothermal share of total state electricity generation
California	69.5%	5.8%
Nevada	24.2%	9.6%
Utah	2.7%	1.2%
Hawaii	1.8%	3.2%
Oregon	1.2%	0.3%
Idaho	0.5%	0.5%
New Mexico	0.3%	0.1%

2022: US produced about 17 TWh (17 billion kWh) = 0.4% of total U.S. utility-scale electricity generation.
(Utility-scale power plants: capacity ≥ 1 megawatt ($1MW_e$) of electricity generation)

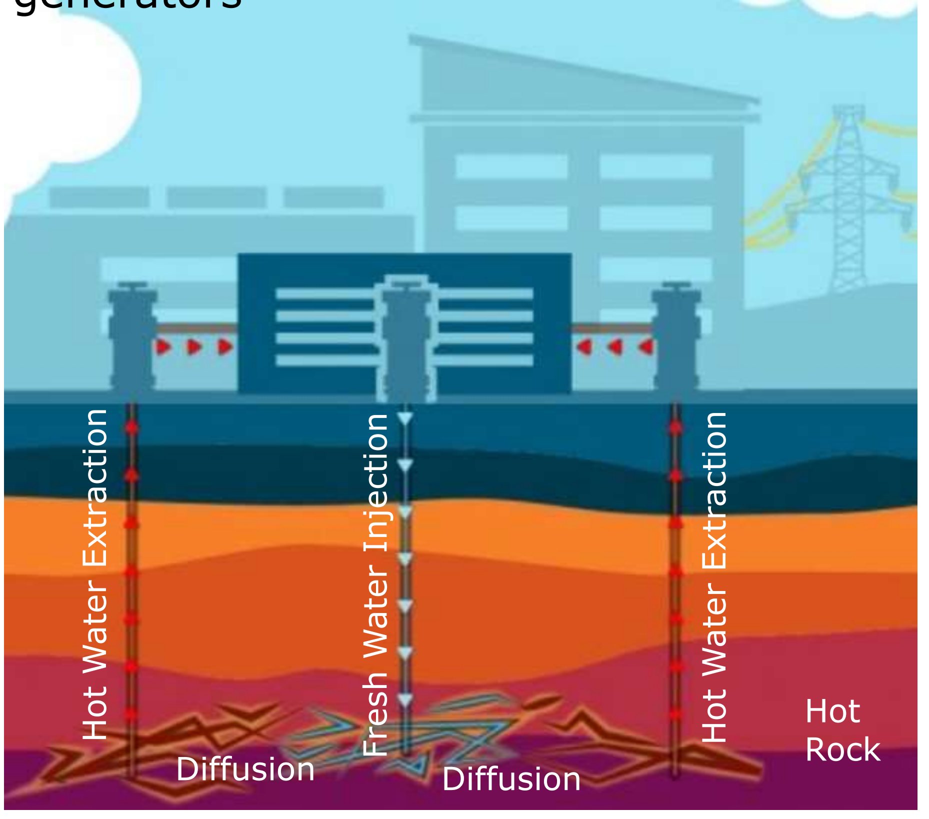
Geothermal Depth Profile

Worldwide simplest (conventional/ancient) direct use: building/district heating.
Utility: Geothermal electrical power plants, Residential: geothermal heat pumps, A/C



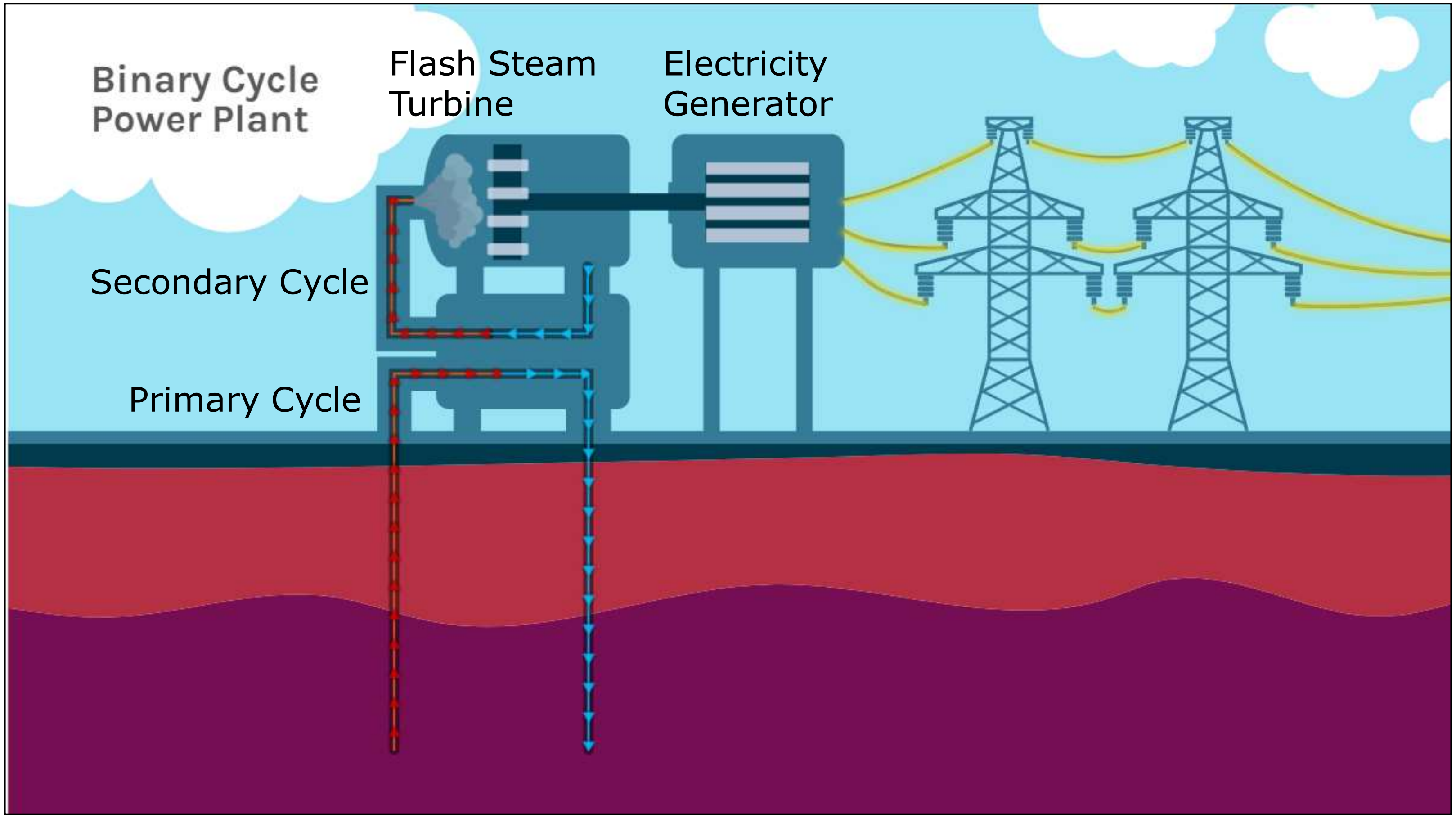
From H. Kennedy, 2020; citing Augustsson & Flovenz, 2--4

Generating technology: Inject fresh water (hydro fracturing), extract hot water → steam → drive steam turbines & electric generators

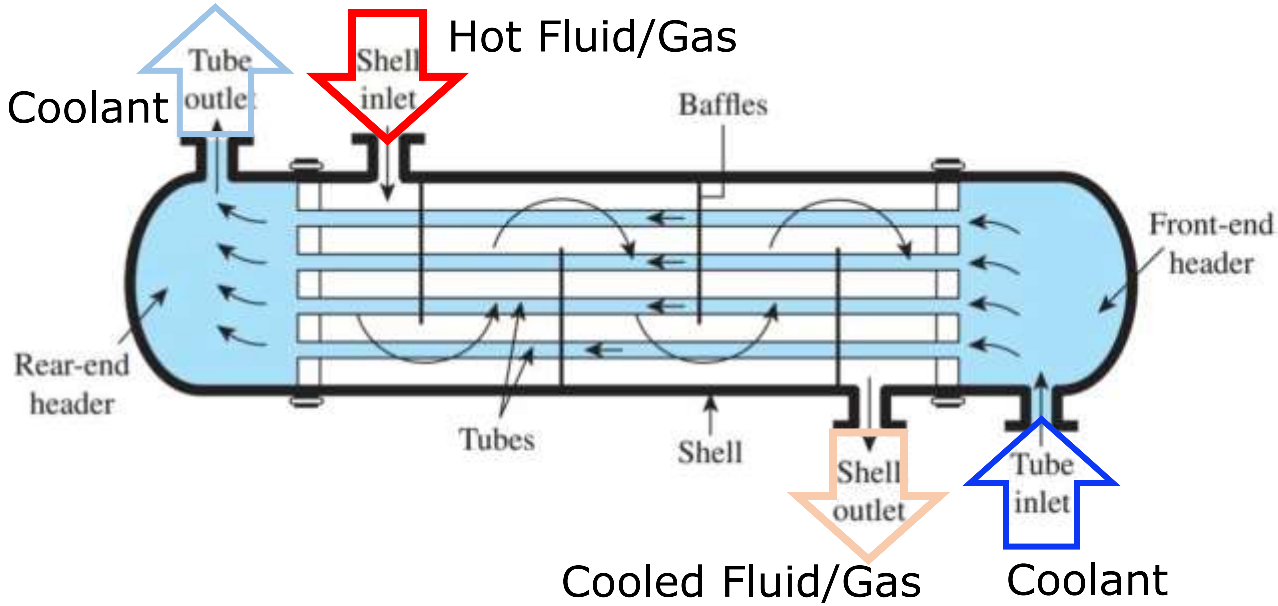


Flash-Steam Power Plant

https://www.energy.gov/eere/geothermal/electricity-generation



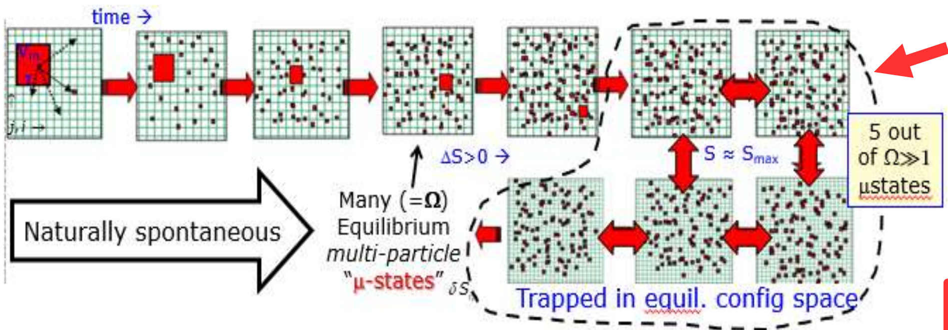
Heat Exchangers (Shell-and-Tube/Finned-Tube)



Finned-Tubes
Heat
Exchanger

Dynamical Equilibrium @ Maximum Entropy

Transitions from one *s.p.* state ($pixel_i$) to another ($pixel_j$) are micro-reversible (unlikely).



$\Omega \gg 1$ *Equilibrium configurations*

Same N = # *particles*,

Same $\langle energy \rangle = T$ *temperature*

m.p. μ*states of max Entropy*

$$S := k_B \cdot Ln\,\Omega = -k_B \cdot \sum_{i,j} p_{ij} \cdot Ln\, p_{ij}$$

Occupation probability $p_{ij} \sim 1/\Omega$

of s.p. state $\{i, j\}$ *in given* μ*state*

Dynamical equilibrium between equivalent states @ max entropy = complexity

all have the same = max likelihood $\rightarrow \Delta S = 0 =$ *reversible transitions*

Spontaneous processes $\Delta S > 0$ *are not reversible*

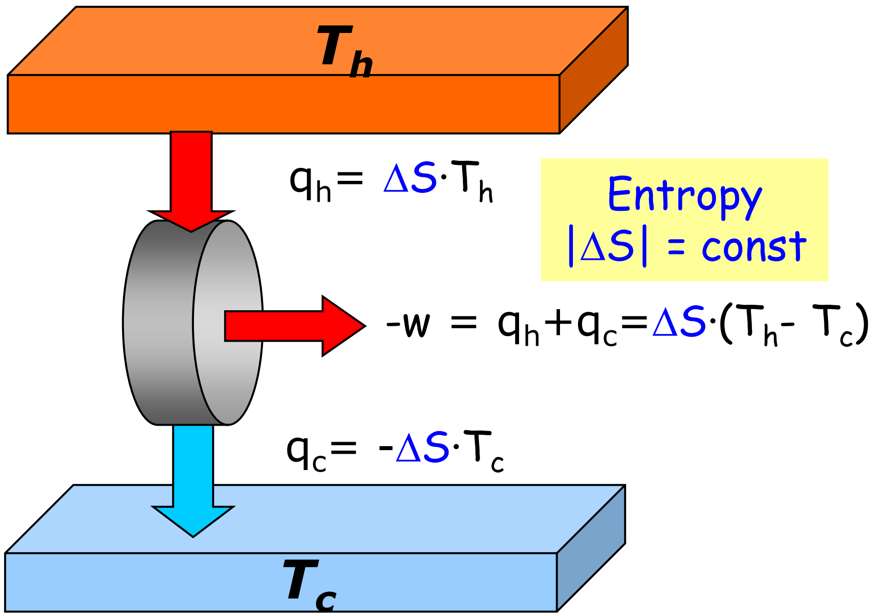
$$Macroscopic\ TD: \Delta S = \frac{q}{T} > 0 \qquad Always\ \Delta S \geq \frac{q}{T}$$

Heat transfer

Extract Geothermal Heat: Efficient Carnot Engines

Cyclic Carnot process ***at constant entropy*** ΔS → work $\boldsymbol{w = -(q_h + q_c) < 0}$ on environment powered by transferring heat from hot to cold sink $(T_h \rightarrow T_c)$.
→ Refrigerator

Ideal Gas: Every cyclic pV engine can be modeled as Carnot process.



Efficiency of an ideal Carnot engine

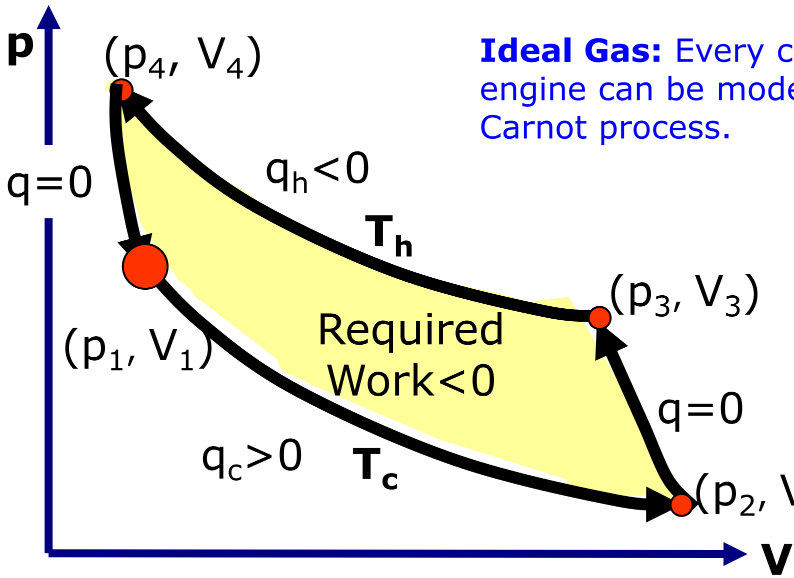
$$\varepsilon_C = 1 + \frac{q_c}{q_h} = 1 - \frac{T_c}{T_h}$$

- ε_C is maximum efficiency of a realistic Carnot-type engine.
- All engines based on *pV* processes can be simulated by a combination of Carnot processes.
- No thermodynamic (*pV*) engine can have an efficiency larger than ε_C.

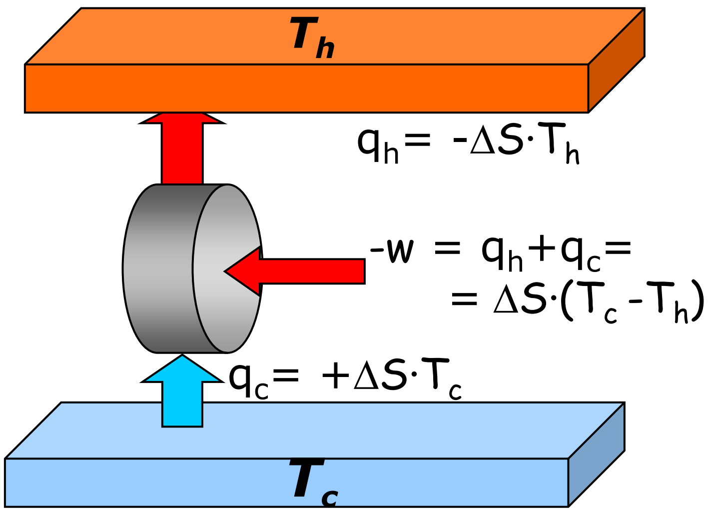
Reversing Carnot process implies sign changes of heat energies and work → External work $\boldsymbol{w>0}$ done on system can transfer heat from a cold reservoir to a hot reservoir $(T_c \rightarrow T_h)$.

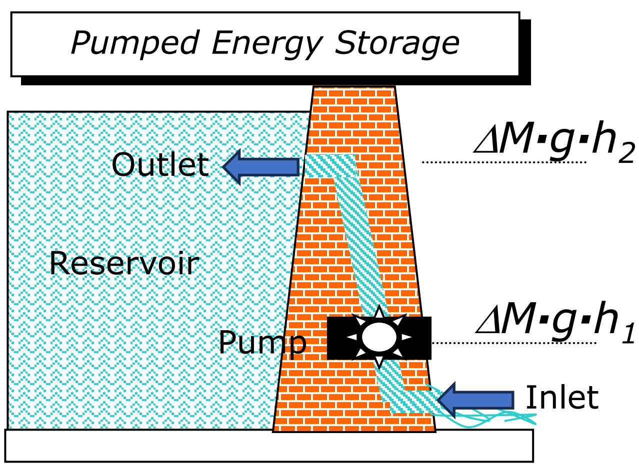
Thermal engine efficiencies $\varepsilon_{therm} \sim 0.3$.

Entropy and Heat Flow in Reverse Carnot Process



Ideal Gas: Every cyclic pV engine can be modeled as Carnot process.



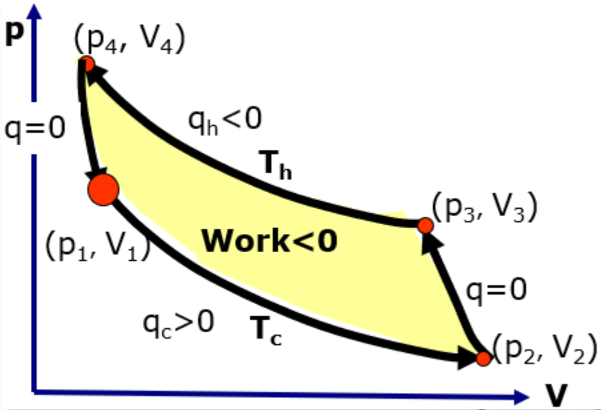


Maximum efficiency $\eta_C = 1 - \varepsilon_C = \frac{q_c}{q_h} = \frac{T_c}{T_h}$

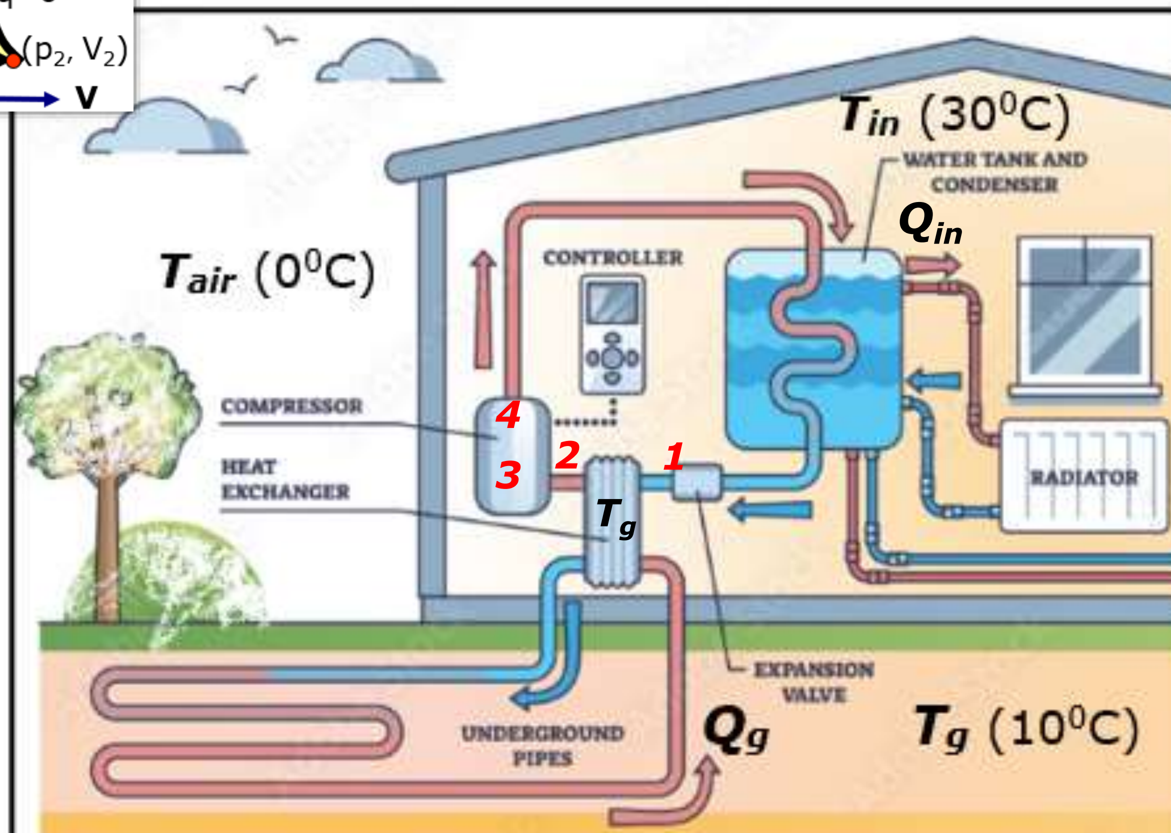
Entropy **ΔS** with heat $\boldsymbol{q_c = \Delta S\cdot T_c}$ from the $\boldsymbol{T_c}$ reservoir preheats the colder ($\boldsymbol{T_h}$) working fluid/gas, which enters an externally powered compressor. The compressor **does work** on the fluid, raising its temperature to $\boldsymbol{T_h}$. Heat energy $\boldsymbol{\Delta S\cdot T_h}$ is then transferred to the $\boldsymbol{T_h}$ heat reservoir.

Analog: Stream of water ΔM from a river carries energy $\Delta M\cdot g\cdot h_1$, enters an externally powered pump that lifts ΔM by (h_2-h_1) to the reservoir head at energy $\Delta M\cdot g\cdot h_2>\Delta M\cdot g\cdot h_1$.

Residential Heat Pump



Carnot heating: In-ground heat pump absorbs heat energy $\boldsymbol{Q_g \approx \Delta S \cdot T_g}$ from under ground $\boldsymbol{T_g}$ heat bath to preheat expanded work fluid/gas. Compressor provides differential heat $\boldsymbol{Q_{in} \approx -\Delta S \cdot T_{in}}$ required for sustaining temperature $\boldsymbol{T_{in}}$.

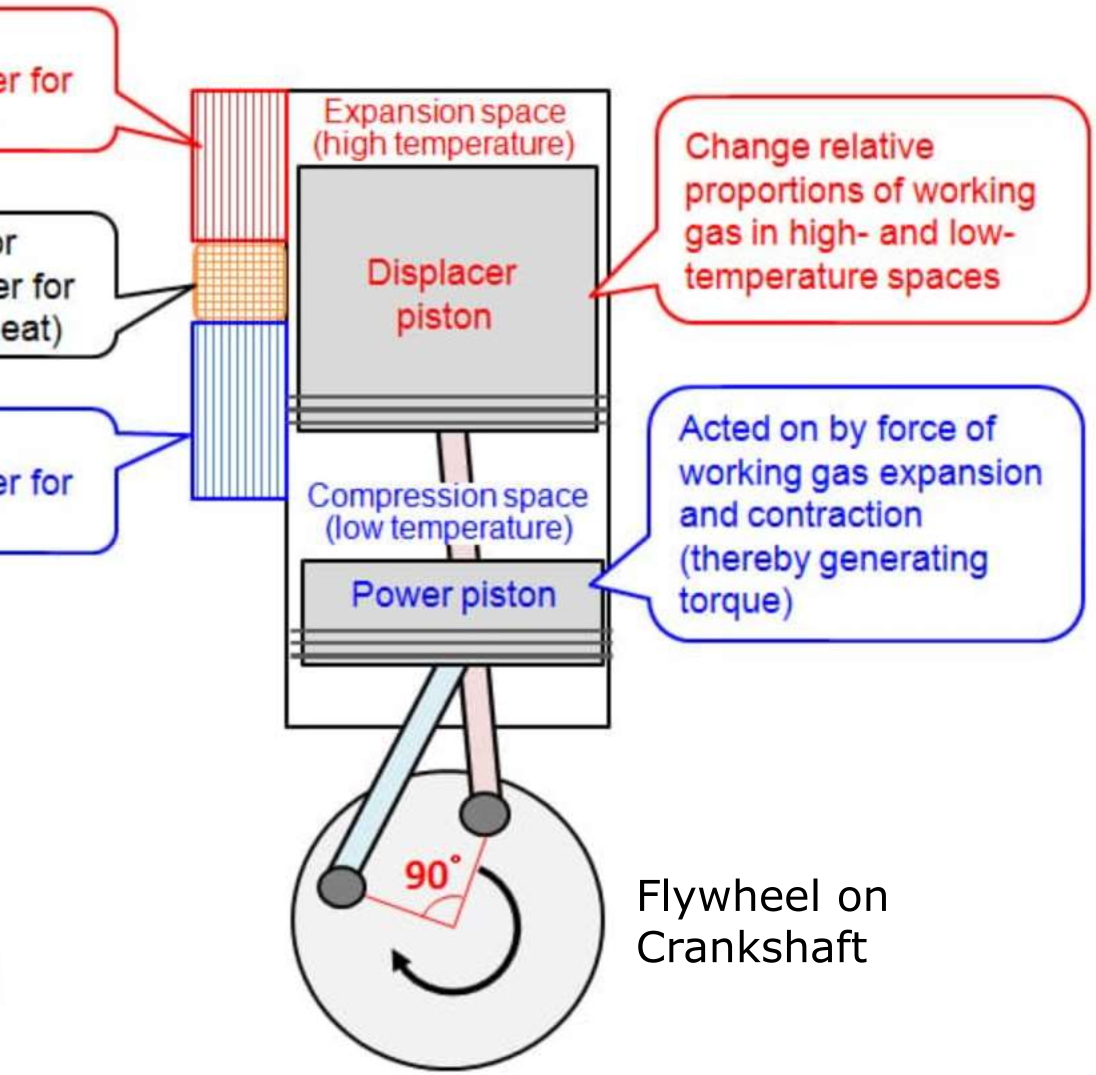


Work fluid transfers heat $\boldsymbol{Q_{in} < 0}$ to tank and interior. Iso-thermal expansion after expansion nozzle in ground loop heat exchanger.

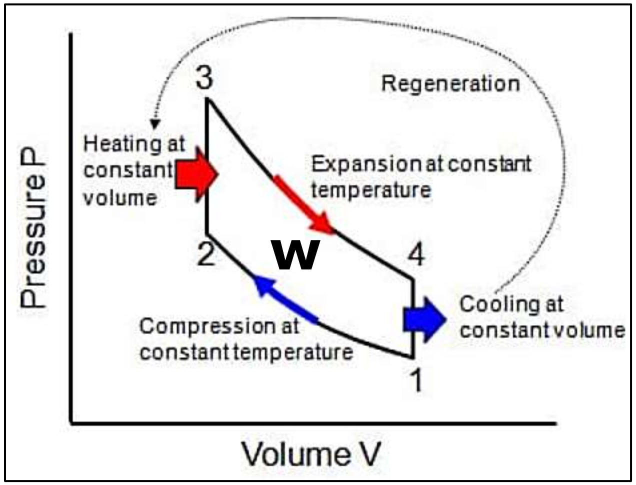
Req. compressor work

$$w = C_{air} \cdot \left(T_{in} - T_{air}\right) - \left|Q_g\right|$$

Stirling Heat Engine: Components

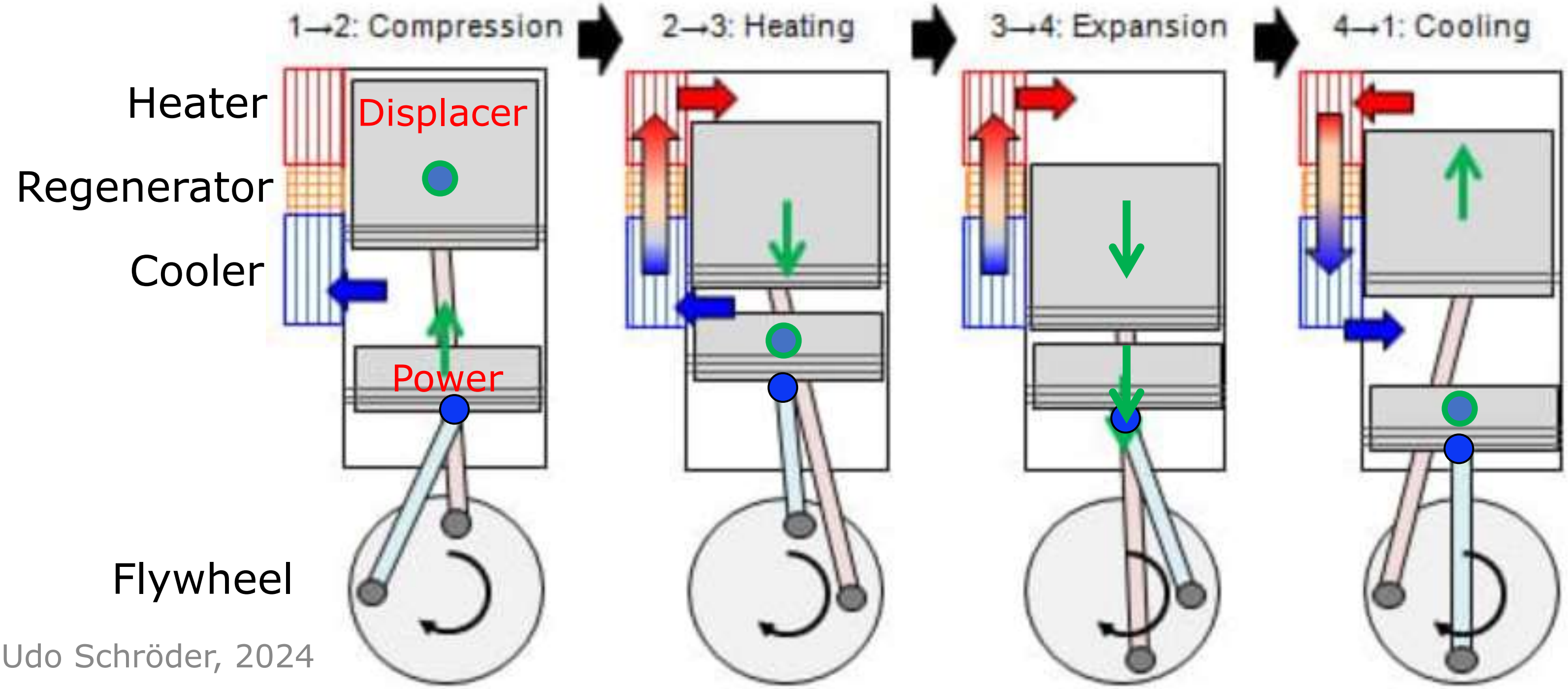


Stirling Heat Engine (β)



Closed-cycle regenerative heat engine with self-contained, permanent working fluid/gas. Displacer directs flow of working gas.

Stirling engine can be driven by any temperature gradient, e.g., solar radiation, nuclear decay heat.
Applications: concentrated solar insolation, submarines, space craft,..



U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

GEOTHERMAL TECHNOLOGIES OFFICE

Fiscal Years 2022–2026

MULTI-YEAR PROGRAM PLAN

Strategic Goal 1: Drive toward a carbon-free electricity grid by supplying 60 gigawatts (GW) of Enhanced Geothermal Systems and hydrothermal resource deployment by 2050.

Strategic Goal 2: Decarbonize building heating and cooling loads by capturing the economic potential for 17,500 Geothermal district Heating installations and by installing GHPs in 28 million households nationwide by 2050.

Strategic Goal 3: Deliver economic, environmental, and social justice advancements through increased geothermal technology deployment.