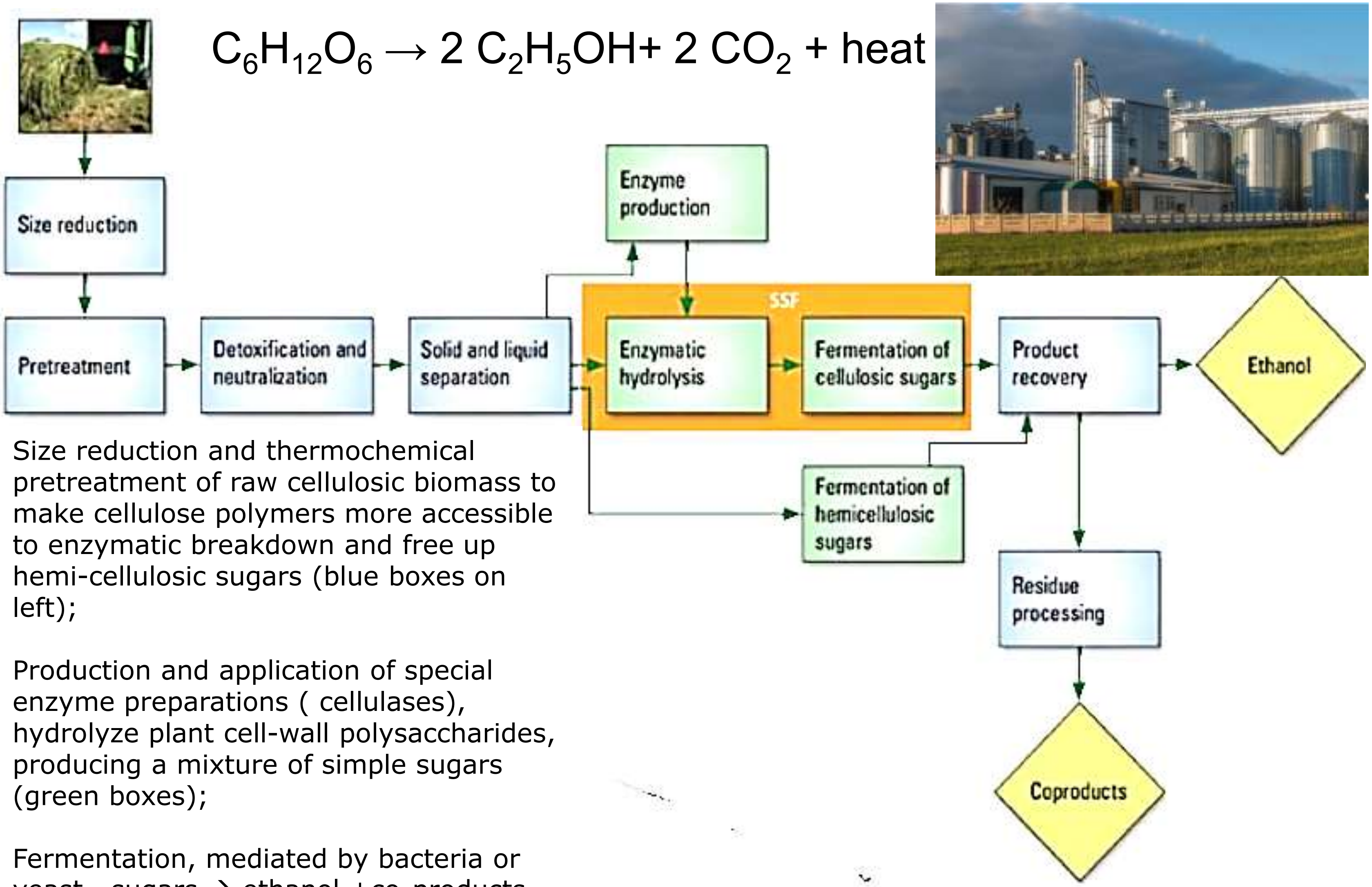
Biological Bio-Ethanol Production

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2 + \text{heat}$$

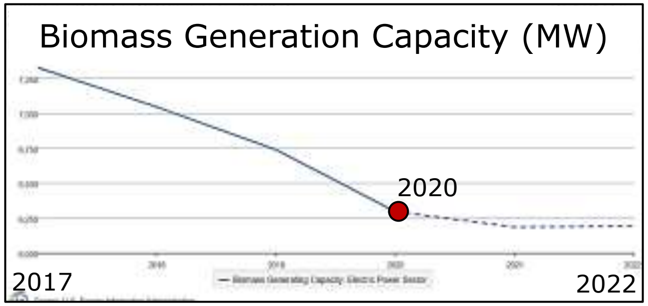


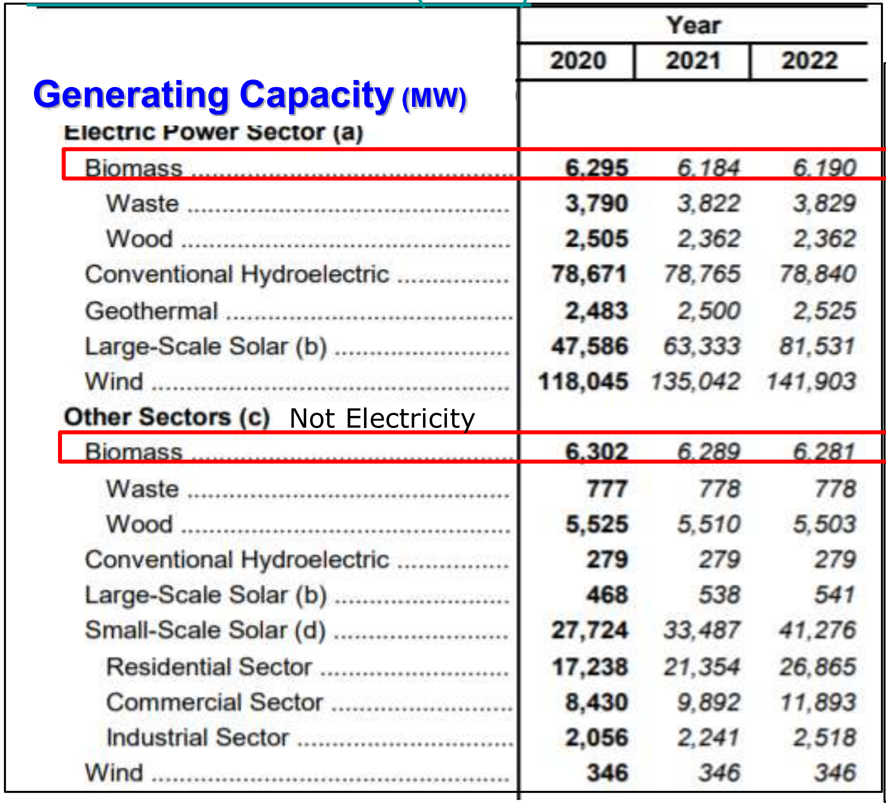
1. Size reduction and thermochemical pretreatment of raw cellulosic biomass to make cellulose polymers more accessible to enzymatic breakdown and free up hemi-cellulosic sugars (blue boxes on left);
2. Production and application of special enzyme preparations (cellulases), hydrolyze plant cell-wall polysaccharides, producing a mixture of simple sugars (green boxes);
3. Fermentation, mediated by bacteria or yeast, sugars → ethanol +co-products (yellow diamonds).
4. Distillation/dehydration to remove water.

Biomass Renewable Electricity Capacity and Generation

US Energy Information Administration: Energy Outlook

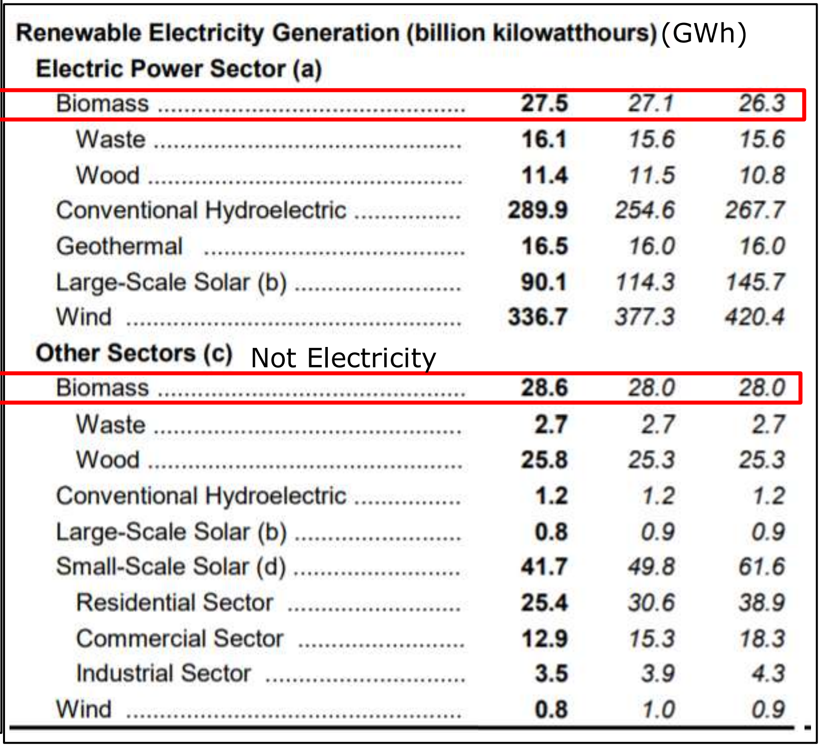
US: Diminishing importance of biomass for *electricity generation (7%)*. 2023, Biomass produced 5% of total U.S. energy consumption, or about 4,978 trillion British thermal units (TBtu).





Generating Capacity (MW)

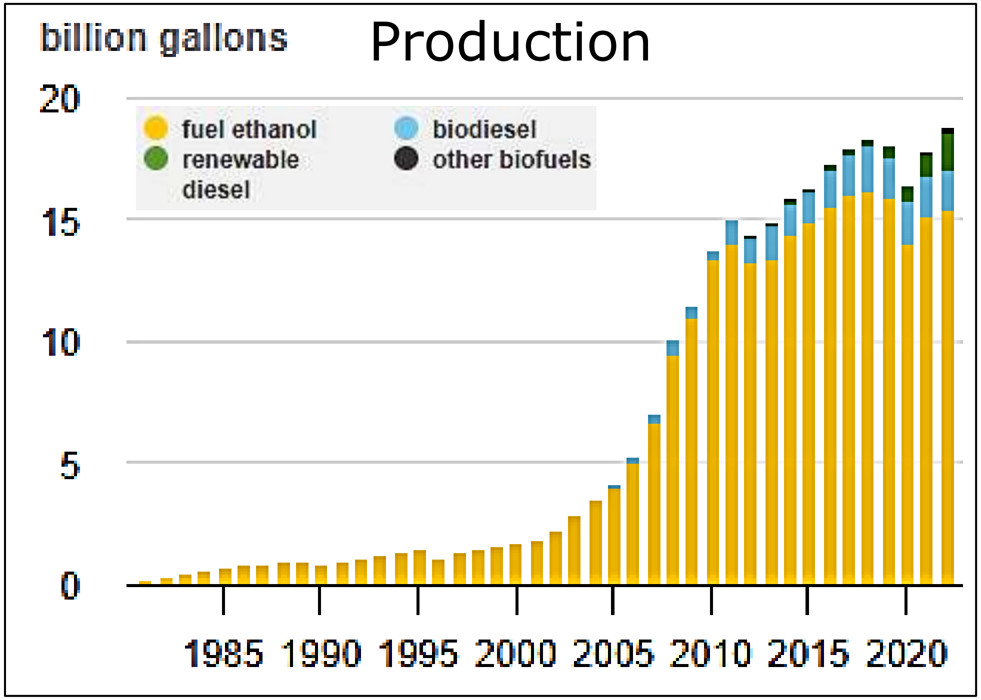
	Year		
	2020	2021	2022
Electric Power Sector (a)			
Biomass	6,295	6,184	6,190
Waste	3,790	3,822	3,829
Wood	2,505	2,362	2,362
Conventional Hydroelectric	78,671	78,765	78,840
Geothermal	2,483	2,500	2,525
Large-Scale Solar (b)	47,586	63,333	81,531
Wind	118,045	135,042	141,903
Other Sectors (c) Not Electricity			
Biomass	6,302	6,289	6,281
Waste	777	778	778
Wood	5,525	5,510	5,503
Conventional Hydroelectric	279	279	279
Large-Scale Solar (b)	468	538	541
Small-Scale Solar (d)	27,724	33,487	41,276
Residential Sector	17,238	21,354	26,865
Commercial Sector	8,430	9,892	11,893
Industrial Sector	2,056	2,241	2,518
Wind	346	346	346



Renewable Electricity Generation (billion kilowatthours) (GWh)

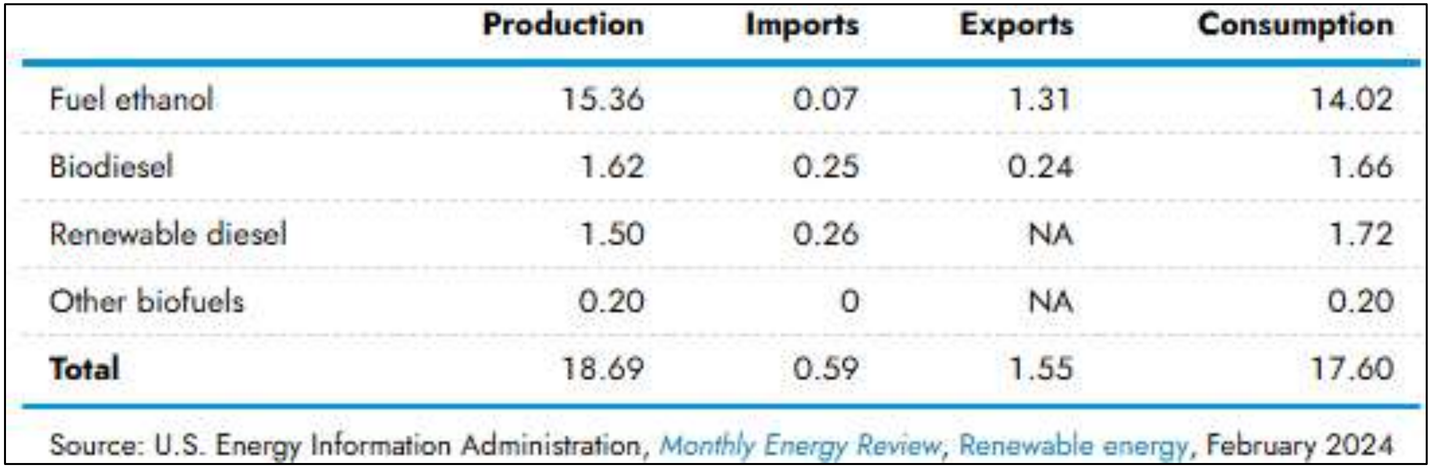
Electric Power Sector (a)			
Biomass	27.5	27.1	26.3
Waste	16.1	15.6	15.6
Wood	11.4	11.5	10.8
Conventional Hydroelectric	289.9	254.6	267.7
Geothermal	16.5	16.0	16.0
Large-Scale Solar (b)	90.1	114.3	145.7
Wind	336.7	377.3	420.4
Other Sectors (c) Not Electricity			
Biomass	28.6	28.0	28.0
Waste	2.7	2.7	2.7
Wood	25.8	25.3	25.3
Conventional Hydroelectric	1.2	1.2	1.2
Large-Scale Solar (b)	0.8	0.9	0.9
Small-Scale Solar (d)	41.7	49.8	61.6
Residential Sector	25.4	30.6	38.9
Commercial Sector	12.9	15.3	18.3
Industrial Sector	3.5	3.9	4.3
Wind	0.8	1.0	0.9

U.S. Biofuels Production & Consumption



Consumption (billion gallons per year) very similar to production: Consume almost all produced quantities.

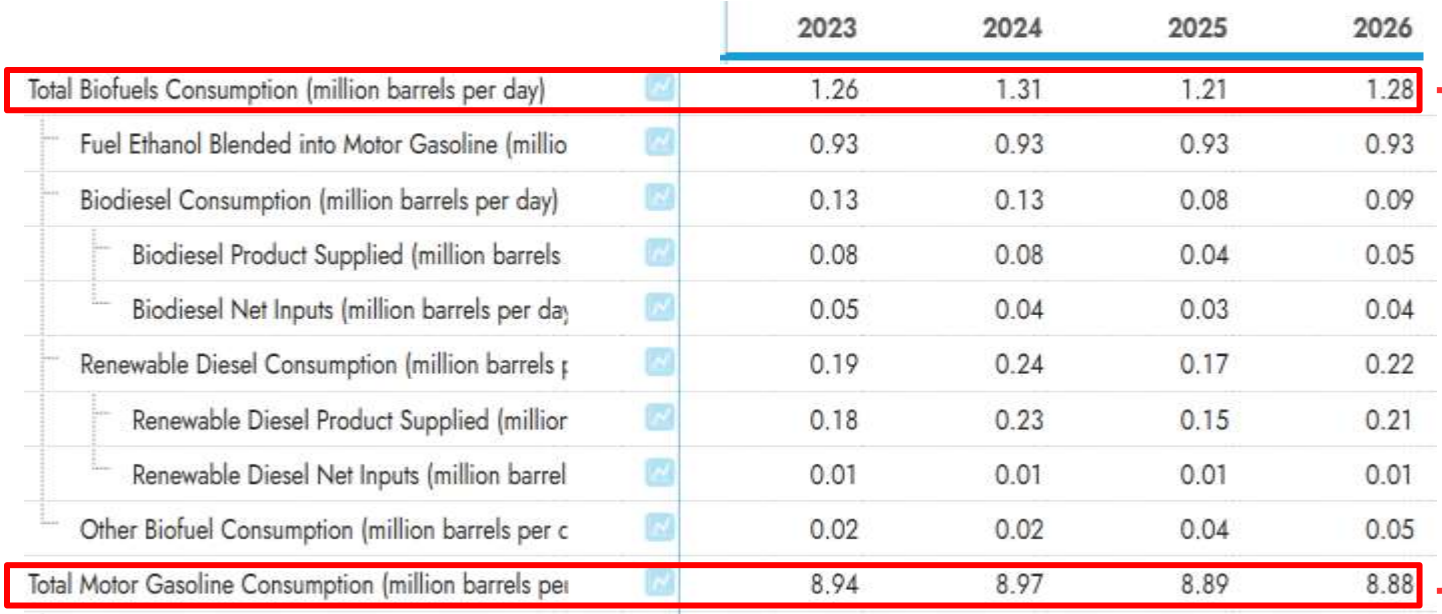
U.S. in 2022: Ethanol—alcohol fuel (lower HV) blended with petroleum gasoline for vehicles; Largest share of U.S. biofuel production (82%) and of consumption (75%)



	Production	Imports	Exports	Consumption
Fuel ethanol	15.36	0.07	1.31	14.02
Biodiesel	1.62	0.25	0.24	1.66
Renewable diesel	1.50	0.26	NA	1.72
Other biofuels	0.20	0	NA	0.20
Total	18.69	0.59	1.55	17.60

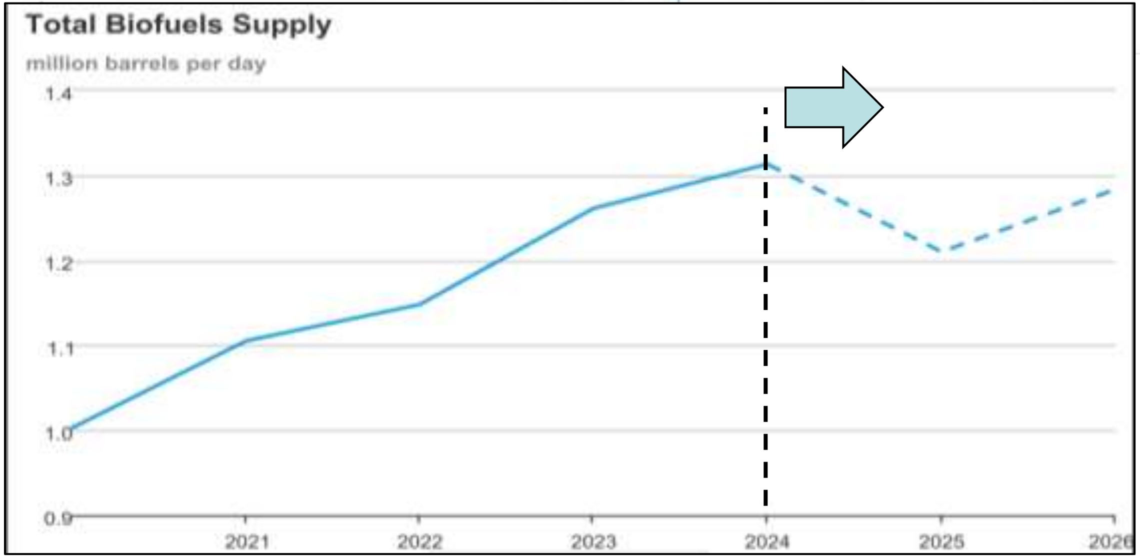
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Renewable energy, February 2024

Transportation Fuels: Status & Outlook



	2023	2024	2025	2026
Total Biofuels Consumption (million barrels per day)	1.26	1.31	1.21	1.28
Fuel Ethanol Blended into Motor Gasoline (millio	0.93	0.93	0.93	0.93
Biodiesel Consumption (million barrels per day)	0.13	0.13	0.08	0.09
Biodiesel Product Supplied (million barrels	0.08	0.08	0.04	0.05
Biodiesel Net Inputs (million barrels per day	0.05	0.04	0.03	0.04
Renewable Diesel Consumption (million barrels p	0.19	0.24	0.17	0.22
Renewable Diesel Product Supplied (millior	0.18	0.23	0.15	0.21
Renewable Diesel Net Inputs (million barrel	0.01	0.01	0.01	0.01
Other Biofuel Consumption (million barrels per c	0.02	0.02	0.04	0.05
Total Motor Gasoline Consumption (million barrels pei	8.94	8.97	8.89	8.88

Compare
≙ "E12"



U.S. corn-based ethanol → agricultural importance. → pump gasoline≈ "E10" (app. 10% ethanol), per federal volume mandates, also state rules & market practice. Higher % occur in practice (fuel companies)

NAS: “Bioenergy from Algae not Sustainable”

Cited from Report by Committee on Sustainable Development of Algal Biofuels
THE NATIONAL ACADEMIES PRESS, 2012.

“Based on a review of literature published until the authoring of this report, the committee concluded that the scale-up of algal biofuel production sufficient to meet at least 5 percent of U.S. demand for transportation fuels4 would place unsustainable demands on energy, water, and nutrients with current technologies and knowledge. However, the potential to shift this dynamic through improvements in biological and engineering variables exists.
For some system designs analyzed, the energy outputs of algal biofuels (and co-products if they are produced) are less than the energy inputs for producing the fuel.
Estimated values for energy return on investment range from 0.13 to 3.33. The estimated consumptive use of fresh water for producing 1 liter of gasoline equivalent of algal biofuel is 3.15 to 3,650 liters, depending on whether the algae or cyanobacteria need to be harvested to be processed to fuels or if they secrete fuel products; whether fresh water, inland saline water, marine water, or wastewater is used as a culture medium; the climatic condition of the region if open ponds are used; and whether the harvest water from algae cultivation is recycled.

In other words, at least 123 billion liters of water would be needed to produce 39 billion liters of algal biofuels or an equivalent of 5 percent of U.S. demand for transportation fuels.

The estimated requirement for nitrogen and phosphorus needed to produce that amount of algal biofuels ranges from 6 million to 15 million metric tons of nitrogen and from 1 million to 2 million metric tons of phosphorus if the nutrients are not recycled or included and used in coproducts.

Those estimated requirements represent 44 to 107 percent of the total nitrogen use and 20 to 51 percent of total phosphorus use in the United States.”

Strategic Issues Bioenergy (as Renewable)

1. Pollution from combustion, particles, smog, net GHG emission,
2. CO_2 atmospheric residence time during vegetation regrowth (not ren.)
3. Deterioration of soil by deforestation, mono-crop plantations,
4. Use of arable land competes with food production → food prices,
5. Energy density, low heating value,
6. Climate/weather dependence,
7. Excessive use of water,
8. Use of fertilizer feed stock (nitrogen, phosphates),
9. Efficiency of fermentation process,
10. Economics, requires mandates & subsidies.

For scalability & sustainable use: Need technological breakthroughs

Geothermal Power

Agenda

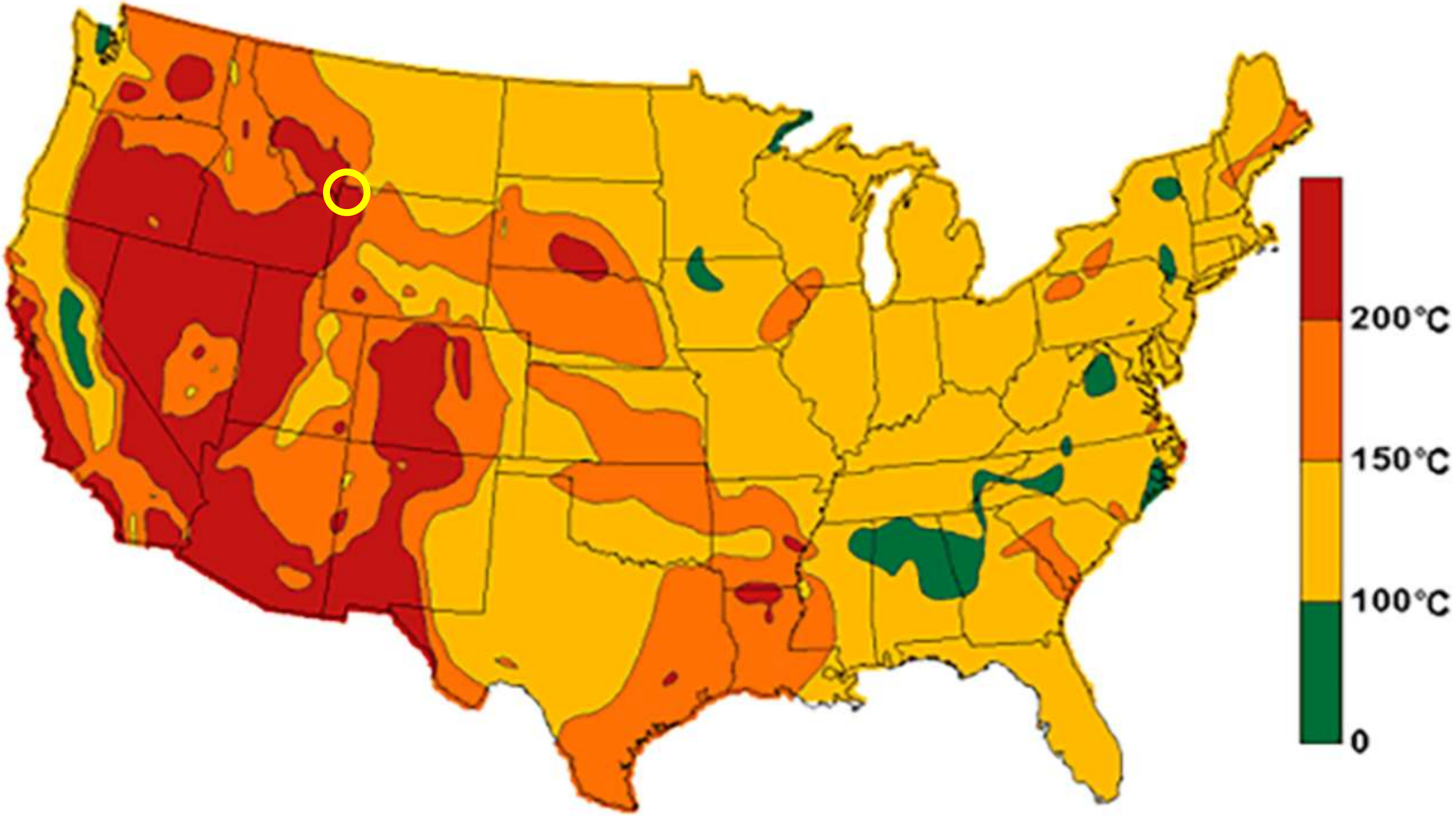
Energy conservation, conversion, and transformation

- Geothermal energy production
  - U.S./global geothermal resources
  - Power plant,
  - Heat exchange, entropy

- Thermodynamics (Cont'd Thermal work and energy)
  - Ideal gas EoS,
  - Thermal processes, equilibration,
  - Cyclic processes,
  - Thermal engines, heat pumps

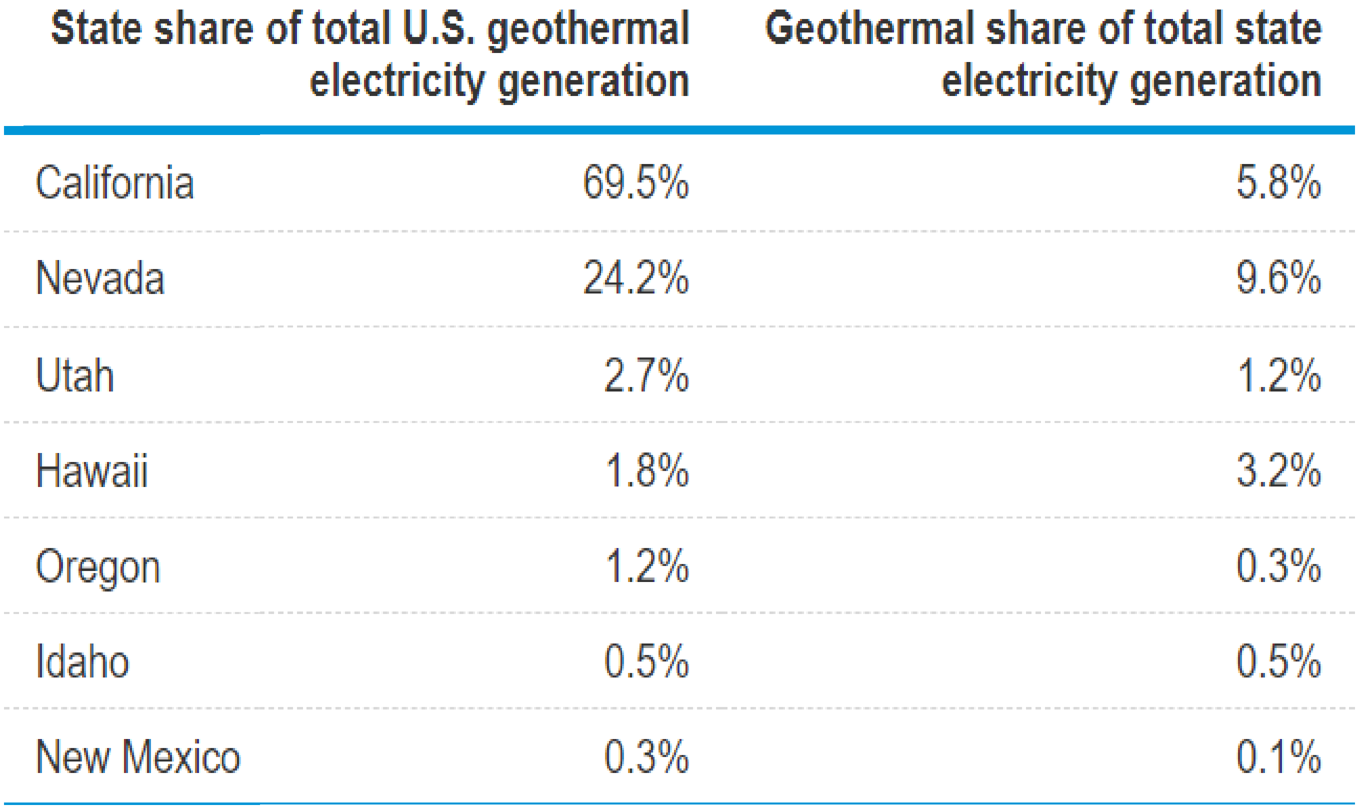
- Conventional thermal power plants
  - Real gases/substances
  - Steam and gas turbines
  - Fossil fuel combustion
  - Carbon capture & sequestration

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

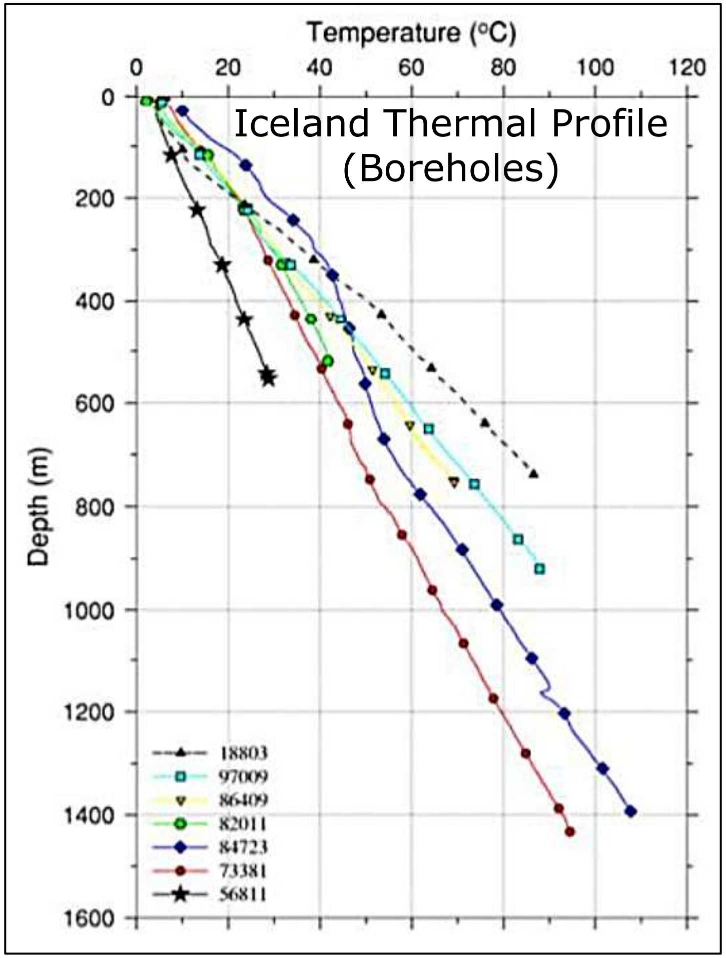


	State share of total U.S. geothermal electricity generation	Geothermal share of total state electricity generation
California	69.5%	5.8%
Nevada	24.2%	9.6%
Utah	2.7%	1.2%
Hawaii	1.8%	3.2%
Oregon	1.2%	0.3%
Idaho	0.5%	0.5%
New Mexico	0.3%	0.1%

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

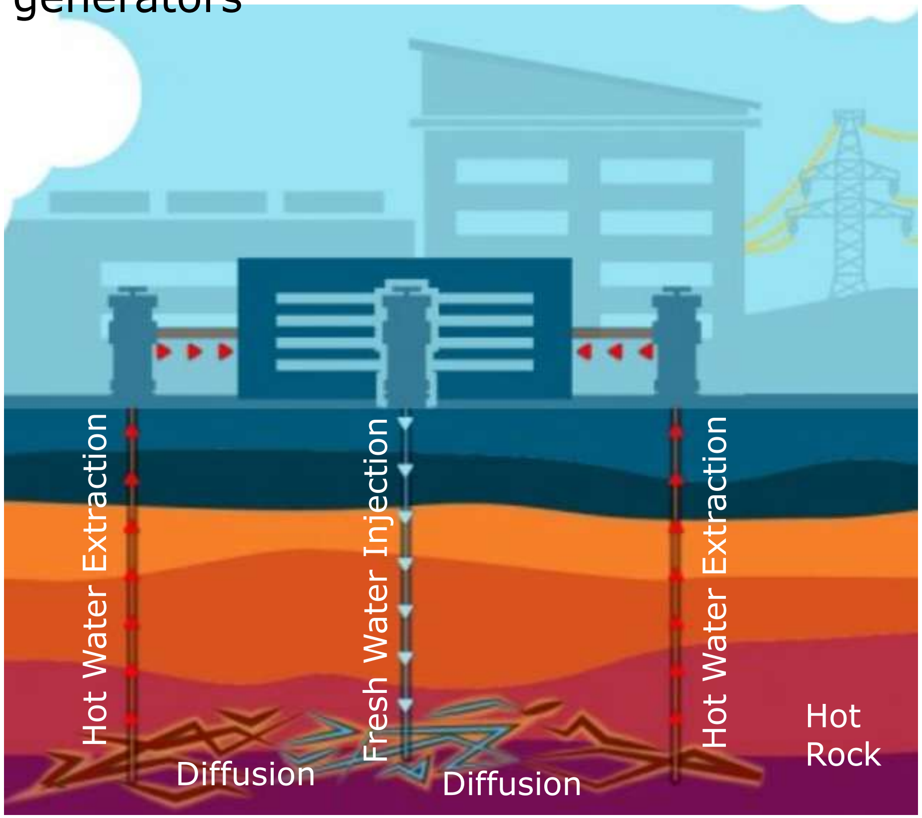
Worldwide simplest (conventional/ancient) direct use: building/district heating.
Utility: Geothermal electrical power plants, Residential: geothermal heat pumps, A/C



Iceland Thermal Profile
(Boreholes)

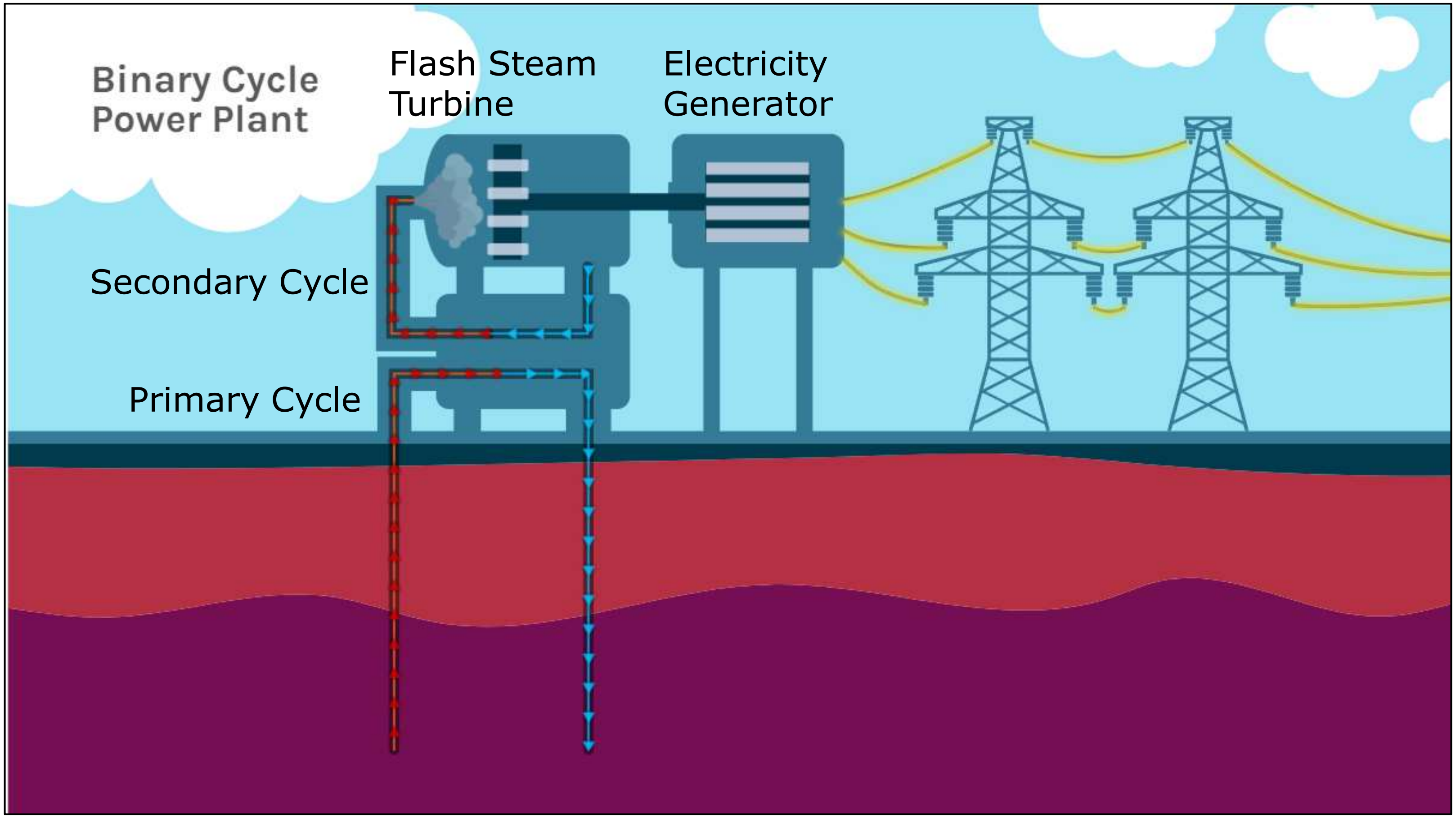
From H. Kennedy, 2020; citing Augustsson & Flovenz, 2--4

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

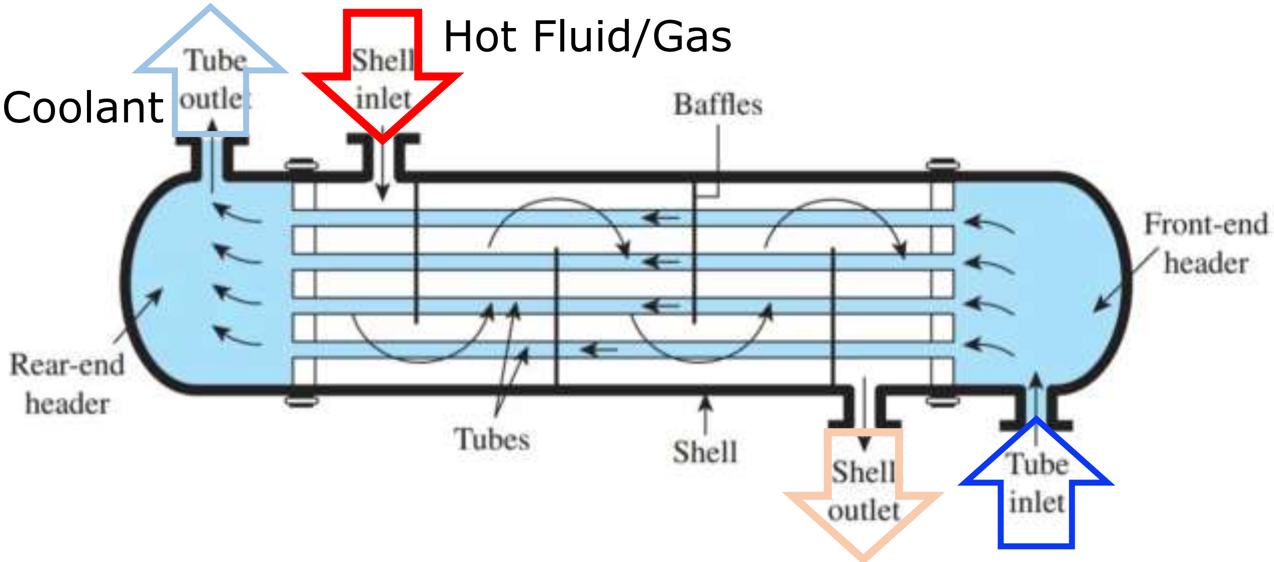


Flash-Steam Power Plant

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



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



Coolant

Hot Fluid/Gas

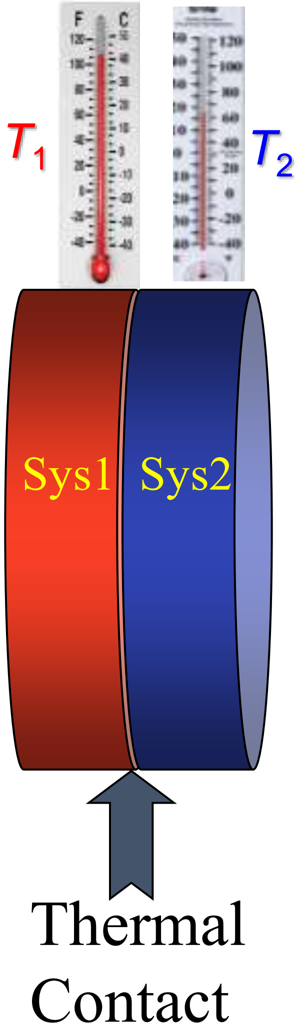
Cooled Fluid/Gas

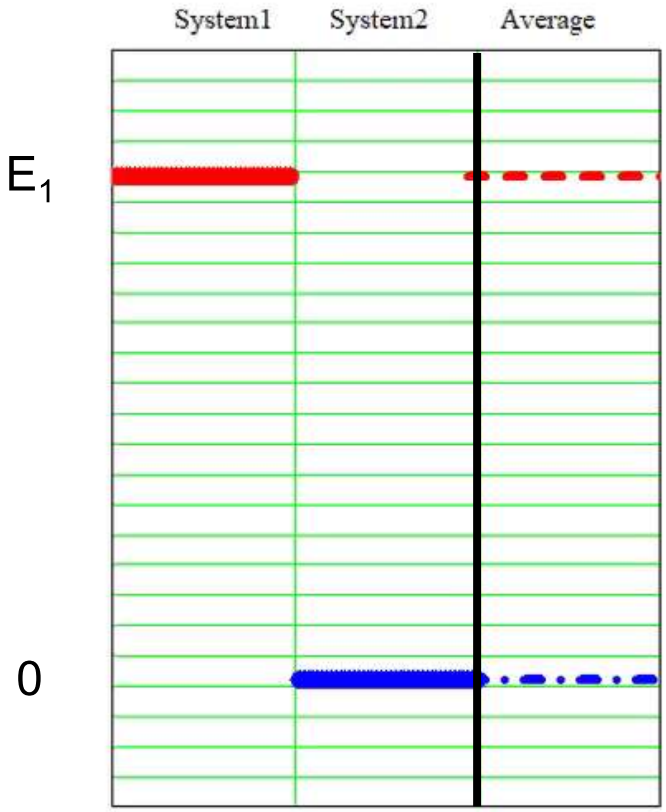
Coolant

Finned-Tubes
Heat
Exchanger

Simulation: Energy Equilibration

Observation: *time*-dependent equilibration of temperatures T_i
$\triangleq$ mean energy per constituent (particle)





Discrete energy states of 2 similar interacting systems

Initial conditions

$\langle E_1 \rangle \approx E = E_{tot}$ & $\langle E_2 \rangle \approx 0$

Initial mean energies
$\langle e_k \rangle_1 = E_1/A_1$ & $\langle e_k \rangle_2 = E_2/A_2$

Random ± energy and
± momentum exchange

Final mean energies
thermalization achieved

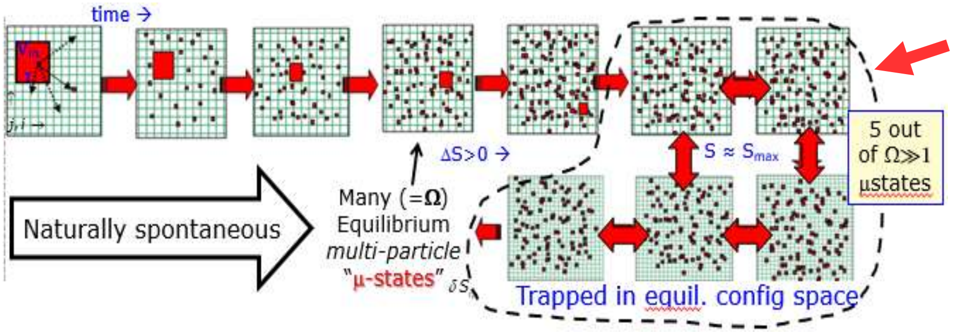
$\langle e_k \rangle_i \rightarrow E_i/A_i = E/(A_1+A_2) \sim T_i = T$

Equilibrium energy fluctuations

$$\left\langle \left(e_i - \langle e_i \rangle\right)^2 \right\rangle := \sigma_{e_i}^2 = k_B \cdot T^2 \cdot C_V$$

Dynamical Equilibrium @ Maximum Entropy, Multiplicity

Transitions from one *s.p.* state (pixel$_i$) to another (pixel$_j$) are micro-reversible (unlikely).



$\Omega \gg 1$ *Equilibrium configurations*

$\langle energy \rangle = E/N \propto T$ *temperature*

m.p. μ*states of max* Entropy

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

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

$$\Omega = \exp\{S/k_B\} \leftrightarrow S := k_B \cdot Ln\,\Omega = -k_B \cdot \sum_{i,j} p_{ij} \cdot Ln\, p_{ij} \Rightarrow \boxed{\left.\begin{matrix} p_{ij} = 0 \\ p_{ij} = 1 \end{matrix}\right\} \delta s_{ij} = 0}$$

Dynamical equilibrium between equivalent states @ max *entropy = complexity*
all have the same = max *likelihood* → $\boxed{\Delta S = 0 \mathrel{\hat{=}} \textit{same complexity}}$

Spontaneous processes $\Delta S > 0$ *occupy previously empty config. space*

⇨ *Set off* <u>*process i → f*</u> *by heating* → $\boxed{Macroscopic\ TD: \Delta S_{if} = \dfrac{q}{T} > 0}$ **Heat transfer**

"heating" increases system randomness in transfer $\Delta E = q$ *in many*

$\boxed{n \approx (q/k_B T)\ steps}$ → *even distribution over all dof* $\langle E \rangle / dof \propto k_B T$

Agenda

Energy conservation, conversion, and transformation

- Geothermal energy production
  - U.S./global geothermal resources
  - Power plant,
  - Heat exchange, entropy

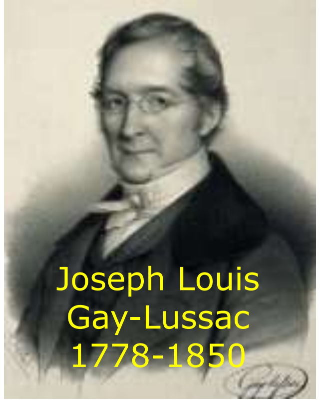
- Thermodynamics (Cont’d Thermal work and energy)
  - Ideal gas EoS,
  - Thermal processes, equilibration,
  - Cyclic processes,
  - Thermal engines, heat pumps

- Conventional thermal power plants
  - Real gases/substances
  - Steam and gas turbines
  - Fossil fuel combustion
  - Carbon capture & sequestration

Thermodynamics: Ideal-Gas Equations of State EoS

Robert Boyle
1627-1691

Guillaume
Amontons
1663-1705



Joseph Louis
Gay-Lussac
1778-1850

Robert Boyle, Guillaume Amontons, Gay-Lussac, Dalton,..

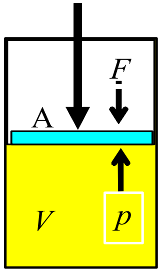
Response of dilute gases of specified amounts (#moles = *n, Avogadro*)

Boyle's Law $P(V)\propto 1/V$ or $\boxed{P\cdot V=const(n,T)}$

Amontons' (Gay−Lussac's) Law $\boxed{P(T)=P(0)\cdot\left[1+\alpha\cdot T_C\right]\propto T}$

Charles' Law $V(T_C)=V(0^0C)\cdot\left[1+\alpha\cdot T_C\right]\rightarrow\boxed{V(T)\propto T}$ *(Kelvin)*

Compression



$\alpha \approx 3.66\cdot10^{-3}/^0C \approx 1/273^0C$ → absolute temperature *T*

EoS of Ideal Gases

Isentropic *T*=const. $\boxed{P\cdot V=n\cdot R\cdot T=N\cdot k_B\cdot T}$

Polytropic EoS

Polytrope coefficient $\gamma=C_P/C_V$

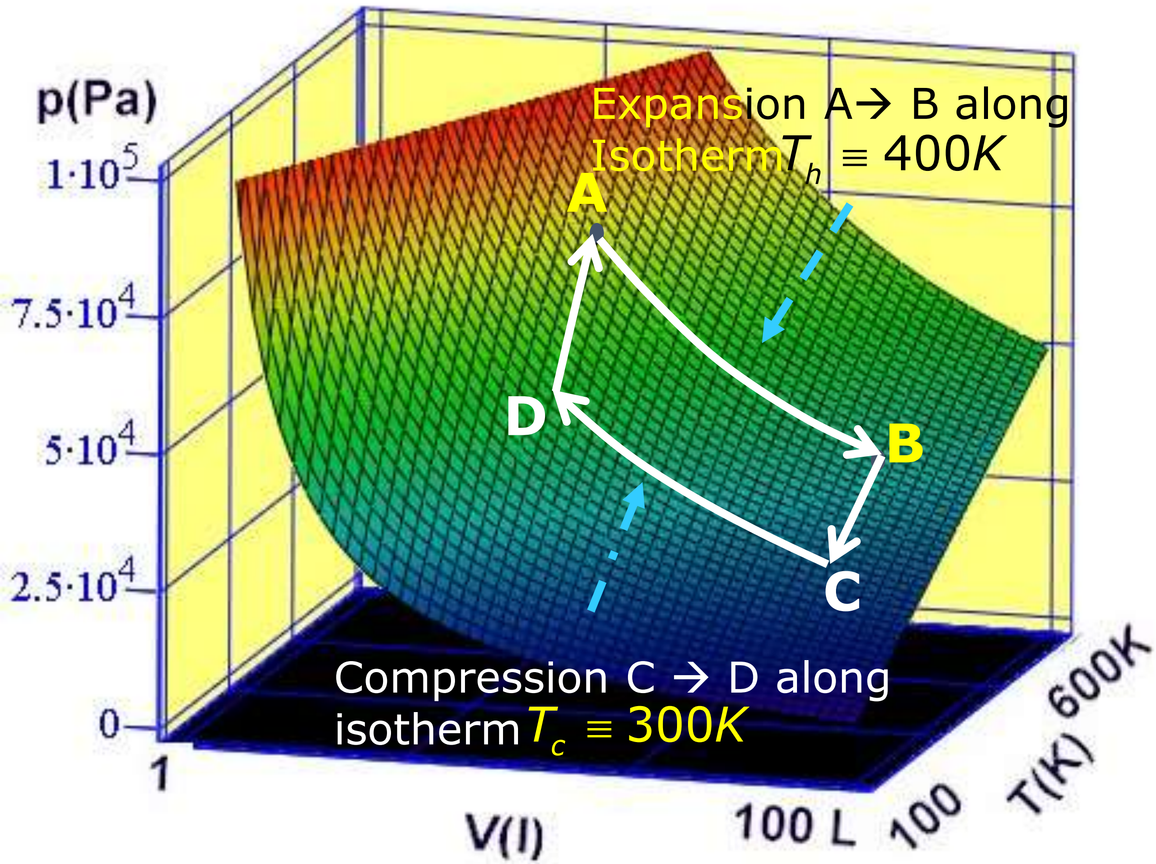
$$\boxed{\begin{array}{l}P\cdot V^{\gamma}=const\,;\\ T\cdot V^{\gamma-1}=const\end{array}}$$

2 Specific Heats @ $P=const.$ *or* $V=const.$

Thermal energy content $\boxed{Q=C_{P,V}\cdot T}$ *Empirical Law*

Reversible Circular Processes on EoS Hyperplane

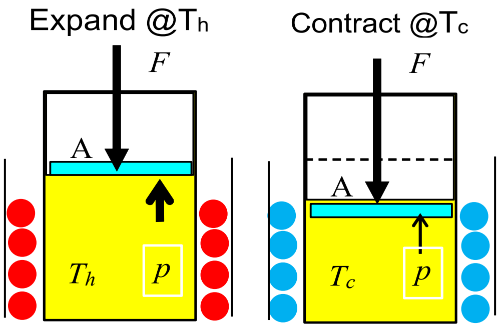
Ideal-Gas EOS $P \cdot V = R \cdot T$



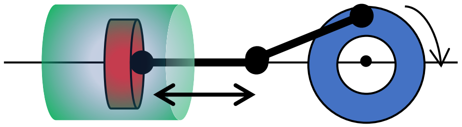
Expansion A→ B along Isotherm $T_h \equiv 400K$

Compression C → D along isotherm $T_c \equiv 300K$

Circular, reversible process
A→B→C→D→A
on the EoS hyperplane



Heating $\boldsymbol{T}_h > \boldsymbol{T}_c$ *Cooling*



returns the IG system to its initial state A after a combination of slow (=reversible) expansion and compression processes.

Ideal Gas Constant *R*

R = 0.0821 liter·atm/mol·K

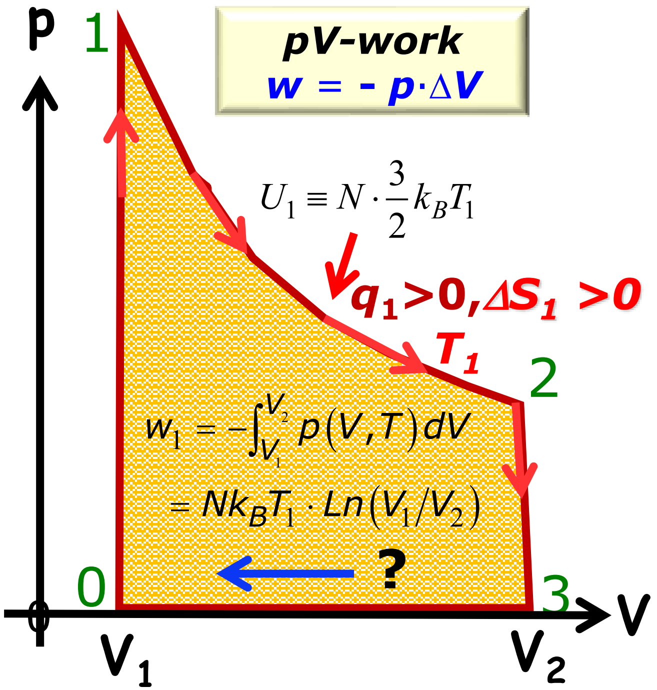
R = 8.3145 J/mol·K

Heat and cool the working IG volume @ specific times → Cyclic thermal engine

Thermal Engine with ***Ideal*** Working Medium

Ideal-gas system (N particles) in alternating contact with Heat Bath @ T_1 and Cold Sink @ $T_2 < T_1$

$EoS: p \cdot V = N \cdot k_B \cdot T$



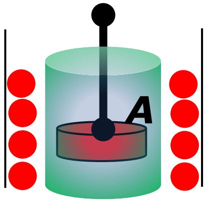
pV-work
$w = -p \cdot \Delta V$

$U_1 \equiv N \cdot \frac{3}{2} k_B T_1$

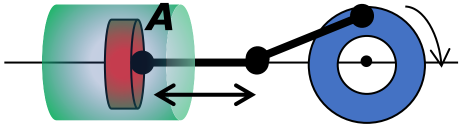
$q_1 > 0, \Delta S_1 > 0$
T_1

$$w_1 = -\int_{V_1}^{V_2} p(V,T)\,dV$$
$$= N k_B T_1 \cdot Ln(V_1/V_2)$$

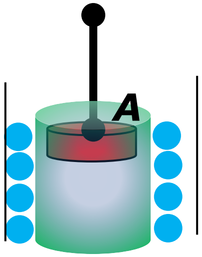
0→1 Heat absorption $q_0 \gg 0$
Isochoric compression
@V_1=const, $w_0=0$



1→2 Isothermal expansion
@T_1=const
gas does work $w_1<0$
absorbs $q_1>0$

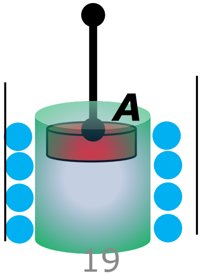


2→3 Isochoric decompression
@V_2=const, $w_2=0$
cools $T_1 \rightarrow T_2$
by emitting $q_2<0$



3→0 compression

0→1 Heating



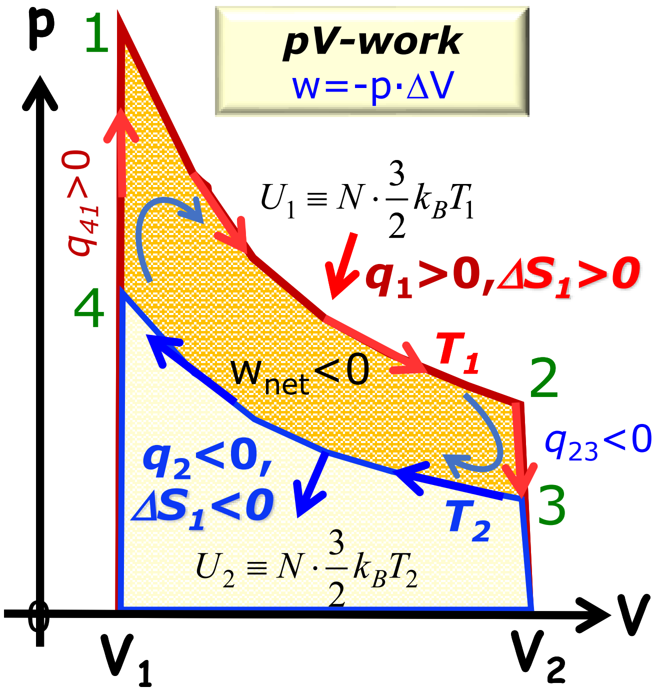
In isothermal expansion, medium does work on surrounding, but its internal energy remains constant: Energy loss is compensated by equal heat absorption → $w_1 = -q < 0$, $\Delta S = (q/T) \propto Ln(V_1/V_2)$

Sign convention: Internal energy gain or loss

Thermal Engine with ***Ideal*** Working Medium

Ideal-gas system (N particles) in alternating contact with Heat Bath @ T_1 and Cold Sink @ $T_2 < T_1$

$$EoS: p \cdot V = N \cdot k_B \cdot T$$

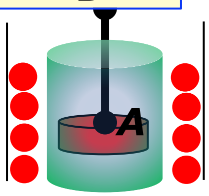


In one cycle the gas absorbs net heat energy and does the net work, $\Delta S_{1\text{-}1}=0$

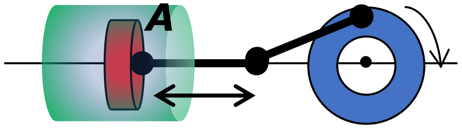
$w_{net} = w_1+w_2=-\Delta q=C_V \cdot [T_2-T_1]$, $\Delta S_1=-\Delta S_2$

Closed clockwise CW *p-V* processes enclose negative work done by system.
CCW processes enclose positive work

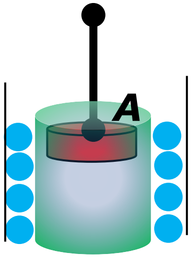
0→1 Heat absorption $q_0 \gg 0$
Isochoric compression
@V_1=const, $w_0=0$



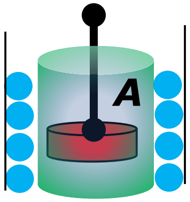
1→2 Isothermal expansion
@T_1=const
gas does work $w_1<0$
absorbs $q_1>0$



2→3 Isochoric decompression
@V_2=const, $w_2=0$
cools $T_1 \rightarrow T_2$
by emitting $q_{23}<0$



3→4 Isothermal compression
@T_2=const<T_1
work done on gas $w_2>0$
needs cooling → emits $q_2<0$

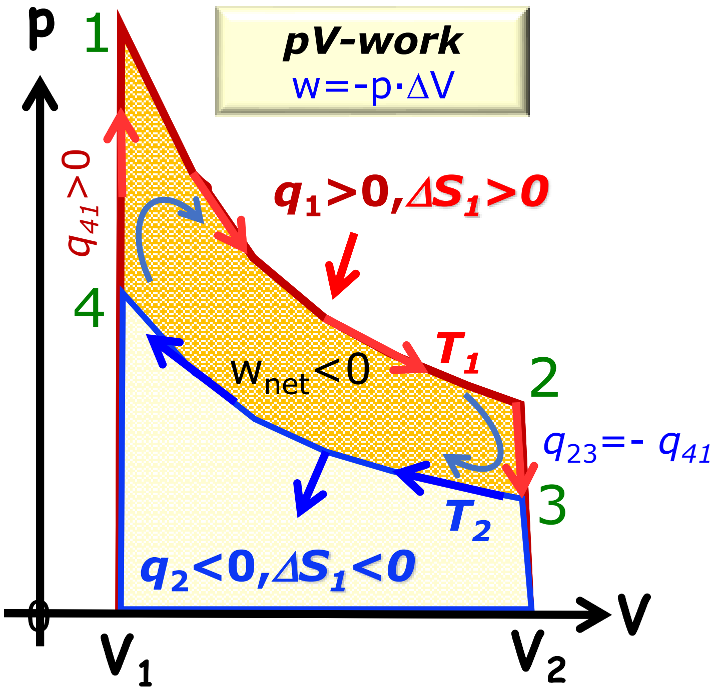


4→1 Isochoric compression@V_1=const,
w=0, heats $T_2 \rightarrow T_1$, by absorbing $q_{41}=-q_{23}$

Thermal Engine with ***Ideal*** Working Medium

Ideal-gas system (N particles) in alternating contact with Heat Bath @ T_1 and Cold Sink @ $T_2 < T_1$

$$\boxed{EoS: p \cdot V = N \cdot k_B \cdot T}$$

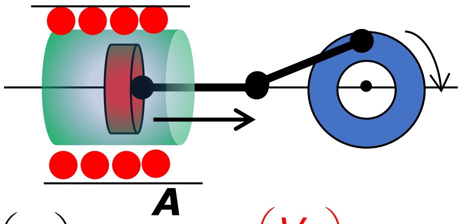


Isochoric legs: No net heat transfer→ no change net ΔS

$$\boxed{q_i = (T \cdot \Delta S)_i \,; \Delta S = |\Delta S_i|}$$

1→2 Isothermal expansion @$\boldsymbol{T_1}$=const

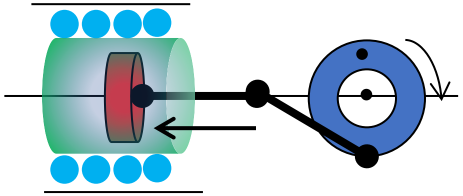
$$w_1 = -\int_{V_1}^{V_2} p(V,T)\,dV$$
$$= Nk_B T_1 \cdot Ln(V_1/V_2)$$



$$\frac{w_1}{T_1} = Nk_B Ln\left(\frac{V_1}{V_2}\right) = \frac{-q_1}{T_1} \to \left(\frac{q}{T}\right)_1 = Nk_B Ln\left(\frac{V_2}{V_1}\right) = \Delta S_1$$

3→4 Isothermal compression @$\boldsymbol{T_2}$<$\boldsymbol{T_1}$

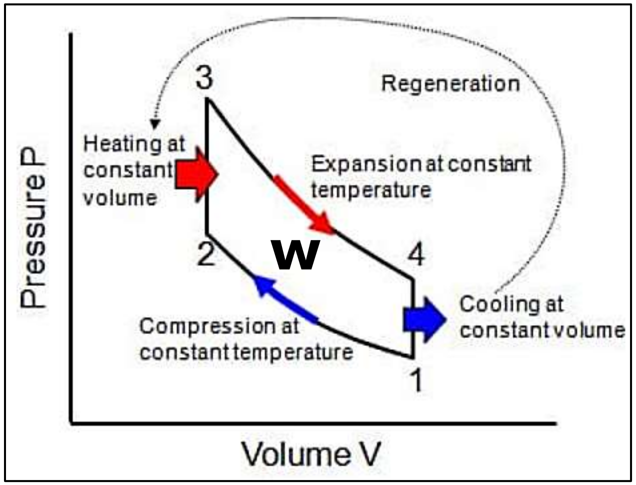
$$w_2 = -\int_{V_2}^{V_1} p(V,T)\,dV$$
$$= -Nk_B T_2 \cdot Ln(V_1/V_2)$$



$$\frac{w_2}{T_2} = Nk_B Ln\left(\frac{V_2}{V_1}\right) = \frac{-q_2}{T_2} \to \left(\frac{q}{T}\right)_2 = Nk_B Ln\left(\frac{V_1}{V_2}\right) = \Delta S_2$$

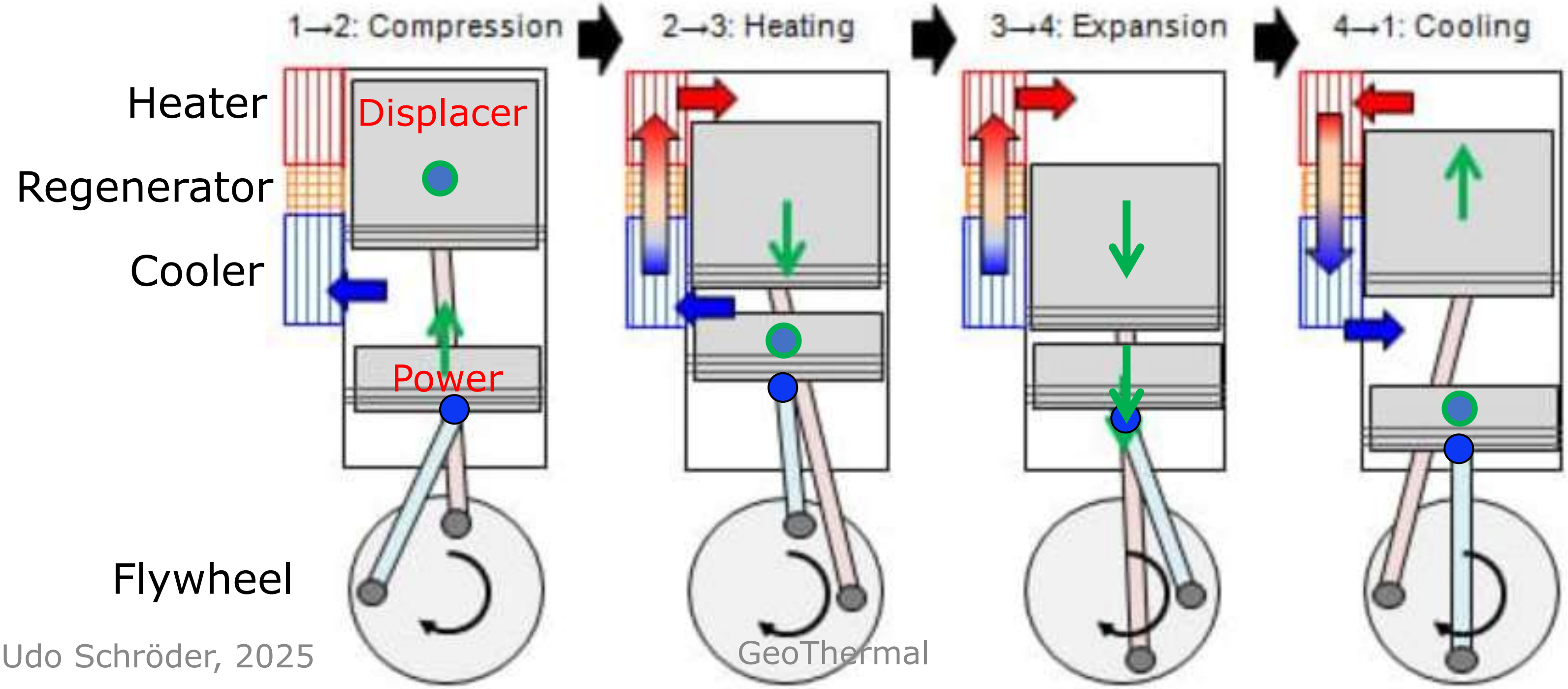
$$\boxed{\Delta S_1 = -\Delta S_2}$$

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,..

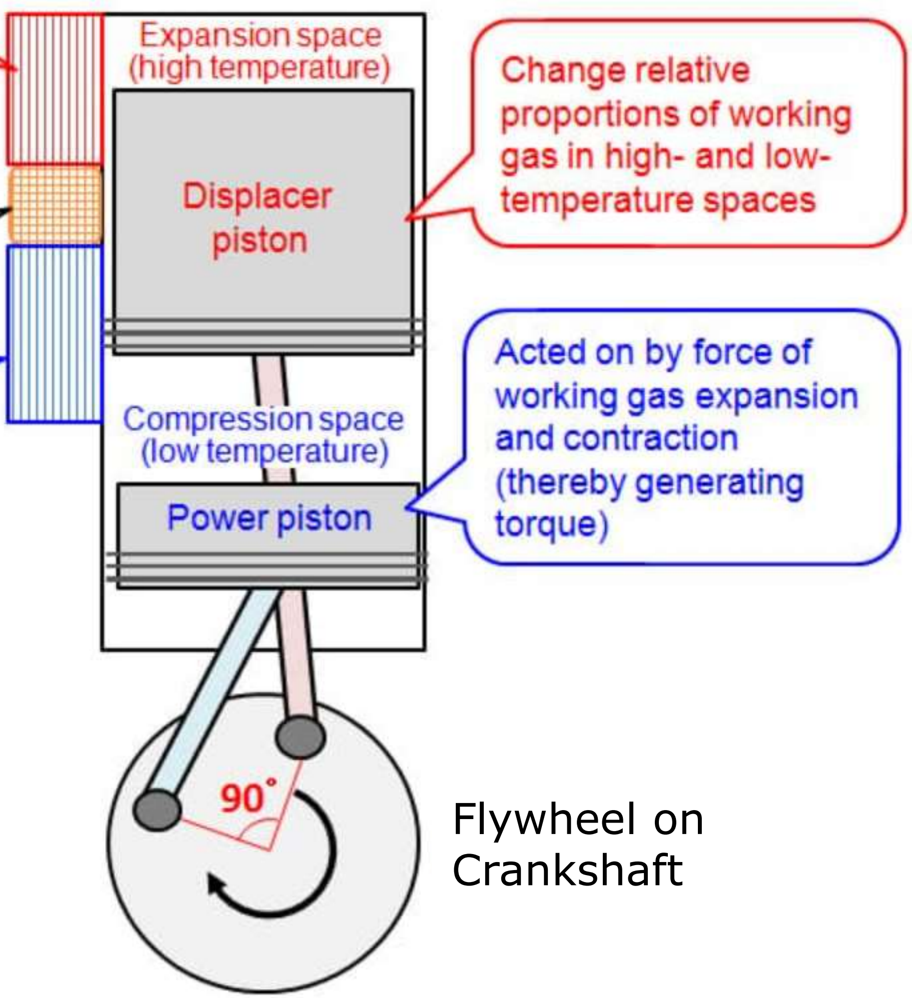


Stirling Heat Engine: Components

Heater
(Heat exchanger for heating)

Regenerator
(Heat exchanger for accumulated heat)

Cooler
(Heat exchanger for cooling)

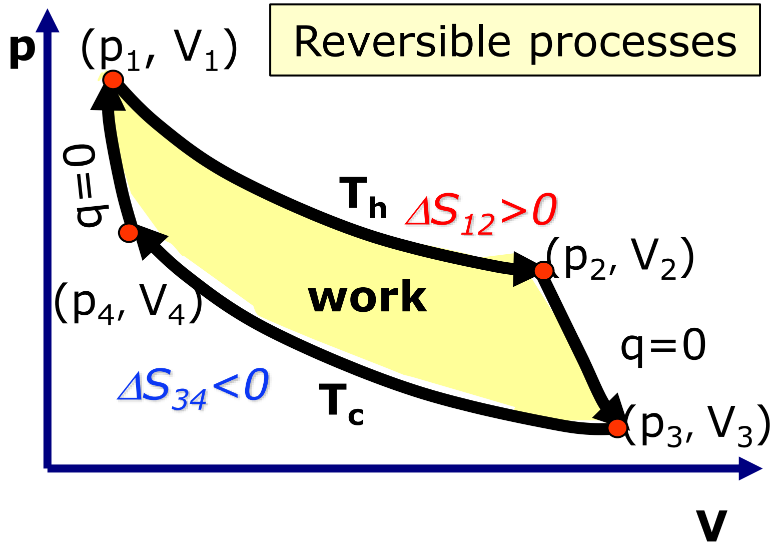


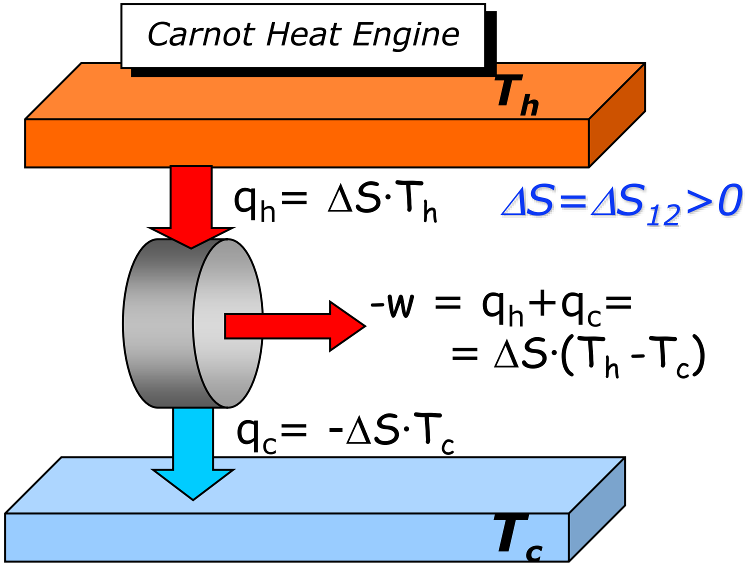
Change relative proportions of working gas in high- and low-temperature spaces

Acted on by force of working gas expansion and contraction (thereby generating torque)

Flywheel on Crankshaft

Entropy Flow in Carnot Engines

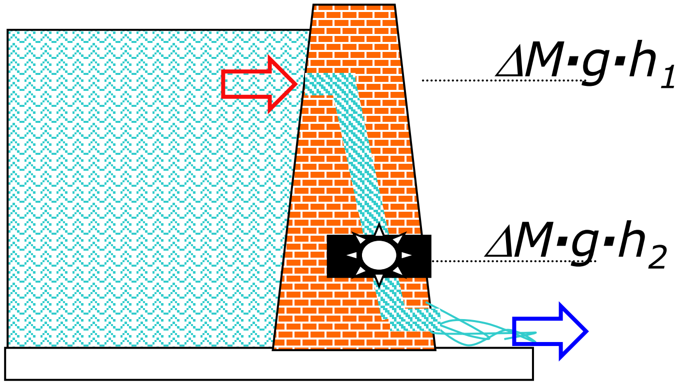




$$\varepsilon = \frac{-w}{q_h} = \frac{q_h + q_c}{q_h}$$

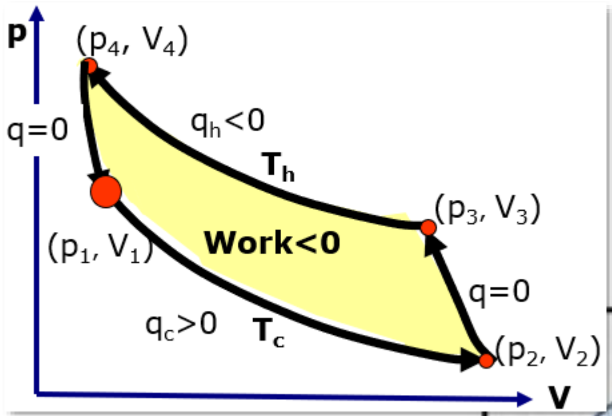
$$\varepsilon = 1 + \frac{q_c}{q_h} = 1 - \frac{T_c}{T_h} \xrightarrow[T_h \to \infty]{} 1$$

Hydrodynamic Power Plant

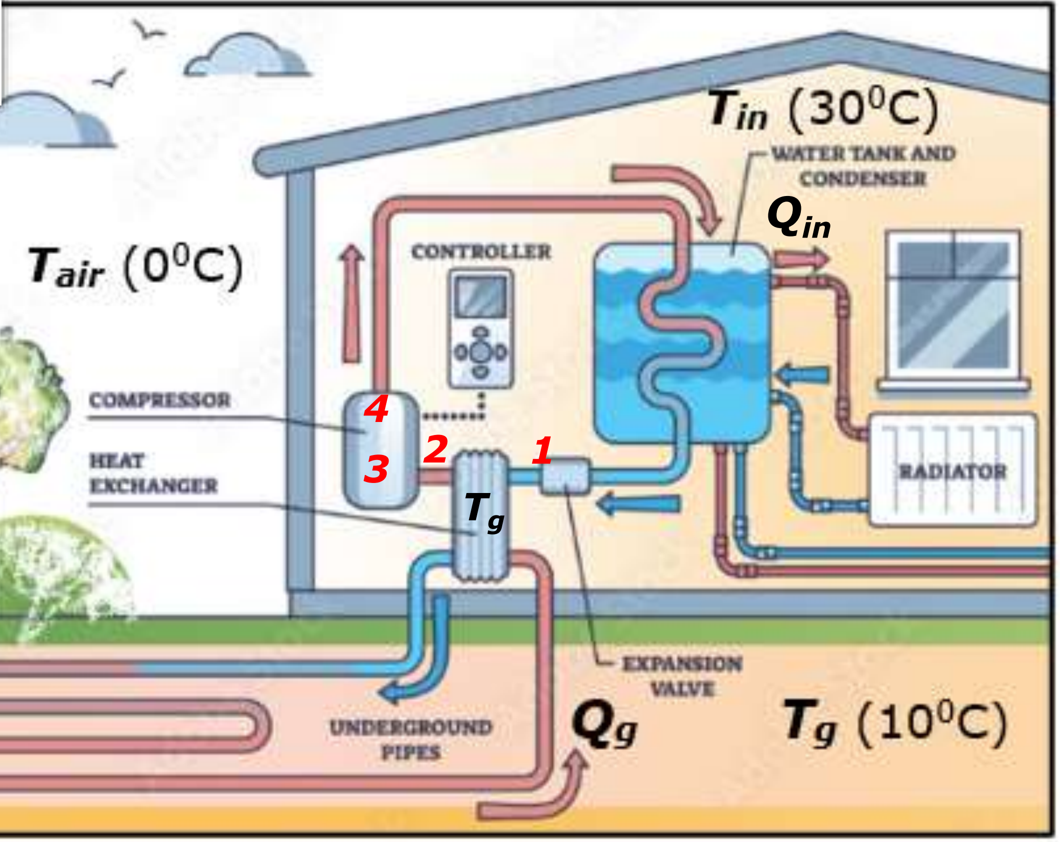


Water stream from reservoir carries energy driving an electric generator.

Residential Heat Pump



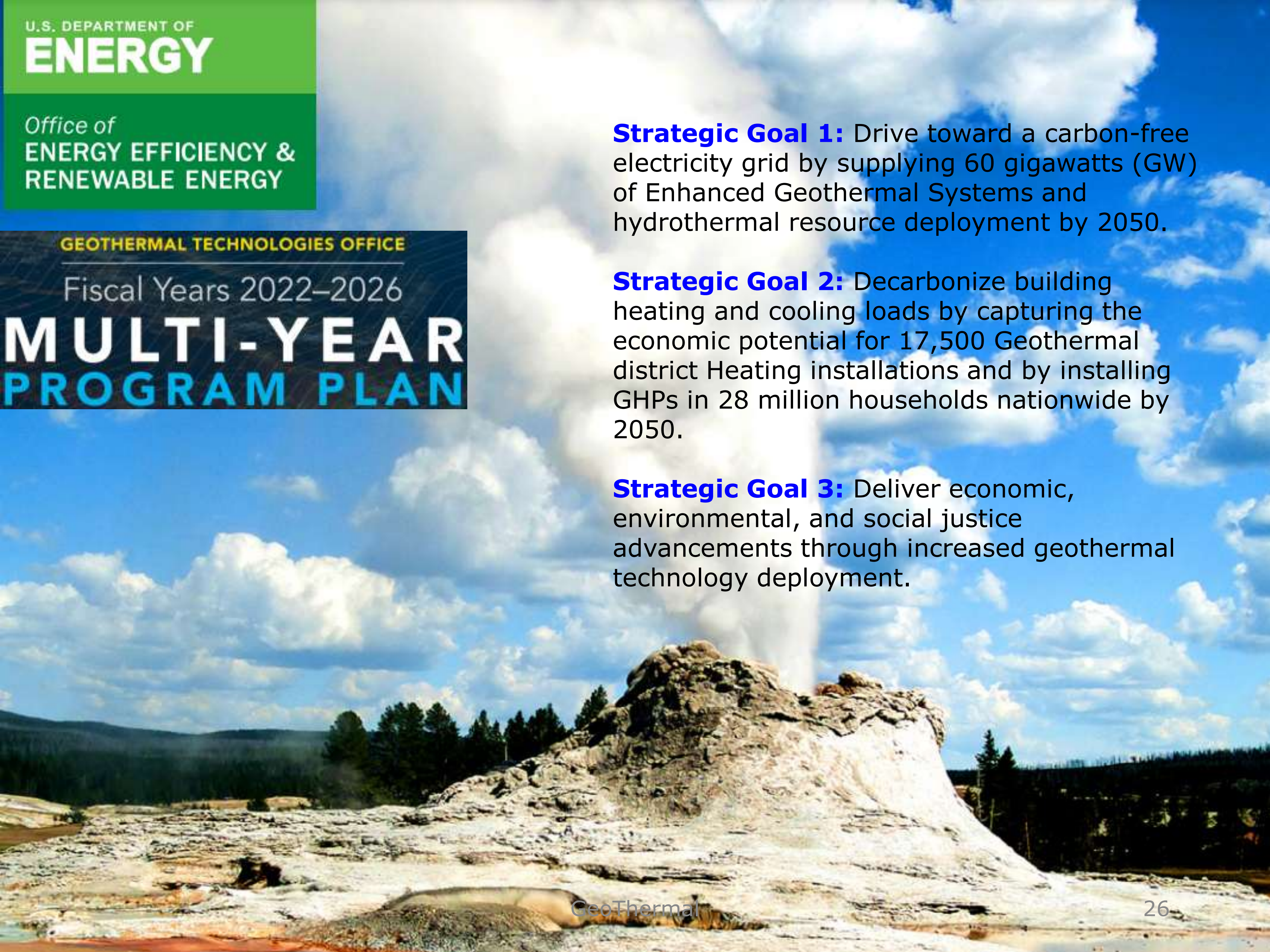
Carnot heating: In-ground heat pump absorbs heat energy $\boldsymbol{Q_g \approx \Delta S \cdot T_g}$ from under ground $\boldsymbol{T_g}$ heat bath to preheat expanded work fluid/gas. Compressor provides differential heat $\boldsymbol{Q_{in} \approx - \Delta S \cdot T_{in}}$ required for sustaining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

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



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.