Energy and Exergy Efficiencies of Geothermal Power Plants

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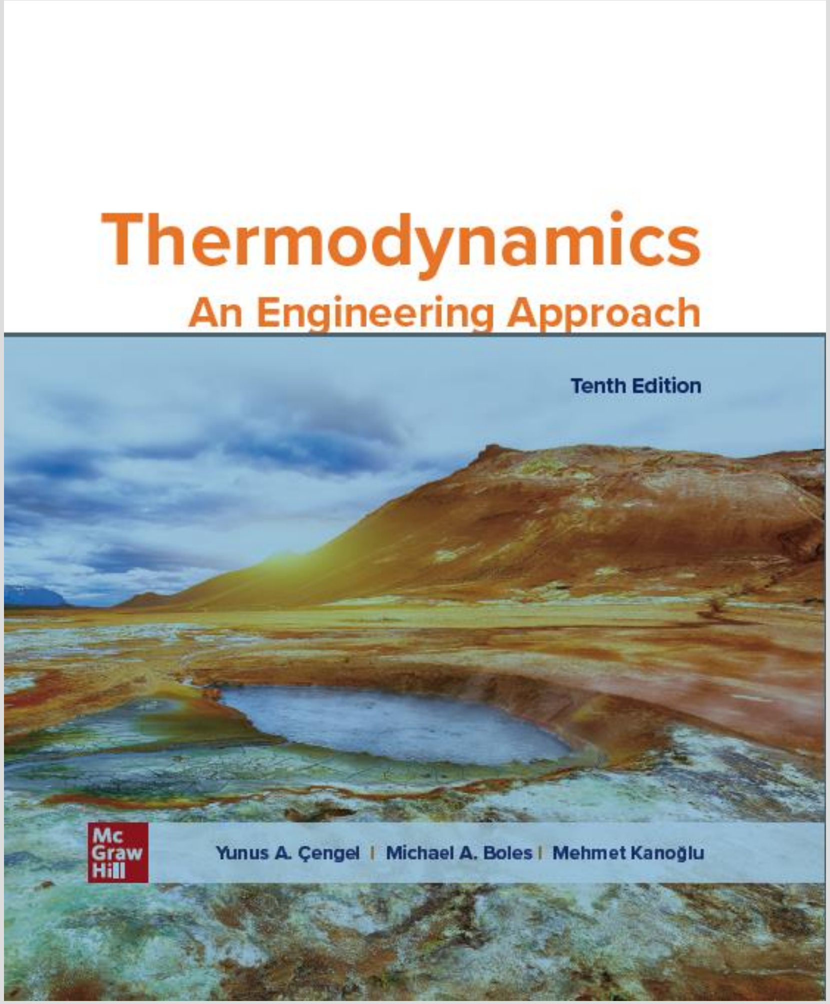
Acknowledgement

This presentation is partly based on the papers below and the 10th ed. of the textbook:

Çengel, Y. A.,
"**Power generation potential of LNG regasification terminals**," *Int J Energy Res. Pp. 1-12,* 2020.



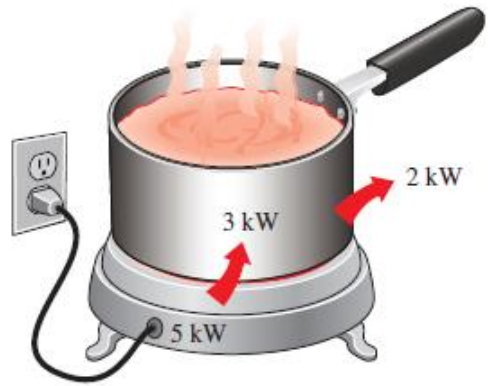
Unless otherwise specified, the artwork is picked from Google images.

Introduction:

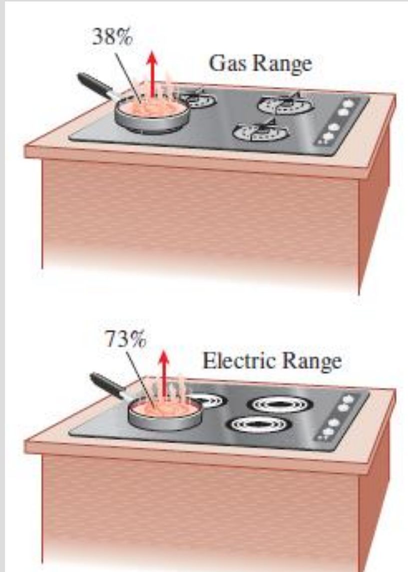
Entropy, Exergy, 2nd Law Efficiency

Efficiency definitions:
Can be vague and confusing

$$\text{Efficiency (performance)} = \frac{\text{Desired output}}{\text{Required input}}$$



$$\text{Efficiency} = \frac{\text{Energy utilized}}{\text{Energy supplied to appliance}} = \frac{3\ \text{kWh}}{5\ \text{kWh}} = 0.60$$



Water heater

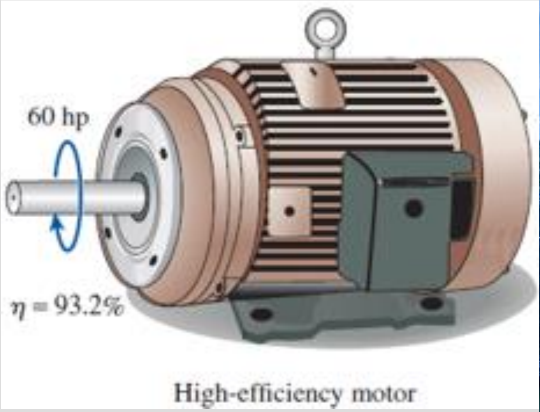
Type	Efficiency
Gas, conventional	55%
Gas, high-efficiency	62%
Electric, conventional	90%
Electric, high-efficiency	94%

$$\eta_{\text{comb equip}} = \frac{\dot{Q}_{\text{useful}}}{\dot{E}_{\text{fuel}}} = \frac{\dot{Q}_{\text{useful}}}{\dot{m}_{\text{fuel}}\text{HV}_{\text{fuel}}} = \frac{\text{Rate of useful heat delivered, kJ/s}}{\text{Rate of chemical fuel energy consumed, kJ/s}}$$

Exergy: Work Potential of Energy

The atmosphere: Infinite energy; but zero work potential

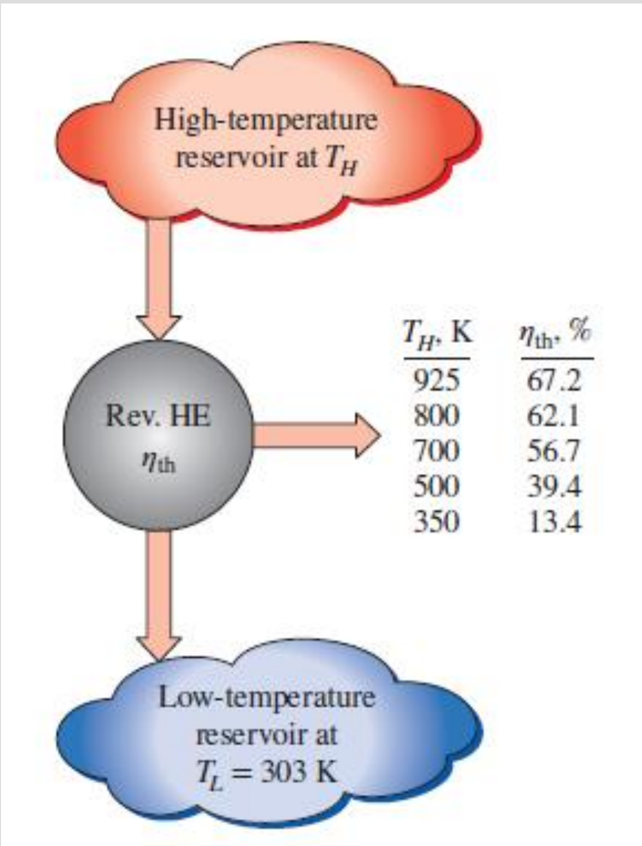
The useful work potential of a given amount of energy at some specified state in a given environment is called *exergy*.



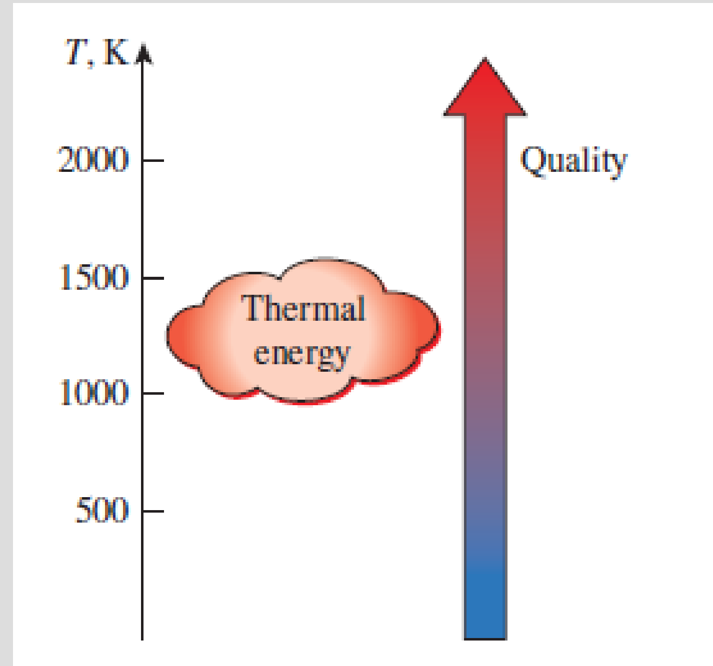
At $T < T_{surroundings}$, the lower the resource temperature, the better.

The **higher** the ‘**hot**’ resource temperature, the higher the efficiency

The **lower** the ‘**cold**’ resource temperature, the higher the efficiency



$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$



The fraction of heat that can be converted to work as a function of source temperature.

The higher the temperature of the thermal energy, the higher its quality (exergy).

Source: Cengel, et al. Thermodynamics: An Engineering Approach, 10th ed., McGraw-Hill, Figs. 6-48 and 6-49.

The 2nd-law (or exergy) efficiency:

η_{II} = Actual performance/Best possible performance

$$\eta_{II} = \frac{\text{Exergy recovered}}{\text{Exergy expended}} = 1 - \frac{\text{Exergy destroyed}}{\text{Exergy expended}}$$

$$\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}} \quad \text{(heat engines)}$$

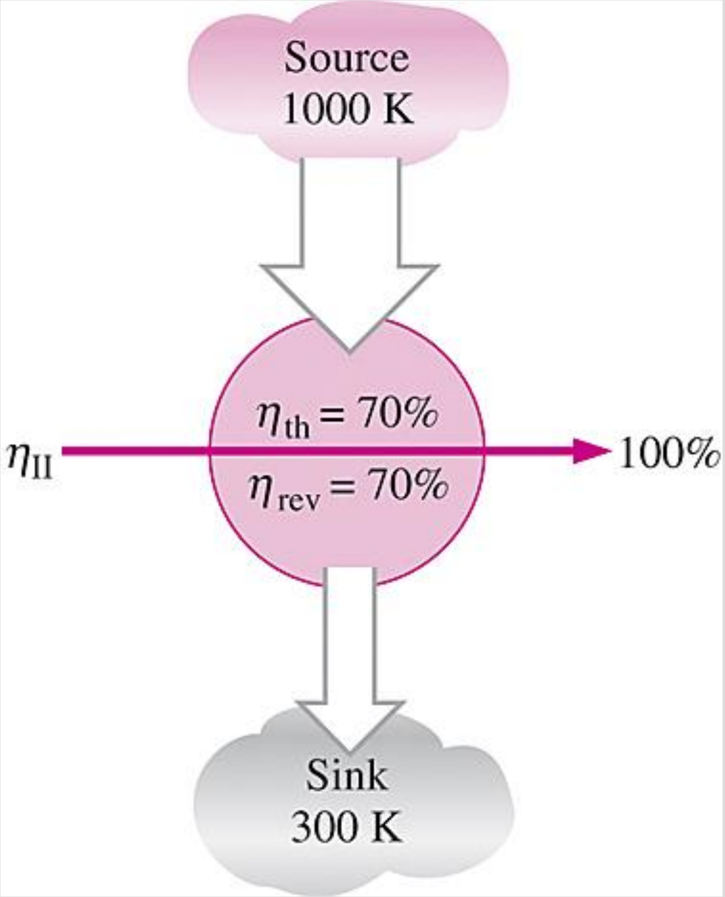
$$\eta_{II} = \frac{W_u}{W_{rev}} \quad \text{(work-producing devices)}$$

$$\eta_{II} = \frac{W_{rev}}{W_u} \quad \text{(work-consuming devices)}$$

$$\eta_{II} = \frac{\text{COP}}{\text{COP}_{rev}} \quad \text{(refrigerators and heat pumps)}$$

The 2nd-law efficiency:

η_{II} = 100% for all reversible devices and processes (perfection)



Q: Can the 2nd-law efficiency be greater than 1st-law efficiency?

Source: Cengel, et al. Thermodynamics: An Engineering Approach, 10th ed., McGraw-Hill, Fig. 9-16.

Electric resistance heaters:

Efficiency: 100%

Yet very wasteful (conversion of electricity to heat)

Heat pumps: COP of 4

Entropy analysis or exergy analysis?
Which is simpler and more meaningful?

Entropy balance: Entropy change = Entropy transfer + Entropy generation

$$\underbrace{S_{in} - S_{out}}_{\substack{\text{Net entropy transfer} \\ \text{by heat and mass}}} + \underbrace{S_{gen}}_{\substack{\text{Entropy} \\ \text{generation}}} = \underbrace{\Delta S_{\text{system}}}_{\substack{\text{Change} \\ \text{in entropy}}}$$

Exergy balance: Exergy change = Exergy transfer - Exergy destruction

$$\underbrace{X_{in} - X_{out}}_{\substack{\text{Net exergy transfer} \\ \text{by heat, work, and mass}}} - \underbrace{X_{\text{destroyed}}}_{\substack{\text{Exergy} \\ \text{destruction}}} = \underbrace{\Delta X_{\text{system}}}_{\substack{\text{Change} \\ \text{in exergy}}}$$

Entropy generation = Exergy destruction÷Room temperature

2nd law efficiency:
A measure of perfection

- **A process with a 2nd law efficiency of 100%:**

  - Is perfect (even if its 1st law efficiency is less than 100%).

  - Entropy generation = 0

  - Exergy destruction = 0

  - Waste = 0

- Something cannot be more perfect than perfect (e.g., reversible processes/cycles).

- The 2nd law defines the upper limit of excellence on performance.

- **Aim of the 2nd Law: 'Perfection' and 'Zero waste'.**

Geothermal Power Plants (Binary):

Energy and Exergy Efficiencies

WHAT IS Geothermal Energy?

Fast Facts

Renewable: Geothermal power plants around the world are still running after 50+ years. And geothermal heat has been used throughout human history!

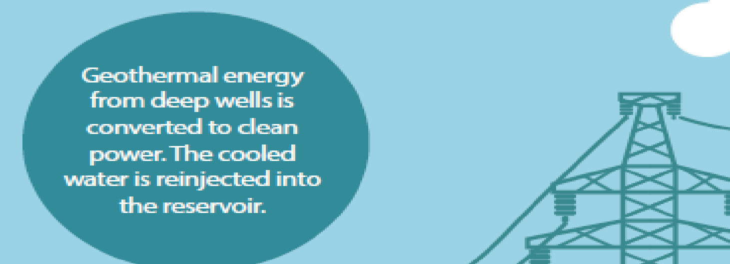
Reliable: Geothermal is always available, regardless of weather conditions.

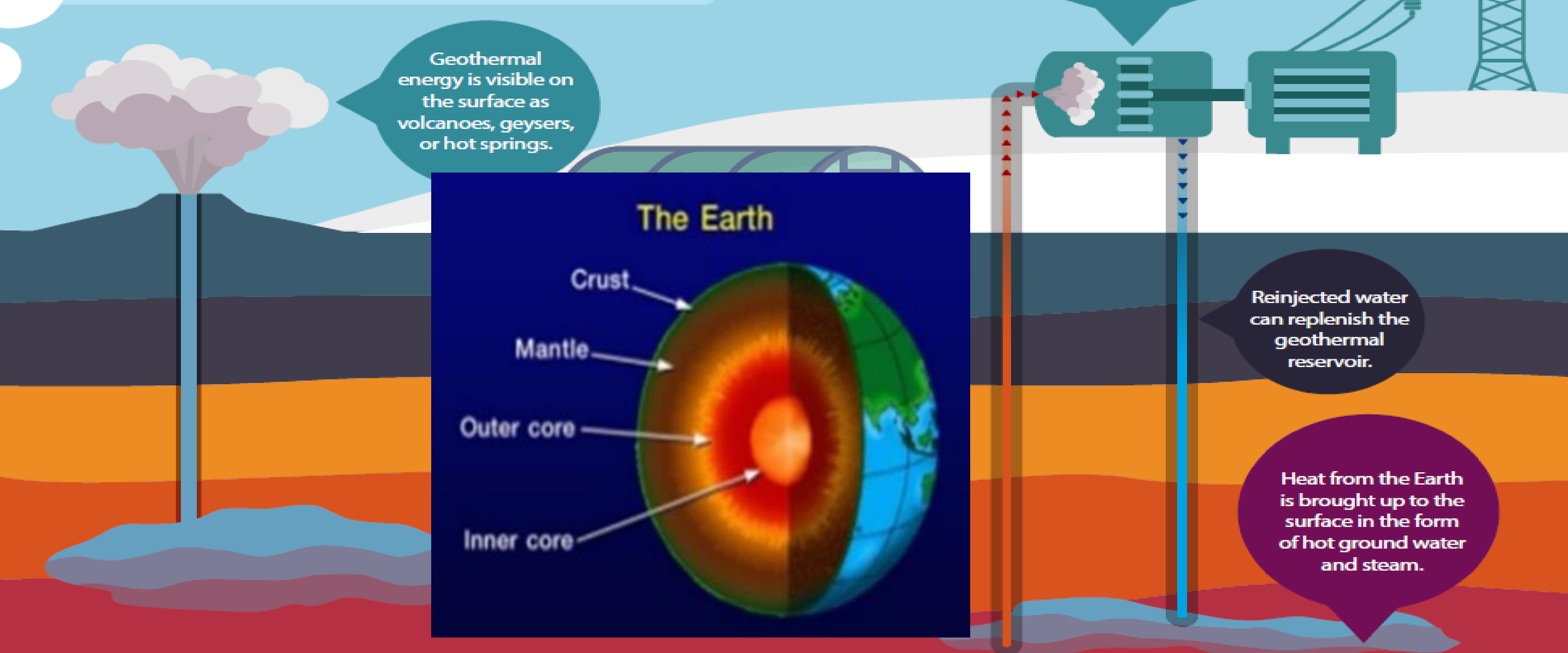
Clean: Geothermal emissions are as low as solar, wind, and hydropower.

GEOTHERMAL

GEO — "Earth" THERMAL — "Heat"

Literally "**heat from the earth**," geothermal energy is a renewable energy heat source found under the surface of the earth.

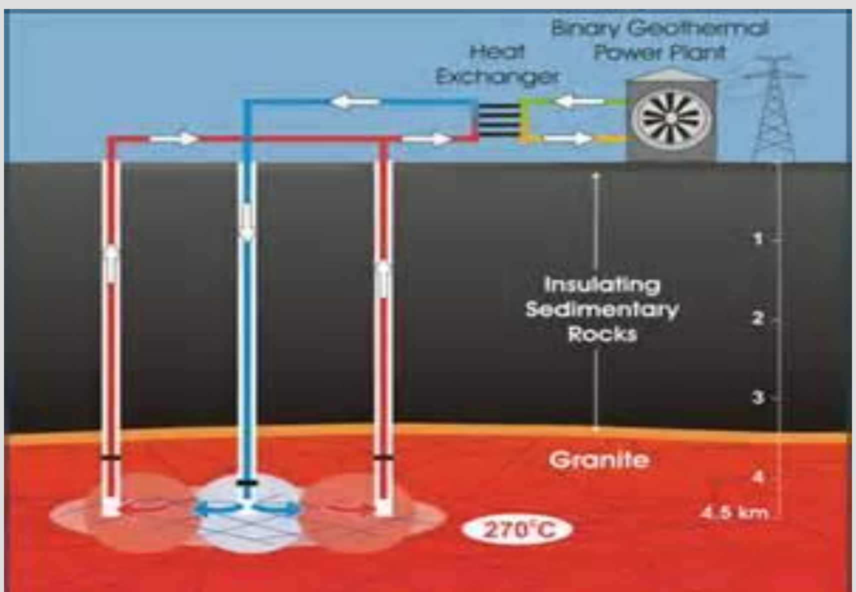




https://www.energy.gov/sites/default/files/2023-02/DOE-EE-2680-GTO-Geothermal-Overview-8-5x11.pdf

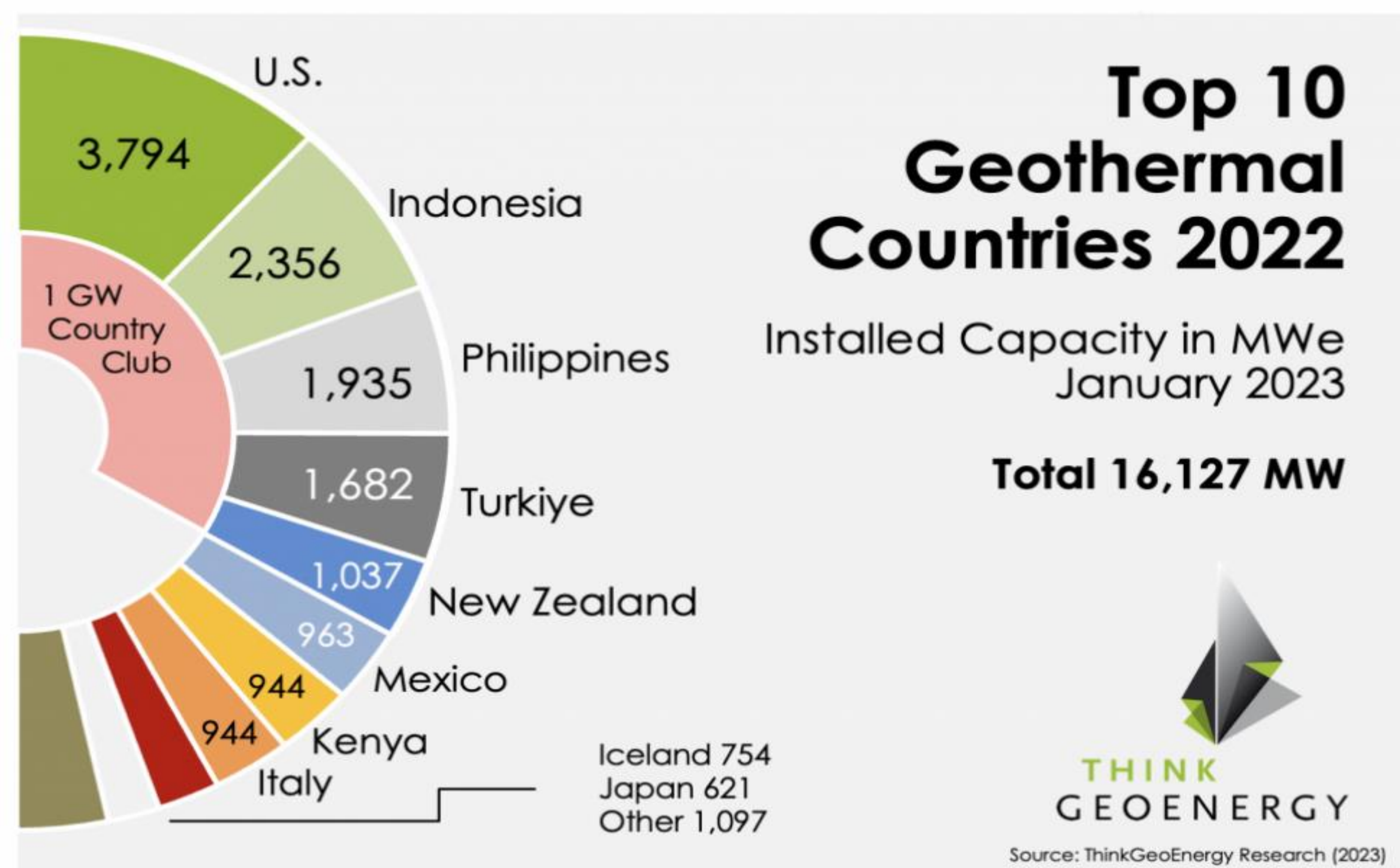
Geothermal energy

Magma energy → Hot water/steam



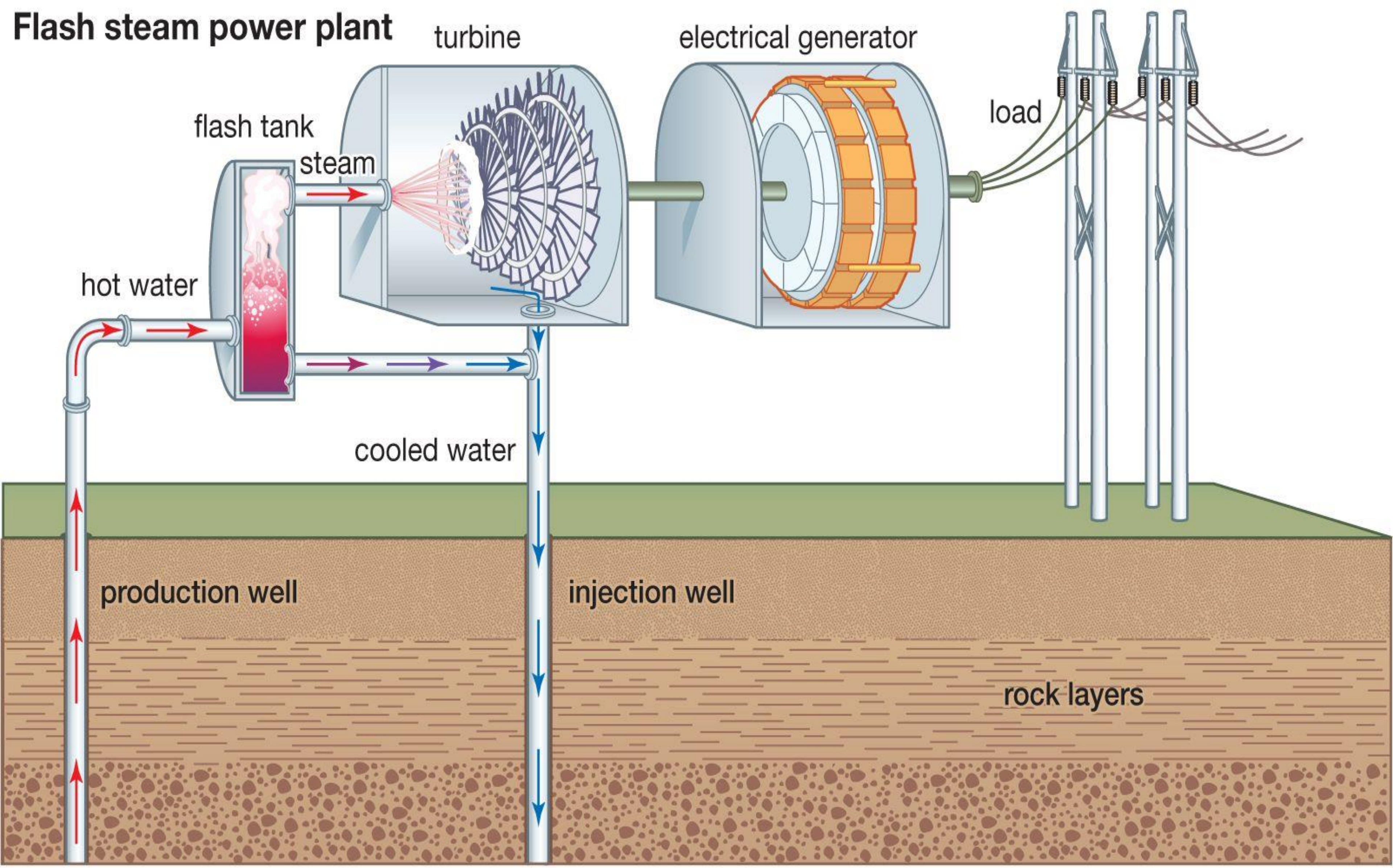
Worldwide: 555 geothermal power plants, 16.1 GW (Jan 2023)

Turkiye: 60 plants, 1.7 GW

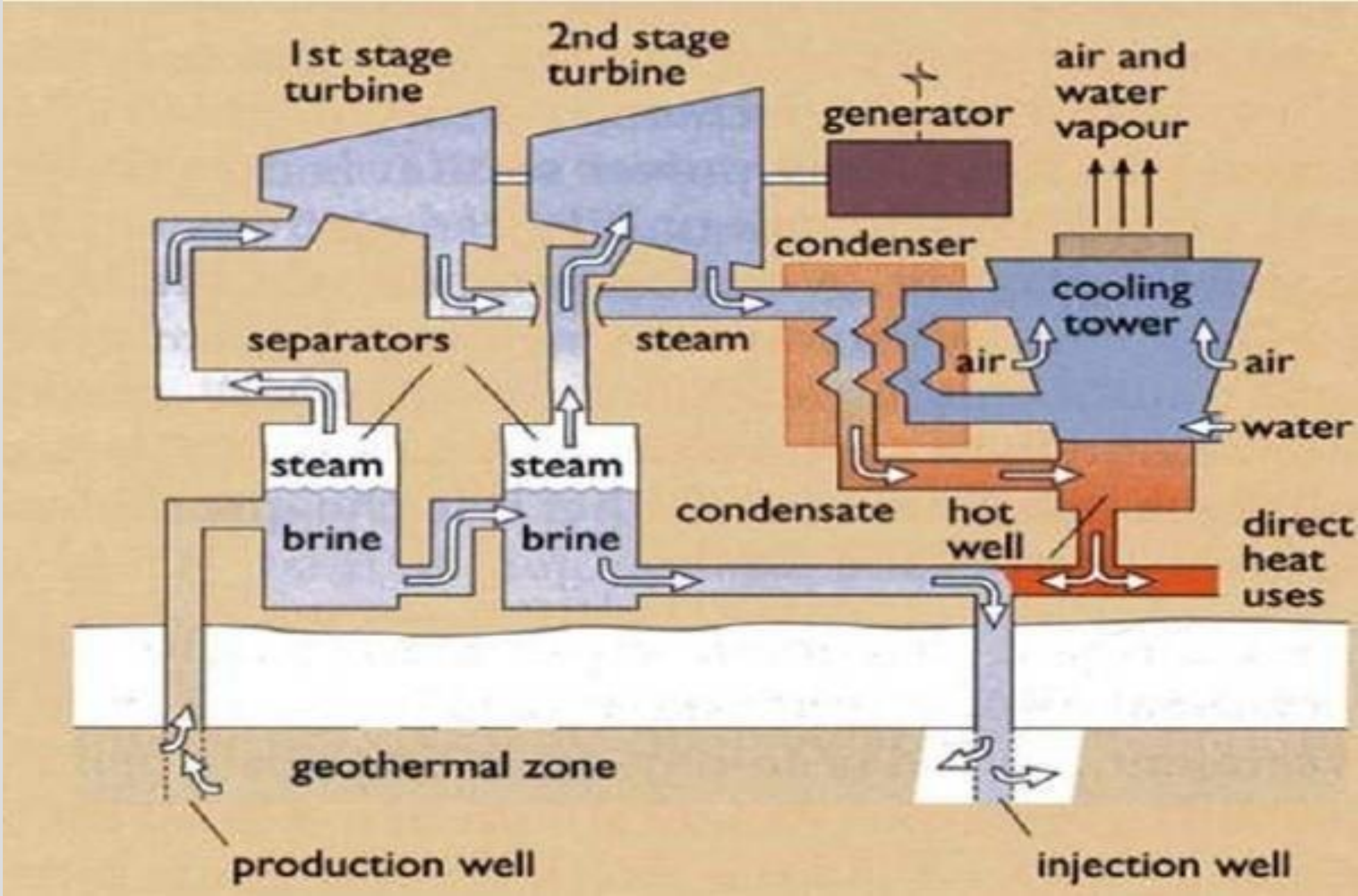


https://www.thinkgeoenergy.com/thinkgeoenergys-top-10-geothermal-countries-2022-power-generation-capacity-mw/

Geothermal power plants:
Single flash systems (direct expansion)

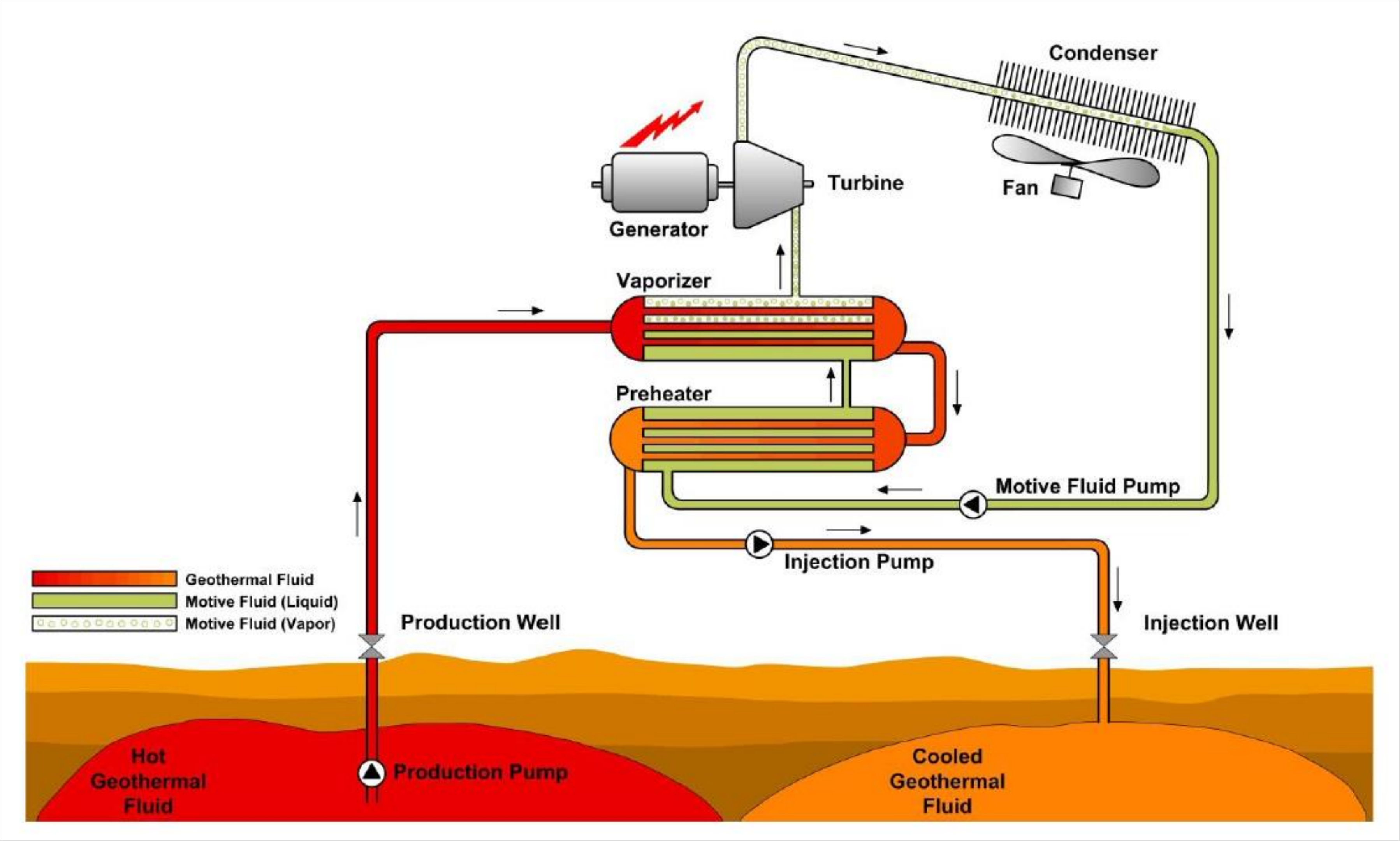


Geothermal power plants:
Double flash systems



Binary geothermal power plant

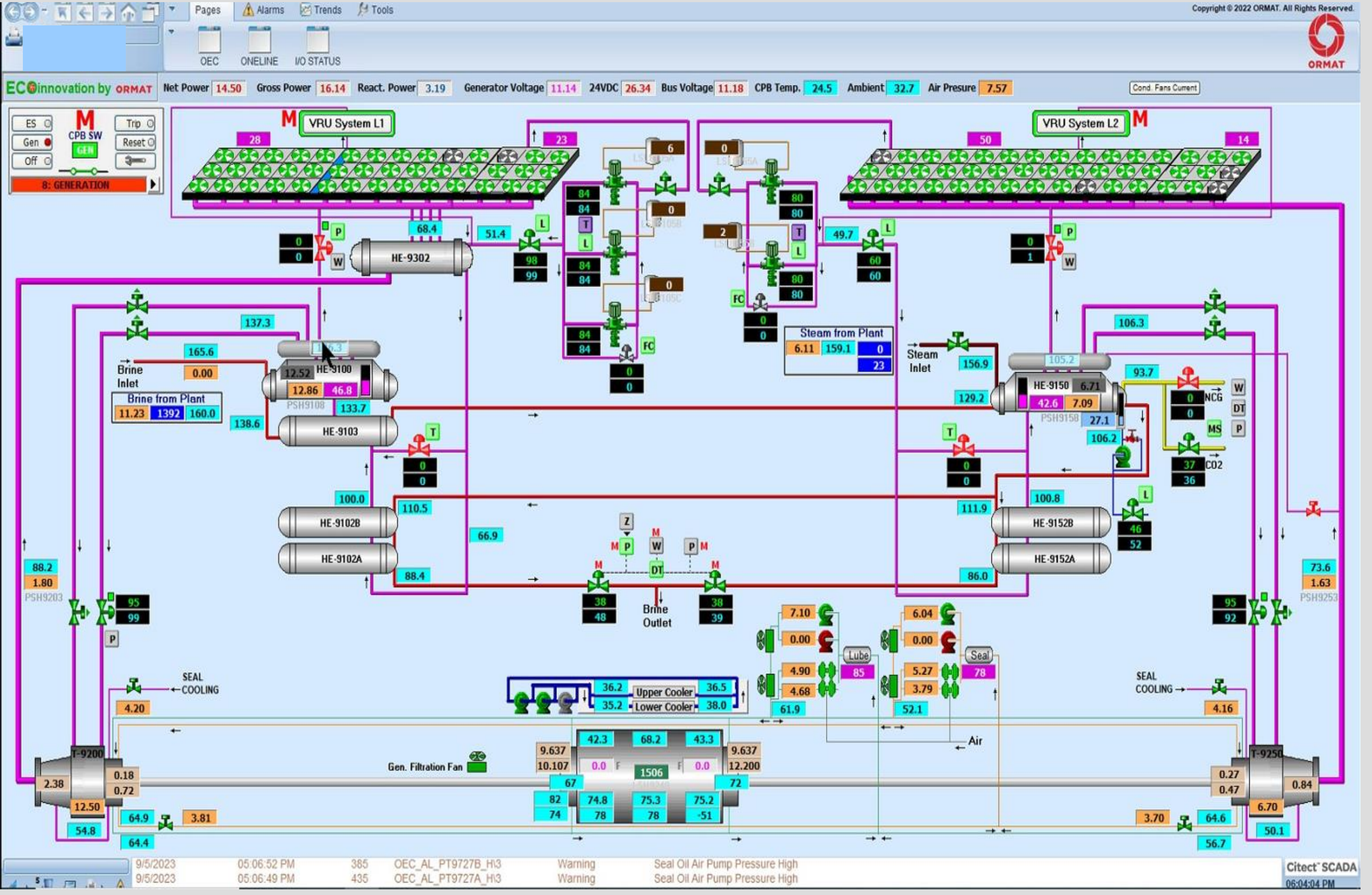
(A typical power plant has two such cycles: HP and LP)



Source: Ormat Technologies, Inc.

A geothermal power plant in Germencik, Turkiye:

A Scada screen (plant schematic and m, T, P, W values)



A geothermal power plant in Germencik, Turkiye:

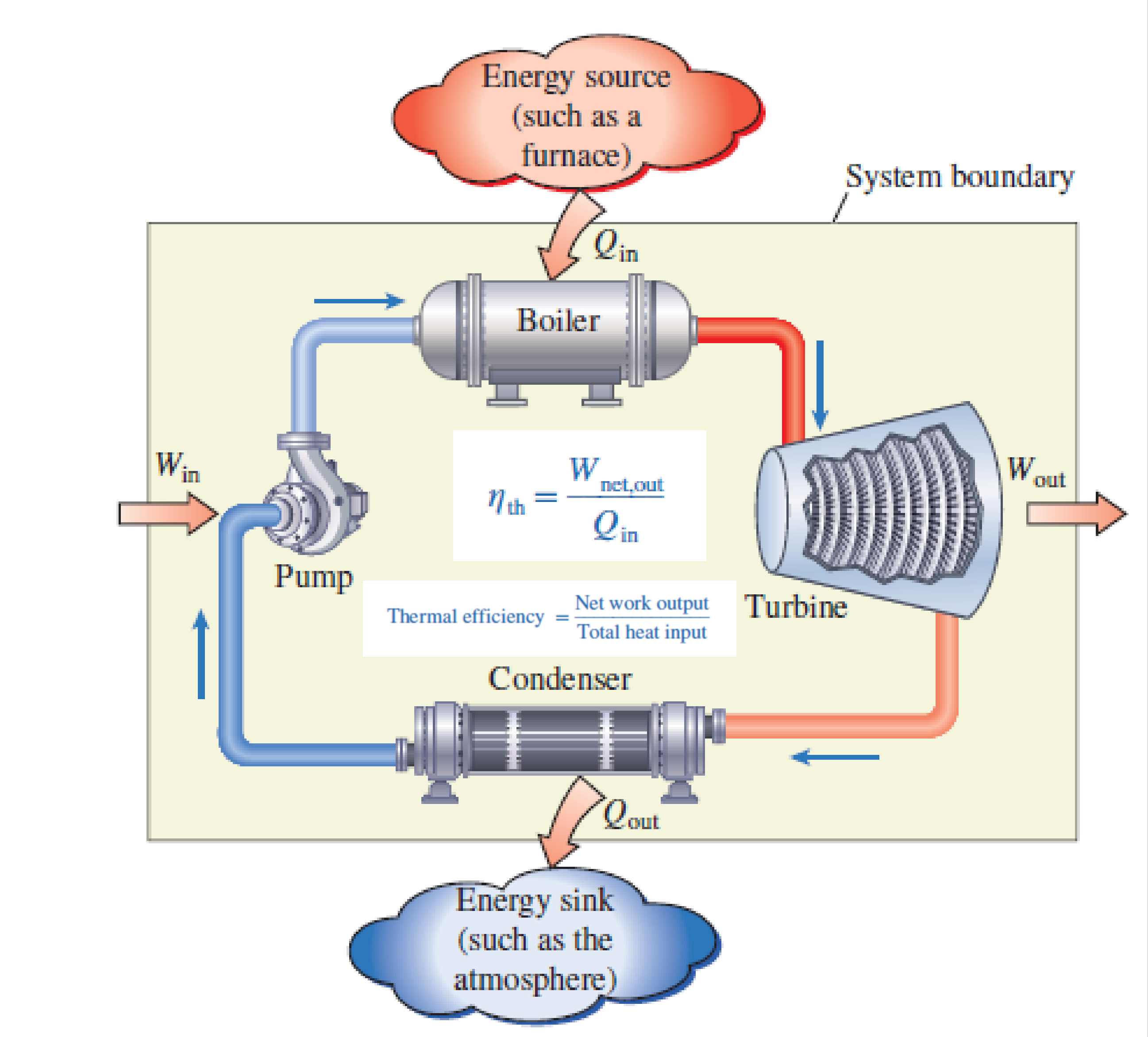
A heat exchanger (vaporizer)

Photo by Yunus Çengel

A geothermal power plant in Germencik, Turkiye:
A heat exchanger (condenser – Air cooled system)

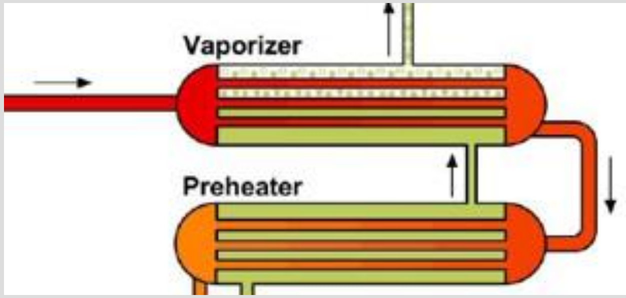
Photo by Yunus Çengel

A basic closed power cycle:
(Coal, natural gas, geothermal, nuclear, etc. power plants)



Source: Cengel, et al. Thermodynamics: An Engineering Approach, 10th ed., McGraw-Hill, Fig. 6-10.

‘Gross’ energy efficiency of a geothermal power plant
(Based on gross electricity generation)



Geothermal energy consumption in a geothermal power plant:

$$E_{\text{geothermal}} = \Delta E_{\text{brine}} + \Delta E_{\text{steam\&NCG}}$$

Or:

$$\begin{aligned} E_{\text{geothermal}} &= m_{\text{brine}}(h_{\text{brine,in}} - h_{\text{reinject,out}}) \\ &+(m_{\text{steam,in}} h_{\text{steam,in}} - m_{\text{condensate}} h_{\text{condensate}} - m_{\text{discharged steam}} h_{\text{discharged steam}}) \\ &+ m_{\text{NCG}}(h_{\text{NCG, in}} - h_{\text{NCG, out}}) \end{aligned}$$

Geothermal plant **gross efficiency** = gross electricity generated by the generator/geothermal energy consumed:

$$\eta_{\text{gross}} = \frac{W_{\text{electric,gross}}}{E_{\text{geothermal}}} = \frac{W_{\text{electric,gross}}}{\Delta E_{\text{brine}} + \Delta E_{\text{steam\&NCG}}}$$

Usually between 10% and 15%

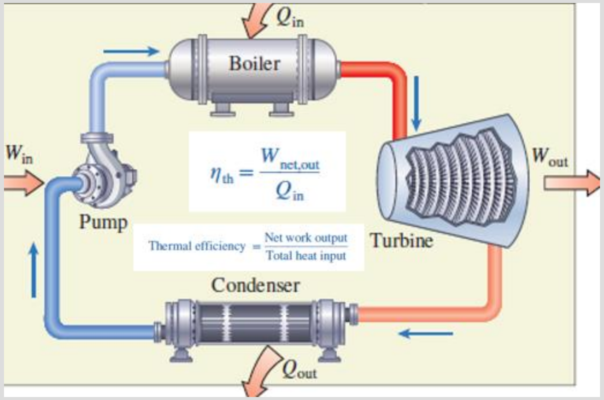
‘Net’ and ‘overall’ efficiency of a geothermal power plant
(Based on net and commercial electricity generation)

Geothermal energy consumption in a geothermal power plant:

$$
\begin{aligned}
E_{geothermal} &= \Delta E_{brine} + \Delta E_{steam\&NCG} \\
&= m_{brine}(h_{brine,in} - h_{reinject,out}) \\
&+(m_{steam,in} h_{steam,in} - m_{condensate} h_{condensate} - m_{discharged\ steam} h_{discharged\ steam}) \\
&+ m_{NCG}(h_{NCG,in} - h_{NCG,out})
\end{aligned}
$$

Geothermal plant **net efficiency** = net electricity generated by the generator/geothermal energy consumed:

$$\eta_{net} = \frac{W_{electric,\ net}}{E_{geothermal}} = \frac{W_{electric,gross} - W_{fans} - W_{pentane\ pumps}}{\Delta E_{brine} + \Delta E_{steam\&NCG}}$$



Geothermal plant **overall efficiency** = net electricity supplied to the grid/geothermal energy consumed:

$$\eta_{overall} = \frac{W_{electric,\ grid}}{E_{geothermal}} = \frac{W_{electric,gross} - W_{fans} - W_{pentane\ pumps} - W_{well\ pumps}}{\Delta E_{brine} + \Delta E_{steam\&NCG}}$$

Energy efficiency of Level 1 and 2 cycles:
(High-pressure and low-pressure cycles)

$$\eta_{\mathrm{L1-cycle,net}} = \frac{W_{\mathrm{electric,L1,net}}}{E_{\mathrm{geothermal,L1}}} = \frac{\eta_{\mathrm{generator}} W_{\mathrm{mechanical,L1,turbine}} - W_{\mathrm{fans,L1}} - W_{\mathrm{pentane\ pumps,L1}}}{\Delta E_{\mathrm{brine,L1}} + \Delta E_{\mathrm{steam\&NCG,L1}}}$$

$$\eta_{\mathrm{L2-cycle,net}} = \frac{W_{\mathrm{electric,L2,net}}}{E_{\mathrm{geothermal,L2}}} = \frac{\eta_{\mathrm{generator}} W_{\mathrm{mechanical,L2,turbine}} - W_{\mathrm{fans,L2}} - W_{\mathrm{pentane\ pumps,L2}}}{\Delta E_{\mathrm{brine,L2}} + \Delta E_{\mathrm{steam\&NCG,L2}}}$$

$$W_{\mathrm{turbine,L1}} = m_{\mathrm{pentane,L1}}(h_{\mathrm{turbine,L1,in}} - h_{\mathrm{turbine,L1,out}})$$

$$W_{\mathrm{turbine,L2}} = m_{\mathrm{pentane,L2}}(h_{\mathrm{turbine,L2,in}} - h_{\mathrm{turbine,L2,out}})$$

Pentane P and T values are higher at Level 1 cycle, and thus $\eta_{\mathrm{L1-cycle,net}} > \eta_{\mathrm{L2-cycle,net}}$

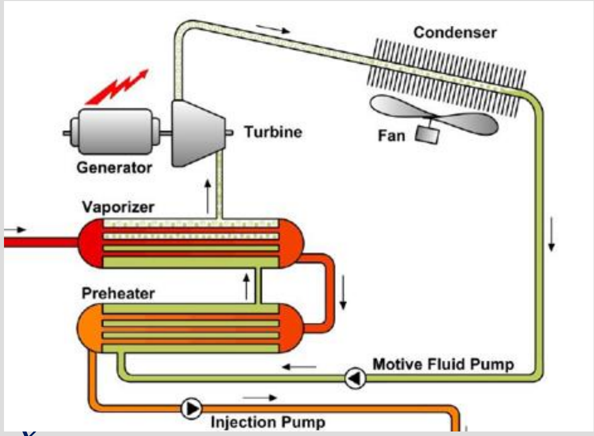
Therefore, when allocating the geothermal resource, Level 1 has a higher priority.

Power plant EXERGY efficiency
(Based on reinjection temperature):

1) Exergy flow (brine, steam, or pentane, T_o = ambient temperature in K):

Flow exergy: $x = h - T_o s$

Exergy change: $\Delta x = (h1 - h2) - T_o(s2 - s1)$



2) Exergy consumed (expended within the geothermal plant):

$$X_{geothermal} = \Delta X_{brine} + \Delta X_{steam\&NCG}$$
$$= m_{brine}(x_{brine,in} - x_{brine,out}) + (m_{steam,in}x_{steam,in} - m_{condensate}x_{condensate}$$
$$- m_{discharged\ steam}x_{discharged\ steam}) + m_{NCG}(x_{NCG,in} - x_{NCG,out})$$

3) Exergy efficiency (based on reinjectioin and surrounding temperature):

$$\eta_{exergy,reinject} = \frac{W_{electric,net}}{X_{geothermal\ (reinject)}} = \frac{W_{electric,gross} - W_{fans} - W_{pentane\ pumps}}{\Delta X_{brine} + \Delta X_{steam\&NCG}}$$

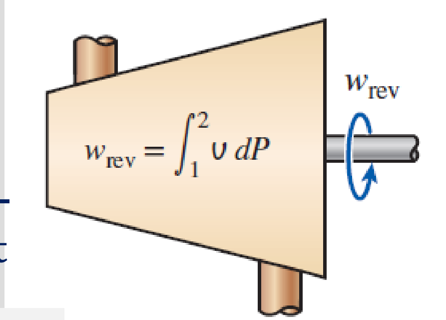
$$\eta_{exergy,surr} = \frac{W_{electric,net}}{X_{geothermal,max}} = \frac{W_{electric,gross} - W_{fans} - W_{pentane\ pumps}}{\Delta X_{brine,max} + \Delta X_{steam\&NCG,max}}$$

Pump efficiency (reversible):

Reversible pump work (minimum work required for pumping from P1 to P2):

$$w_{rev} = \upsilon(P_2 - P_1)$$

$$\eta_{pump} = \frac{W_{pump,shaft,ideal}}{W_{pump,shaft}} = \frac{W_{pump,hydraulic}}{W_{pump,shaft}} = \frac{V\Delta P}{W_{pump,shaft}}$$



V = Volume flow rate of brine passing through the pump, m3/s

ΔP = $P_{discharge} - P_{suction} = P_{out} - P_{in}$: Pressure increase by the pump, kPa

$W_{pump,shaft}$ = Shaft power transmitted by the motor to the pump, kW

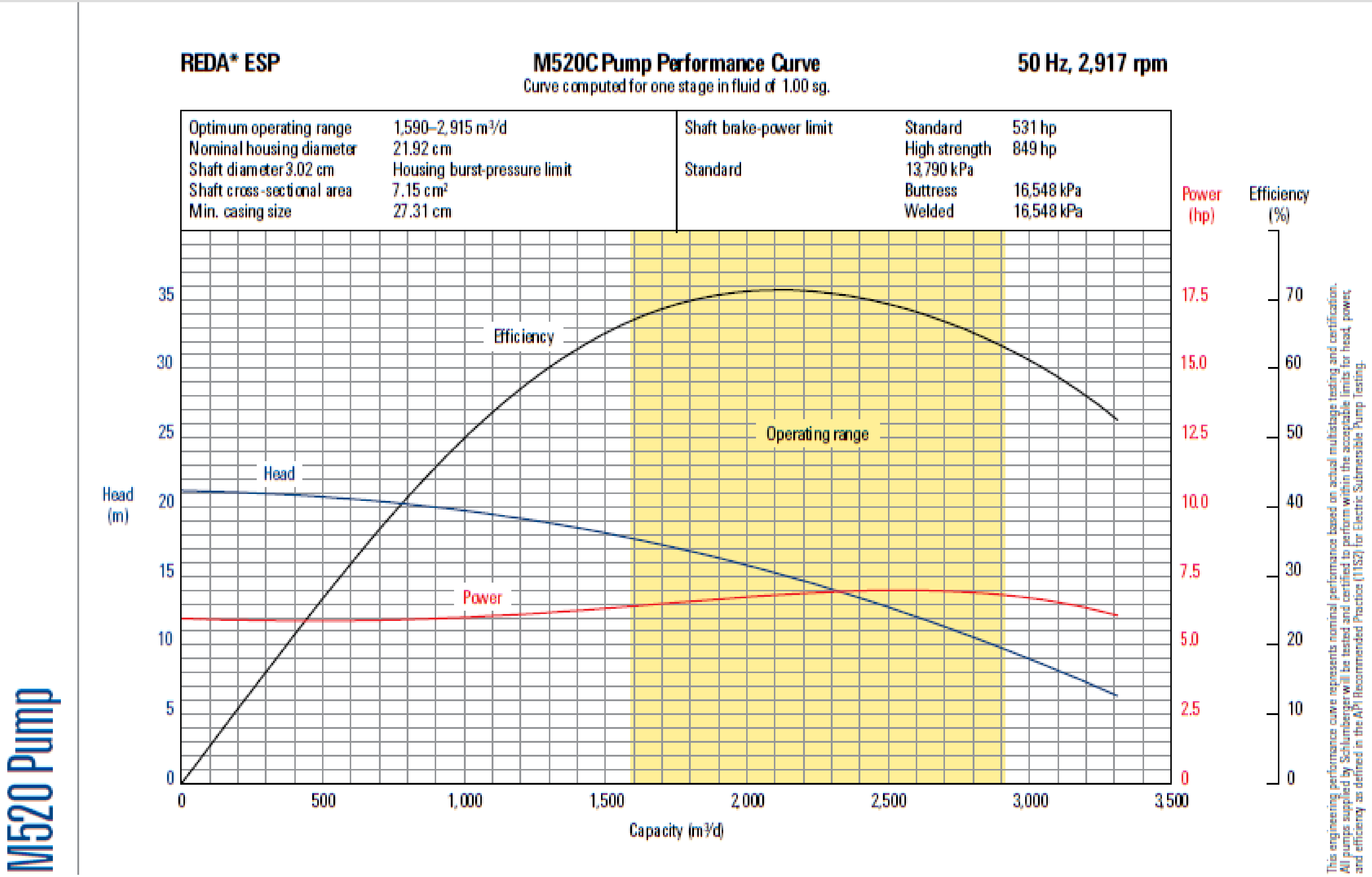
Motor: $$\eta_{motor} = \frac{\text{Mechanical power output}}{\text{Electric power input}} = \frac{\dot{W}_{shaft,out}}{\dot{W}_{elect,in}}$$

$$\eta_{pump-motor} = \eta_{pump}\eta_{motor} = \frac{W_{pump,hydraulic}}{W_{motor,electric}} = \frac{V\Delta P}{W_{motor,electric}}$$

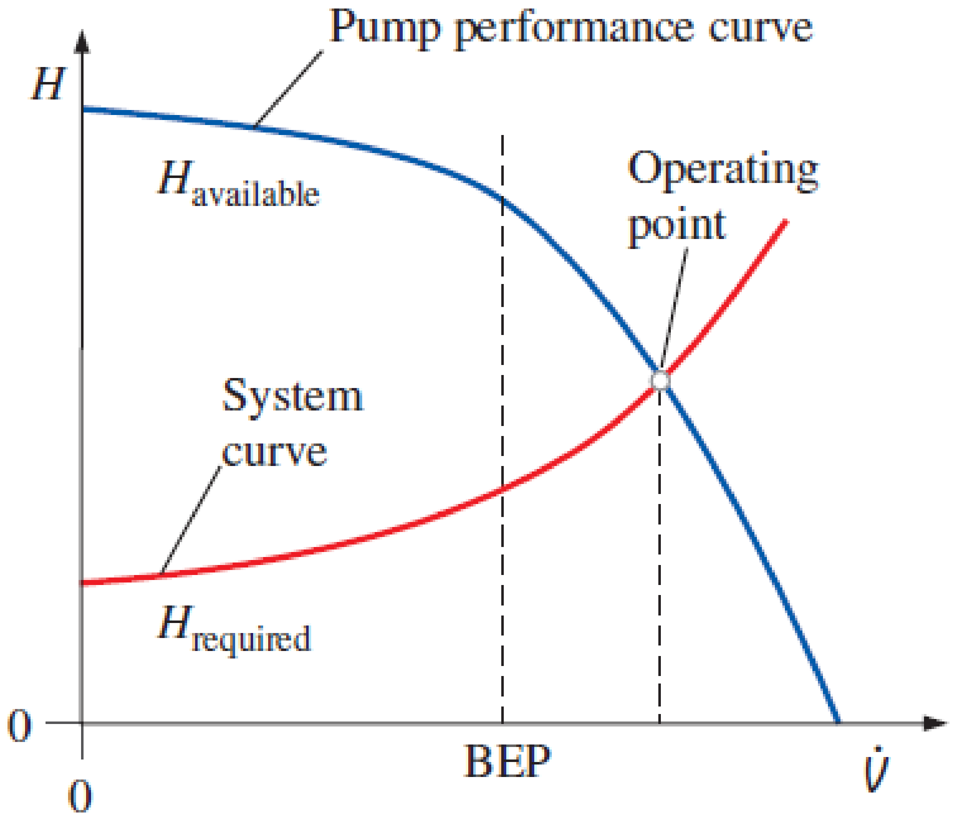
Typical pump efficiency: 70 – 85%

Typical motor efficiency (large motors): 92-96%

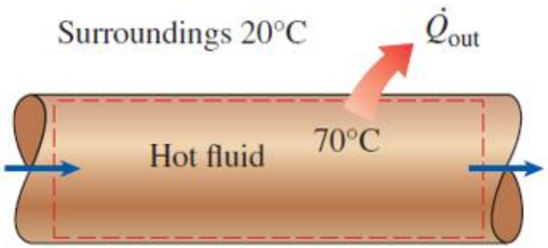
Pump performance curves
(Schlumberger REDA ESP)

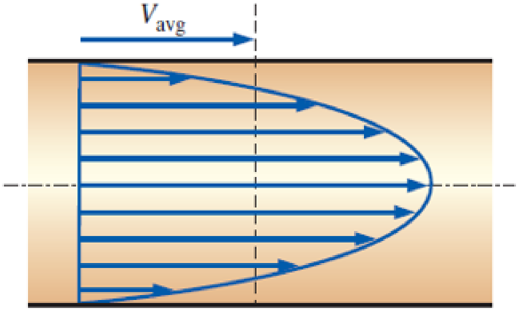


Operating point of pumps:

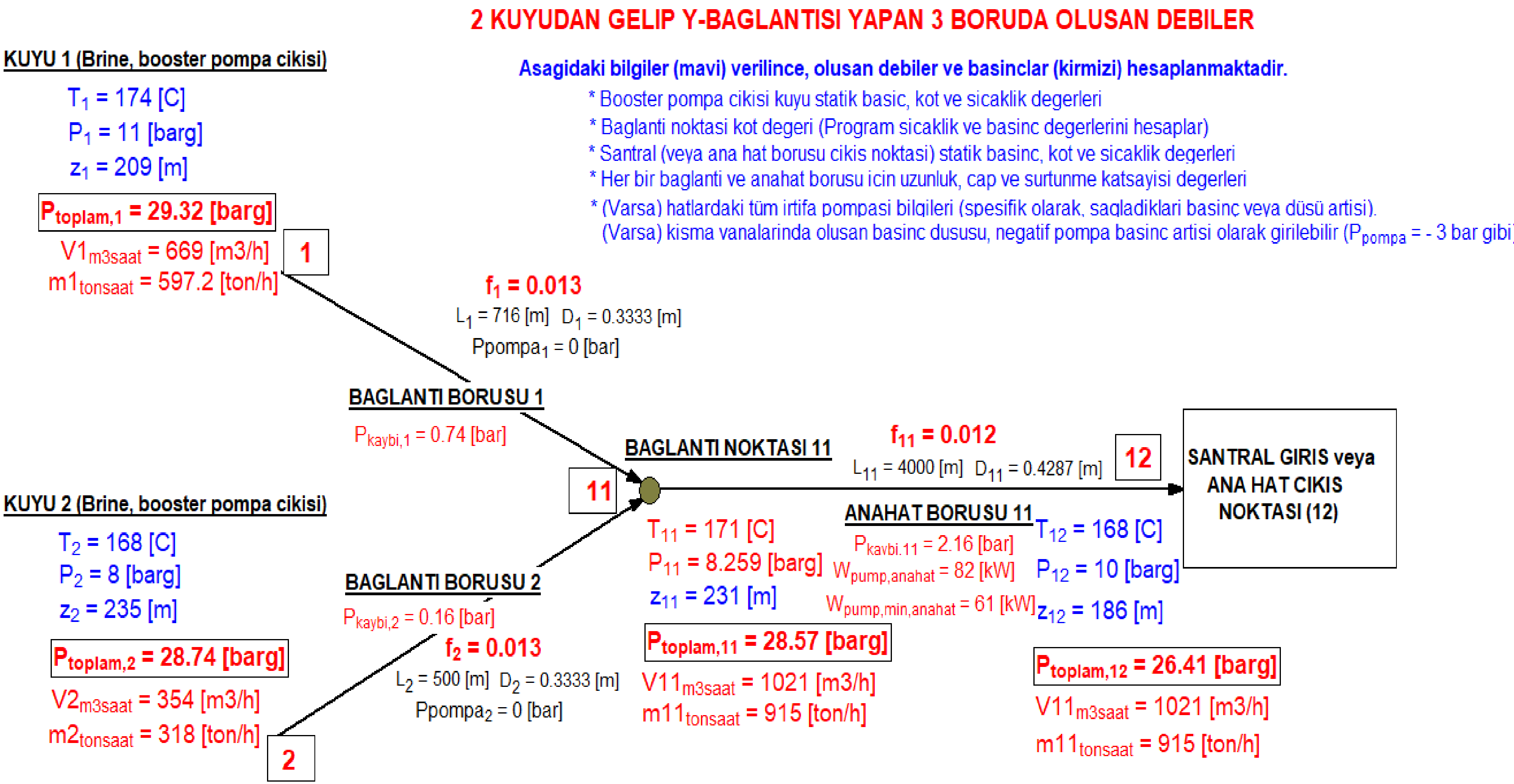


Pipe flow/skin friction
(Causes pressure loss; requires pumps to overcome)





Power consumption due to pipe friction (2 wells)



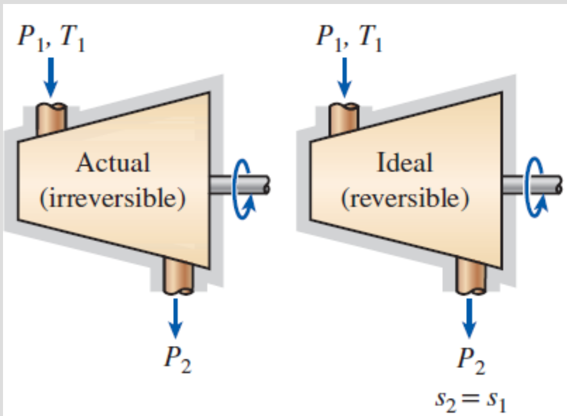
"Ana hatta boru surtunmesini yenmek icin gerekli pompa gucu"
W_pump_min_anahat= m11*P_kaybi[11]*100/rho[11] "Minimum pompa guc tuketimi, kW"
W_pump_anahat= W_pump_min_anahat/Eta_pompa "Actuak pompa guc tuketimi, kW"

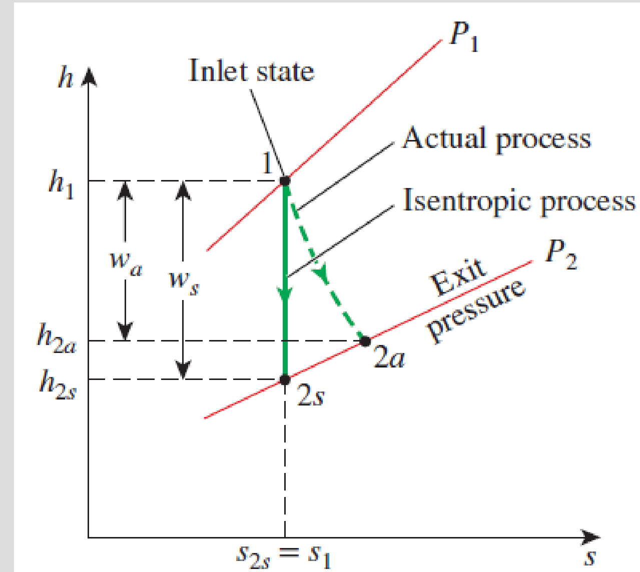
$W_{pump,min,anahat}$ = 61 [kW]

Turbine and generator efficiencies

Turbine efficiency (isentropic):

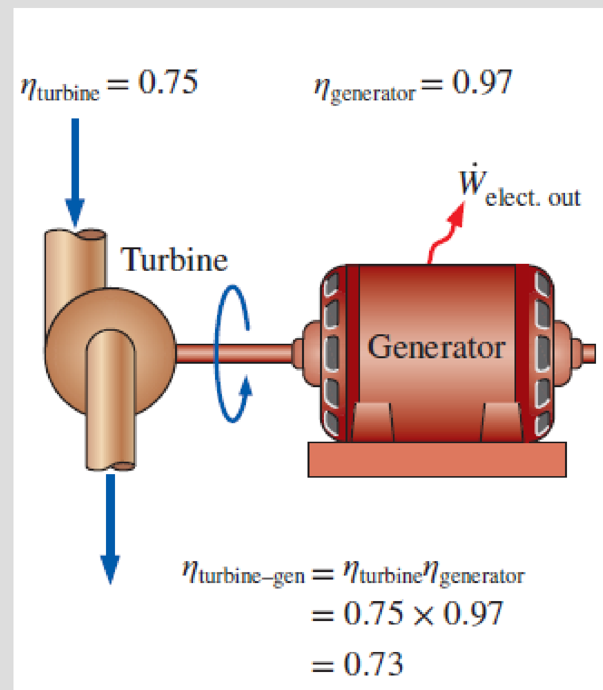
$$\eta_T = \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} = \frac{w_a}{w_s} \cong \frac{h_1 - h_{2a}}{h_1 - h_{2s}}$$





$$\eta_{generator} = \frac{W_{electric,\ out}}{W_{mechanical,\ in}} = \frac{W_{generator,\ electric}}{W_{turbine,\ mechanical}}$$

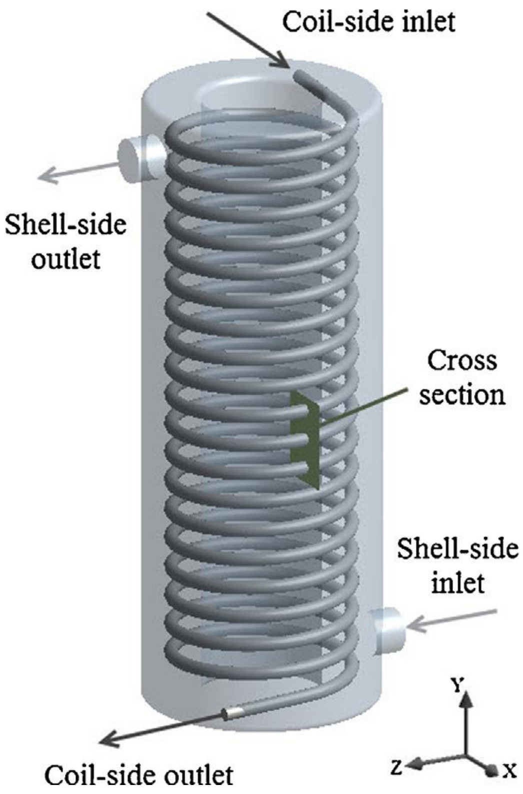
$$\eta_{turbine-gen} = \eta_{turbine}\eta_{generator} = \frac{\dot{W}_{elect,out}}{\dot{W}_{turbine,e}} = \frac{\dot{W}_{elect,out}}{|\Delta \dot{E}_{mech,fluid}|}$$



Typical turbine isentropic efficiency: 88-92%

Typical generator efficiency: 98%

Heat exchangers: Shell&tube, coil, plate, car radiator (air-water)



Heat exchanger effectiveness-1: General

$$Q = Q_{\text{brine}} = Q_{\text{pentane}}$$

$$Q = [m(h_{\text{in}} - h_{\text{out}})]_{\text{brine}} = [m(h_{\text{out}} - h_{\text{in}})]_{\text{pentane}}$$

In terms of specific heats:

$$Q = \left[mC_p(T_{\text{in}} - T_{\text{out}})\right]_{\text{brine}} = \left[mC_p(T_{\text{out}} - T_{\text{in}})\right]_{\text{pentane}}$$

Effectiveness = Ratio of the actual heat transfer (Q_{actual}) to the maximum heat transfer ($Q_{\max}$):

$$\varepsilon_{\text{hx}} = \frac{Q_{\text{actual}}}{Q_{\max}} = \frac{Q}{Q_{\max}} = \frac{Q_{\text{pentane}}}{Q_{\max}} = \frac{Q_{\text{brine}}}{Q_{\max}}$$

Calculation of $Q_{\max}$:

$$Q_{\max} = (mC_p)_{\min}(T_{\text{hot fluid, in}} - T_{\text{cold fluid, in}}) = C_{\min}(T_{\text{brine, in}} - T_{\text{pentane, in}})$$

or

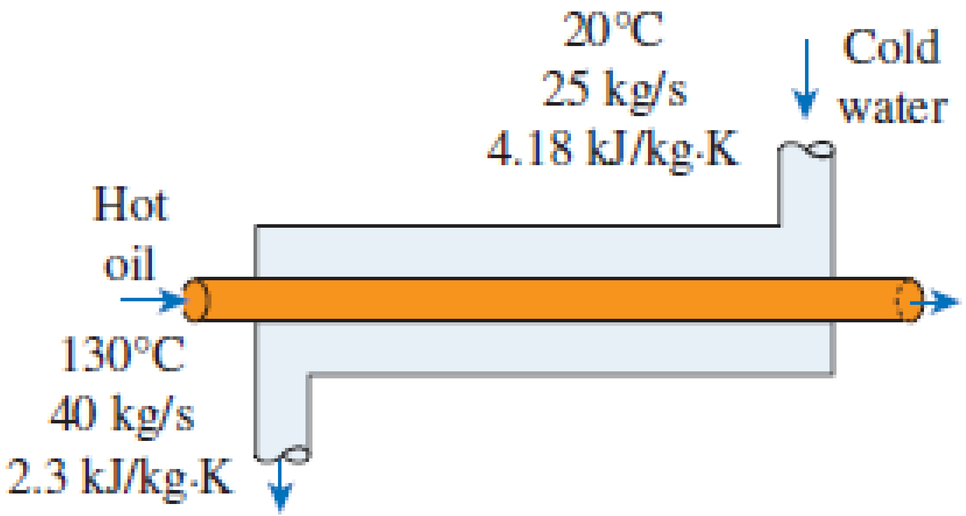
$$Q_{\max} = \left[m\left(h_{@\text{T}_{\text{brine, in}}} - h_{@\text{T}_{\text{pentane, in}}}\right)\right]_{\text{C\_min fluid}}$$

Here:

$C = mC_p$ = Thermal capacity of the fluid

$C_{\min} = (mC_p)_{\min}$ = The smaller of the two thermal capacities (usually pentane).

Heat exchanger effectiveness-2: Evaluation of Q_{max}



$$C_c = \dot{m}_c c_{pc} = 104.5 \text{ kW/K}$$

$$C_h = \dot{m}_h c_{ph} = 92 \text{ kW/K}$$

$$C_{\min} = 92 \text{ kW/K}$$

$$\Delta T_{\max} = T_{h,\text{in}} - T_{c,\text{in}} = 110°\text{C}$$

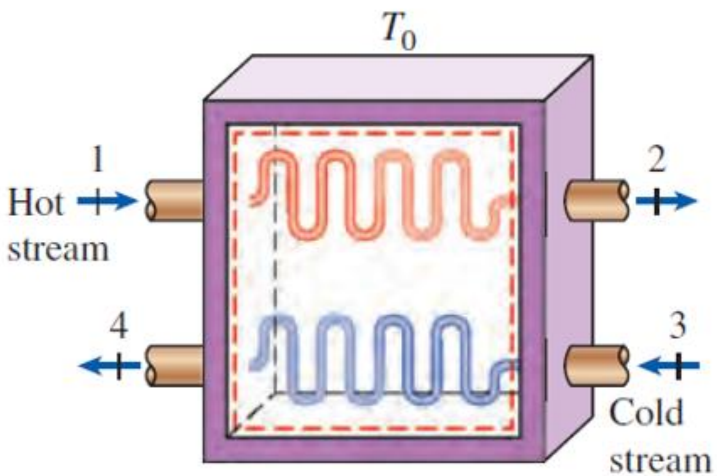
$$\dot{Q}_{\max} = C_{\min}\, \Delta T_{\max} = 10{,}120 \text{ kW}$$

Second-Law (exergy) Efficiency of heat exchangers

$$\eta_{II,HX} = \frac{\dot{m}_{cold}(x_{flow,4} - x_{flow,3})}{\dot{m}_{hot}(x_{flow,1} - x_{flow,2})} \quad \text{or} \quad \eta_{II,HX} = 1 - \frac{T_0 \dot{S}_{gen}}{\dot{m}_{hot}(x_{flow,1} - x_{flow,2})}$$

$$\dot{S}_{gen} = \dot{m}_{hot}(s_2 - s_1) + \dot{m}_{cold}(s_4 - s_3) + \dot{Q}_{loss}/T_b$$

$$\eta_{II,HX} = \frac{\dot{m}_{cold}(x_{flow,4} - x_{flow,3}) + \dot{Q}_{loss}(1 - T_0/T_b)}{\dot{m}_{hot}(x_{flow,1} - x_{flow,2})} = 1 - \frac{T_0 \dot{S}_{gen}}{\dot{m}_{hot}(x_{flow,1} - x_{flow,2})}$$



If the heat exchanger (or mixing chamber) is not adiabatic and the temperature of the boundary (the outer surface of the heat exchanger) T_b is equal to T_0, the definition above still holds (except the entropy generation term needs to be modified).

If $T_b > T_0$, then the exergy of the lost heat at the boundary should be included in the recovered exergy. But, if the extended system is considered, the exergy lost becomes exergy destroyed in the immediate surroundings, and thus the 2nd law efficiency relations are still valid in that case.

Last word on renewable energy:
Use it or lose it

"Unused renewable energy …

… is wasted energy."

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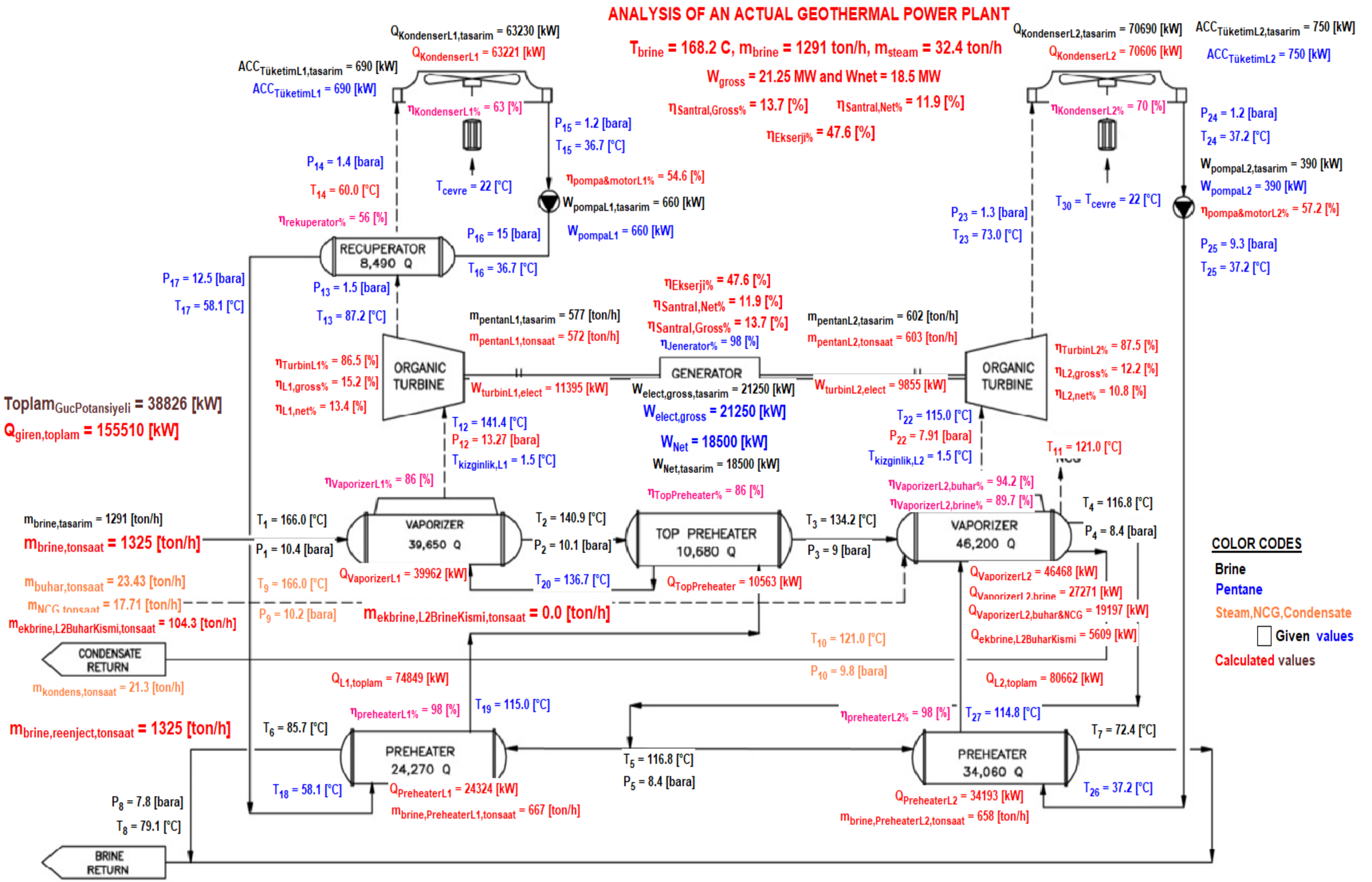
Example:

Efficiency analysis of a geothermal power plant

Efficiency analysis of a geothermal power plant:

Energy&exergy efficiencies of the plant; Effectiveness of HXs



Power plant efficiencies:
(Gross, net, overall, and exergy efficiencies)

		Plant Efficiencies					
		Design	Actual (Time of operation on 20 September 2023)				
			00:00	02:00	04:00	06:00	08:00
Geothermal energy consumption[1]	Amount, MW	155	137	138	138	142	141
Power plant energy efficiency	Gross, %[2]	13.7%	13.7%	13.9%	14.3%	14.6%	14.6%
	Net, %[3]	11.9%	12.3%	12.5%	12.7%	13.1%	13.2%
	Overall, %[4]	10.0%	10.8%	11.1%	11.5%	11.8%	11.8%
Geothermal exergy consumption, MW (Relative to reinjection temperature)		42.5	33.9	34.7	35.4	36.0	36.5
Power plant exergy efficiency, %		43.5%	43.0%	49.6%	49.9%	49.6%	51.6%

[1]Geothermal energy consumption = (energy entering the plant with brine and steam) - (energy leaving the plant with reinjection)

[2]Plant gross efficiency = Gross power generation/Geothermal energy consumption

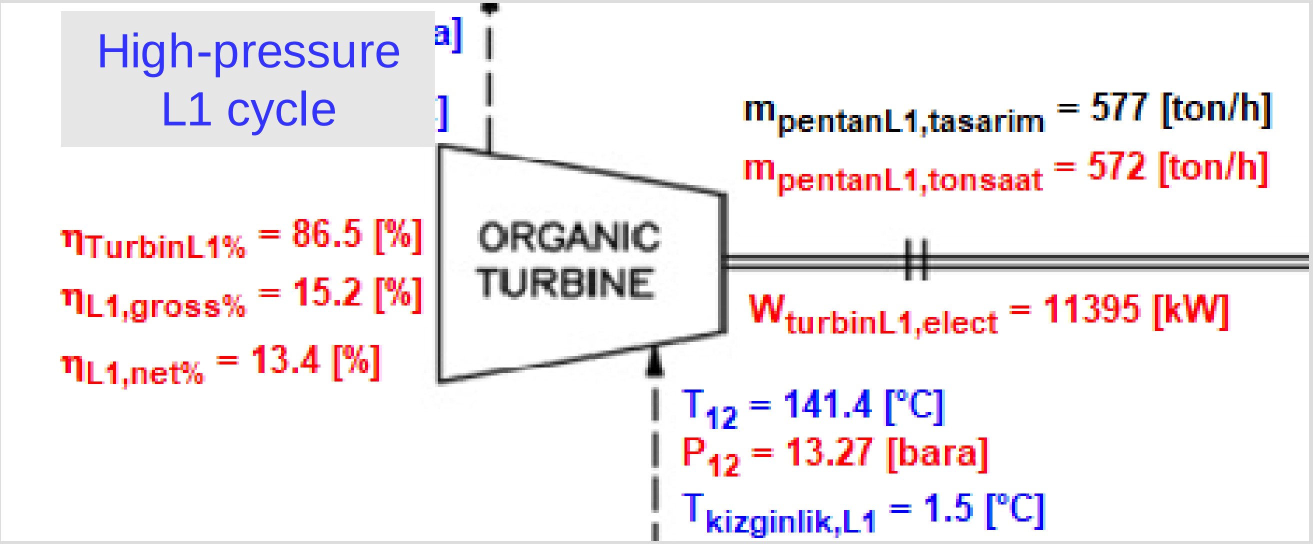
[3]Plant net efficiency = Net power generation/Geothermal energy consumption

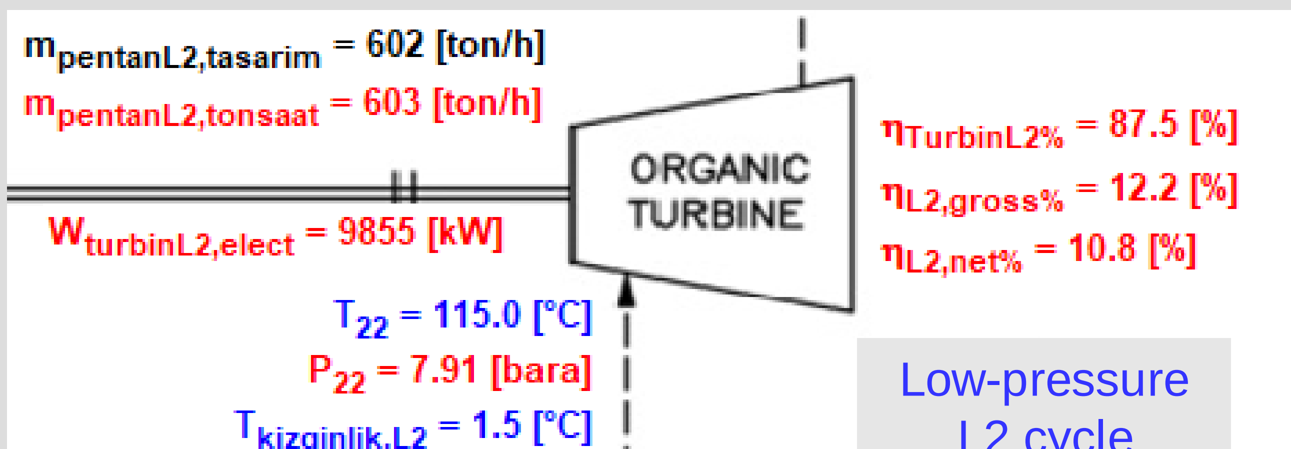
[4]Plant overall efficiency = Electric power sold to utilities (grid)/Geothermal energy consumption

Turbine efficiencies:

High-pressure L1 cycle and low-pressure L2 cycle

High-pressure L1 cycle



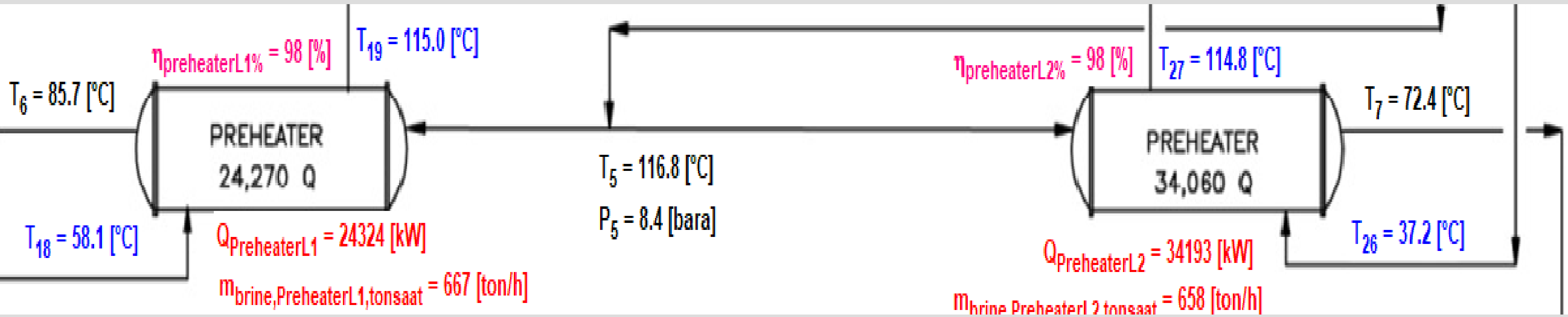


Low-pressure L2 cycle

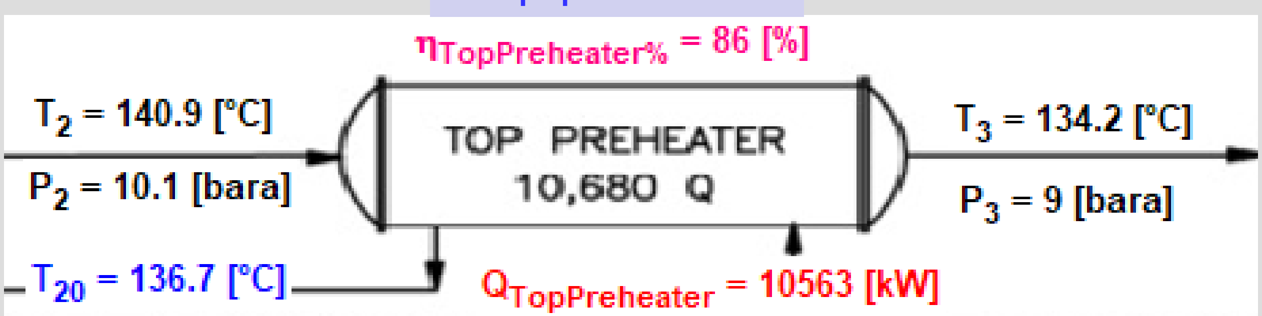
Preheater performance:
High-pressure L1 cycle and low-pressure L2 cycle

High-pressure L1 cycle

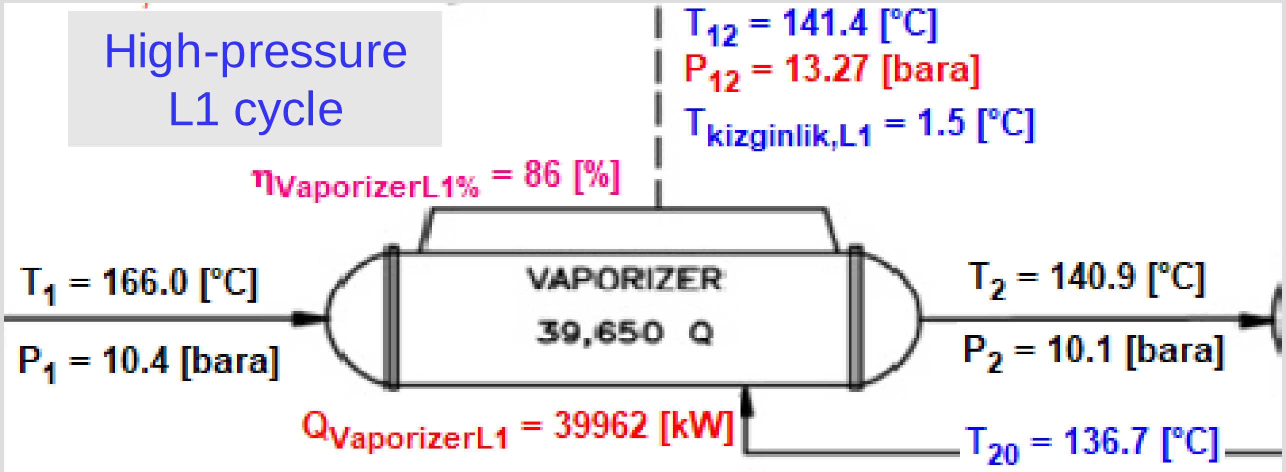
Low-pressure L2 cycle

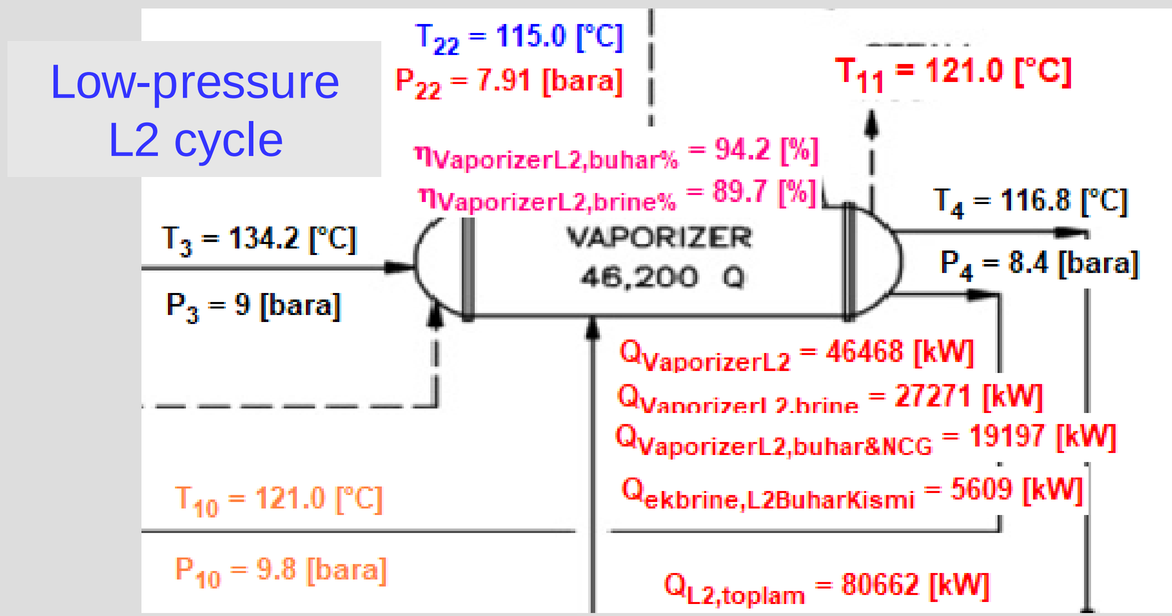


High-pressure L1 cycle Top preheater



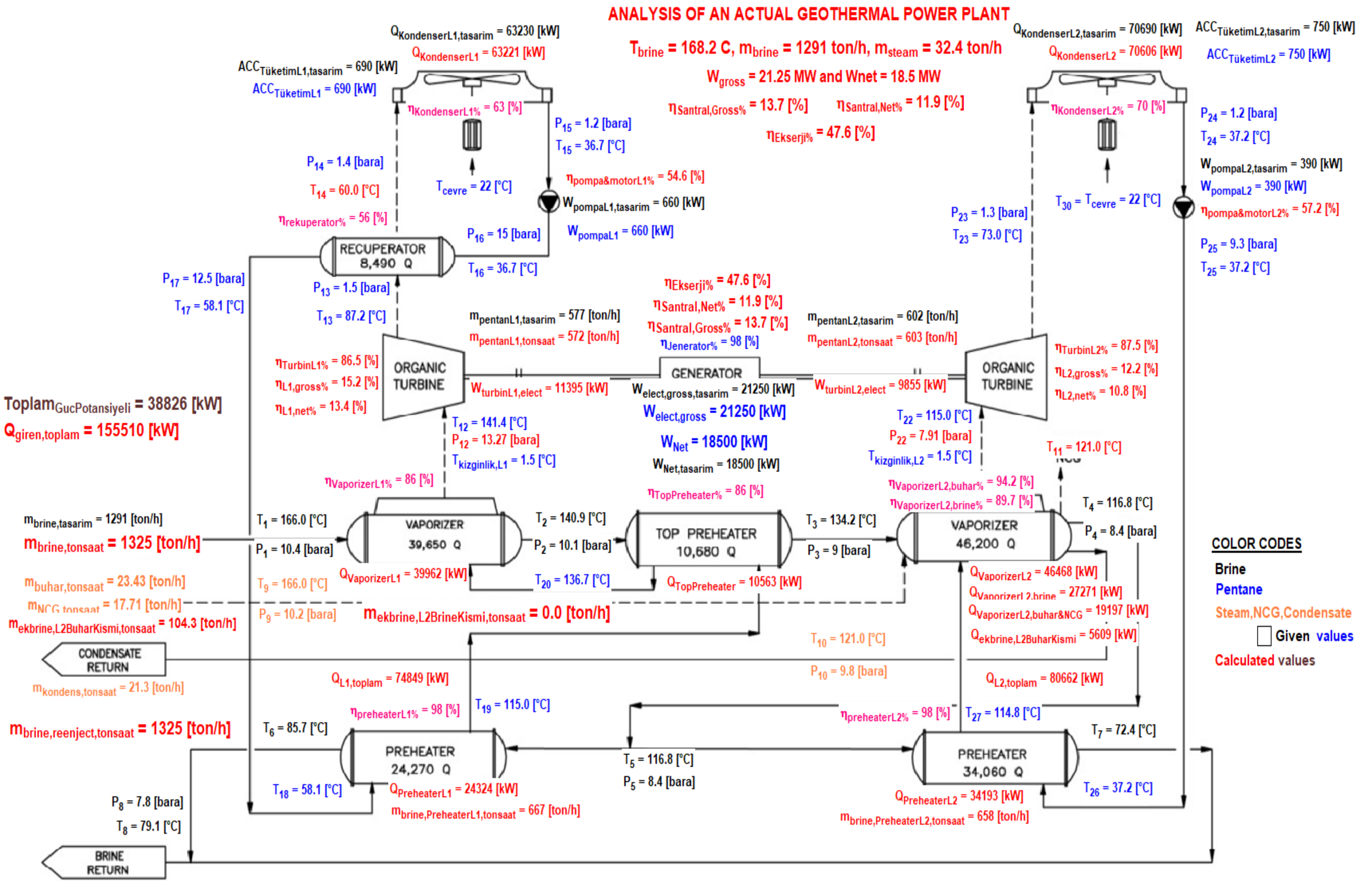
Vaporizer performance:
High-pressure L1 cycle and low-pressure L2 cycle





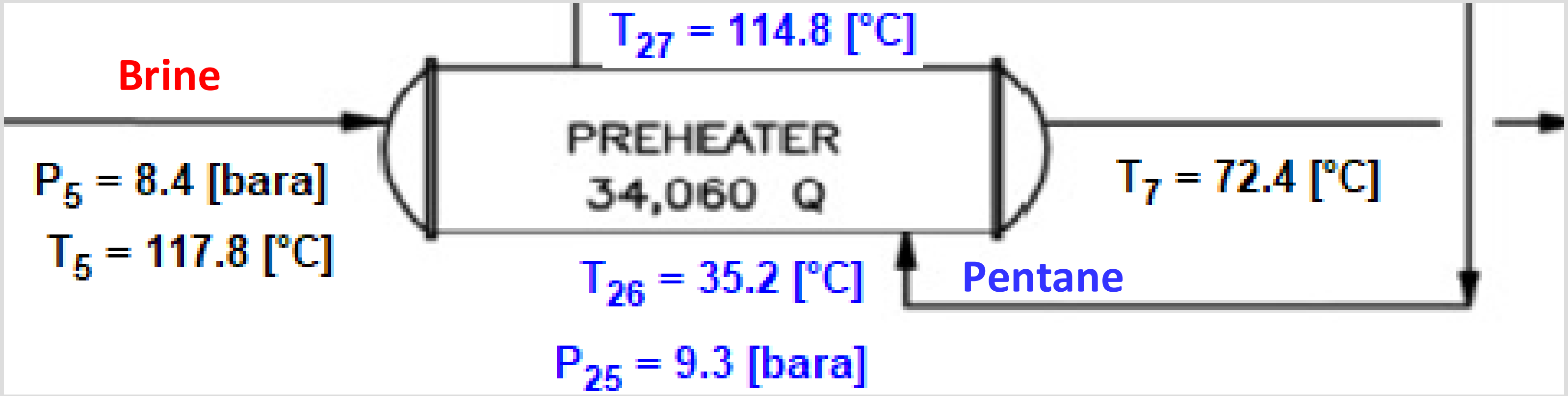
Diagnostics based on analysis:

Power production increase when the HXs are washed



Don't trust instrument readings (check by analysis):

What you read is NOT necessarily what what it is



$$Q = Q_{\text{brine}} = Q_{\text{pentane}}$$

$$Q = [m(h_{\text{in}} - h_{\text{out}})]_{\text{brine}} = [m(h_{\text{out}} - h_{\text{in}})]_{\text{pentane}}$$