

Energy and Exergy Efficiencies of Geothermal Power Plants

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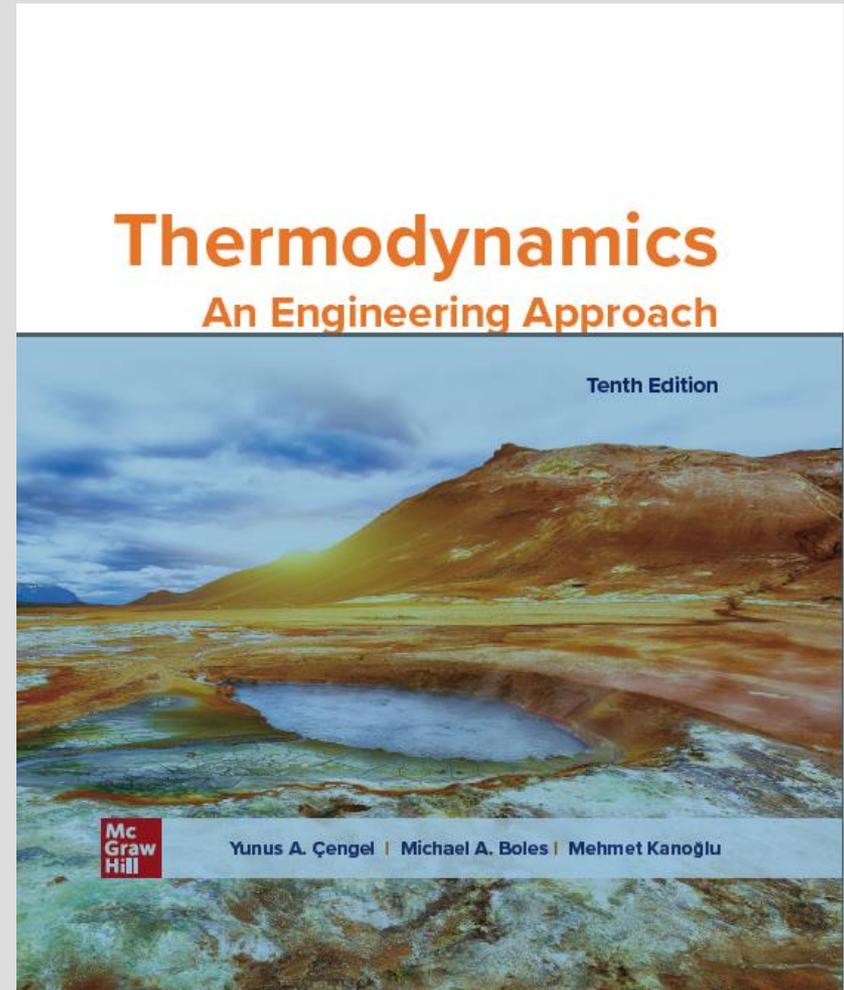
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3 Mayıs 2024

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.



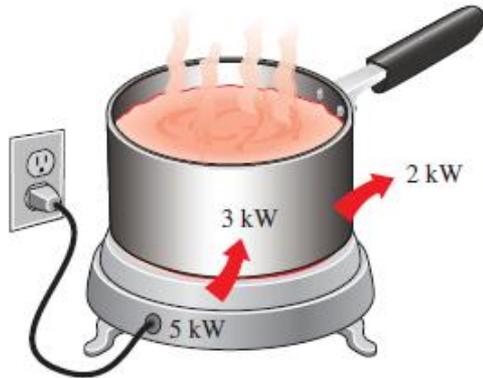
Unless otherwise specified, the artwork is picked from Google images.

Introduction:

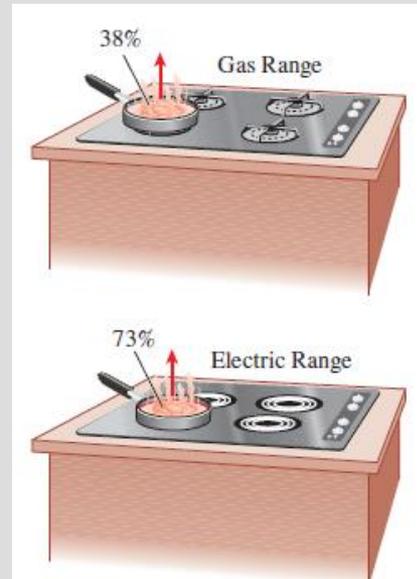
Entropy, Exergy, 2nd Law Efficiency

Efficiency definitions: Can be vague and confusing

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



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



Water heater

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

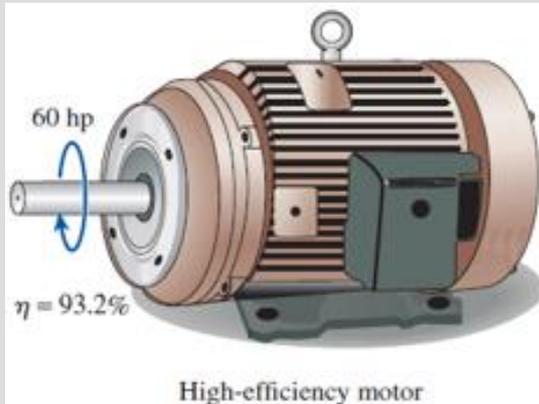


$$\eta_{\text{comb equip}} = \frac{\dot{Q}_{\text{useful}}}{\dot{E}_{\text{fuel}}} = \frac{\dot{Q}_{\text{useful}}}{\dot{m}_{\text{fuel}} \text{HV}_{\text{fuel}}} = \frac{\text{Rate of useful heat delivered, kJ/s}}{\text{Rate of chemical fuel energy consumed, kJ/s}}$$

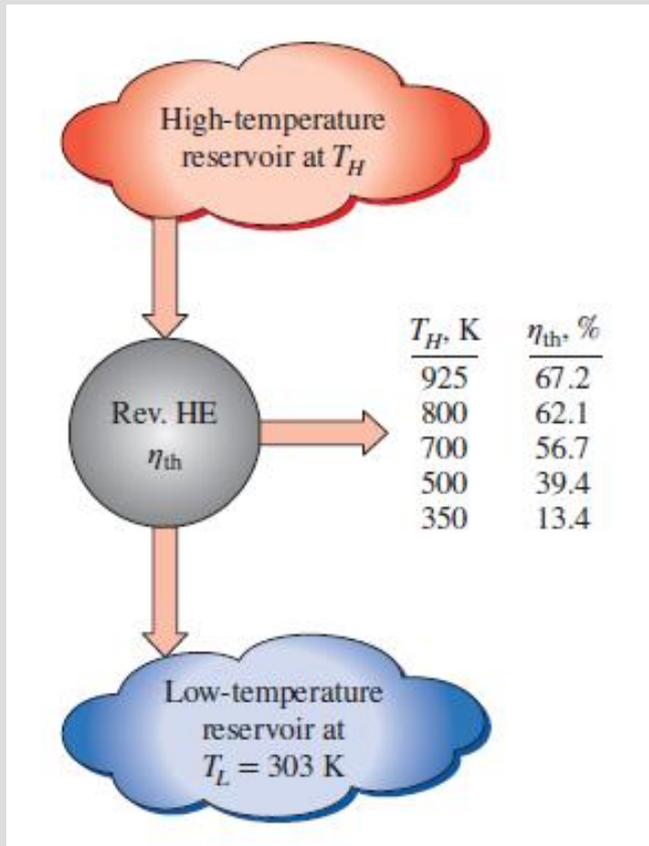
Exergy: Work Potential of Energy

The atmosphere: Infinite energy; but zero work potential

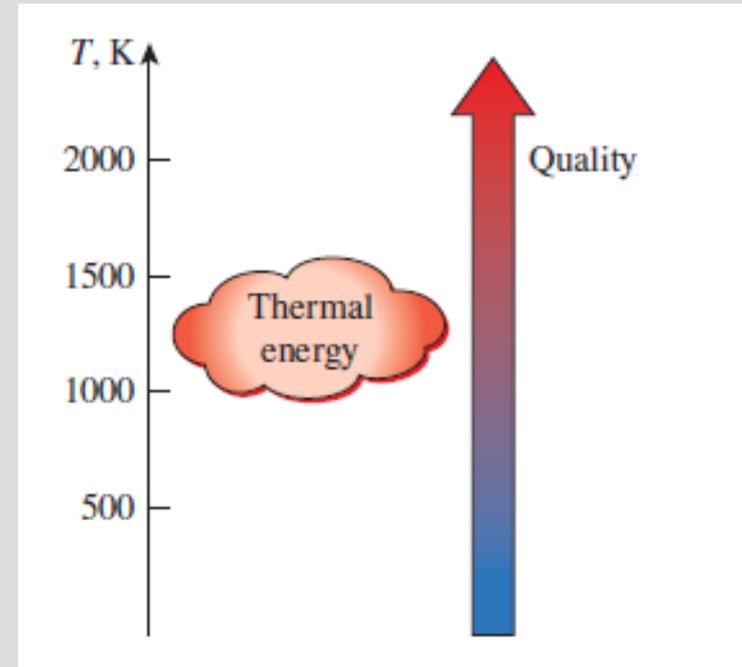
The useful work potential of a given amount of energy at some specified state in a given environment is called *exergy*.



At $T < T_{\text{surroundings}}$, 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



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



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).

The 2nd-law (or exergy) efficiency:

η_{II} = Actual performance/Best possible performance

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

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

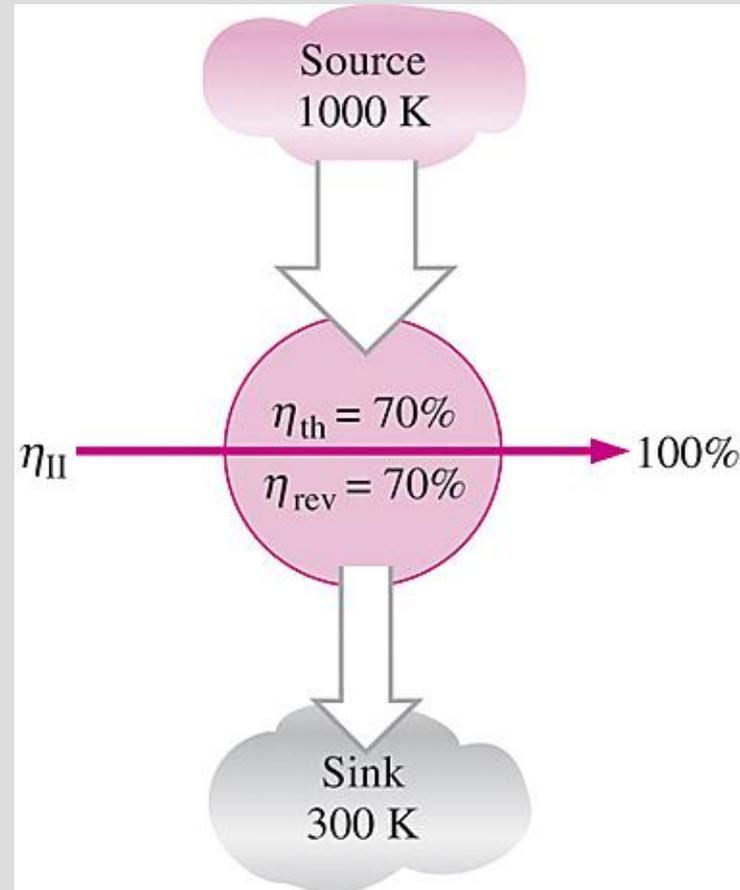
$$\eta_{II} = \frac{W_u}{W_{rev}} \quad (\text{work-producing devices})$$

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

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

The 2nd-law efficiency:

$\eta_{II} = 100\%$ for all reversible devices and processes (perfection)



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

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

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

Exergy balance: Exergy change = Exergy transfer - Exergy destruction

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

Entropy generation = Exergy destruction ÷ Room temperature

- **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.

GEO THERMAL

“Earth”

“Heat”

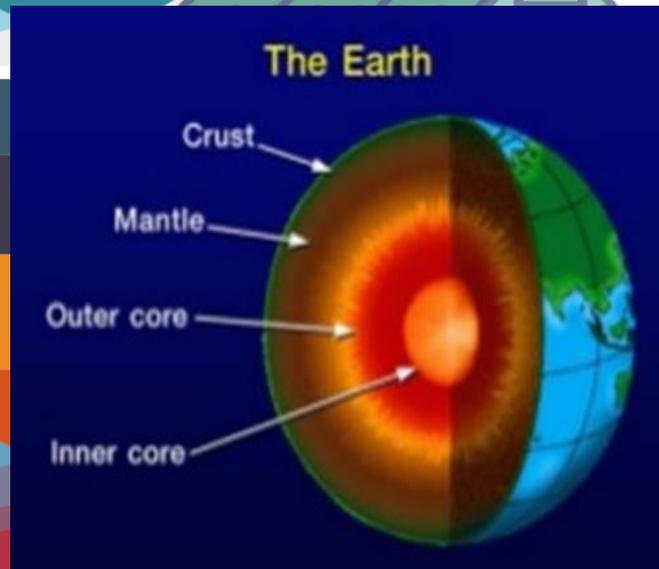
Literally “**heat from the earth**,” geothermal energy is a renewable energy heat source found under the surface of the earth.

Geothermal energy is visible on the surface as volcanoes, geysers, or hot springs.

Geothermal energy from deep wells is converted to clean power. The cooled water is reinjected into the reservoir.

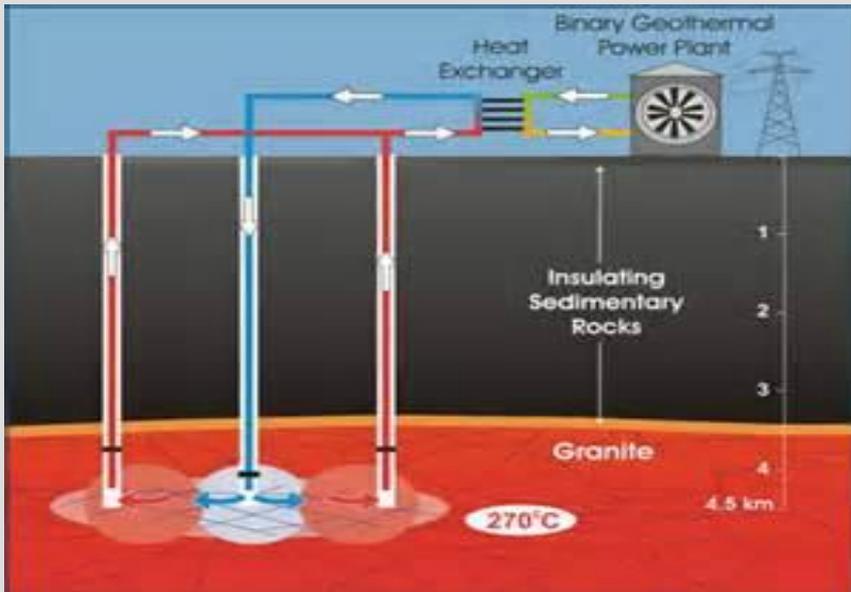
Reinjected water can replenish the geothermal reservoir.

Heat from the Earth is brought up to the surface in the form of hot ground water and steam.



Geothermal energy

Magma energy → Hot water/steam



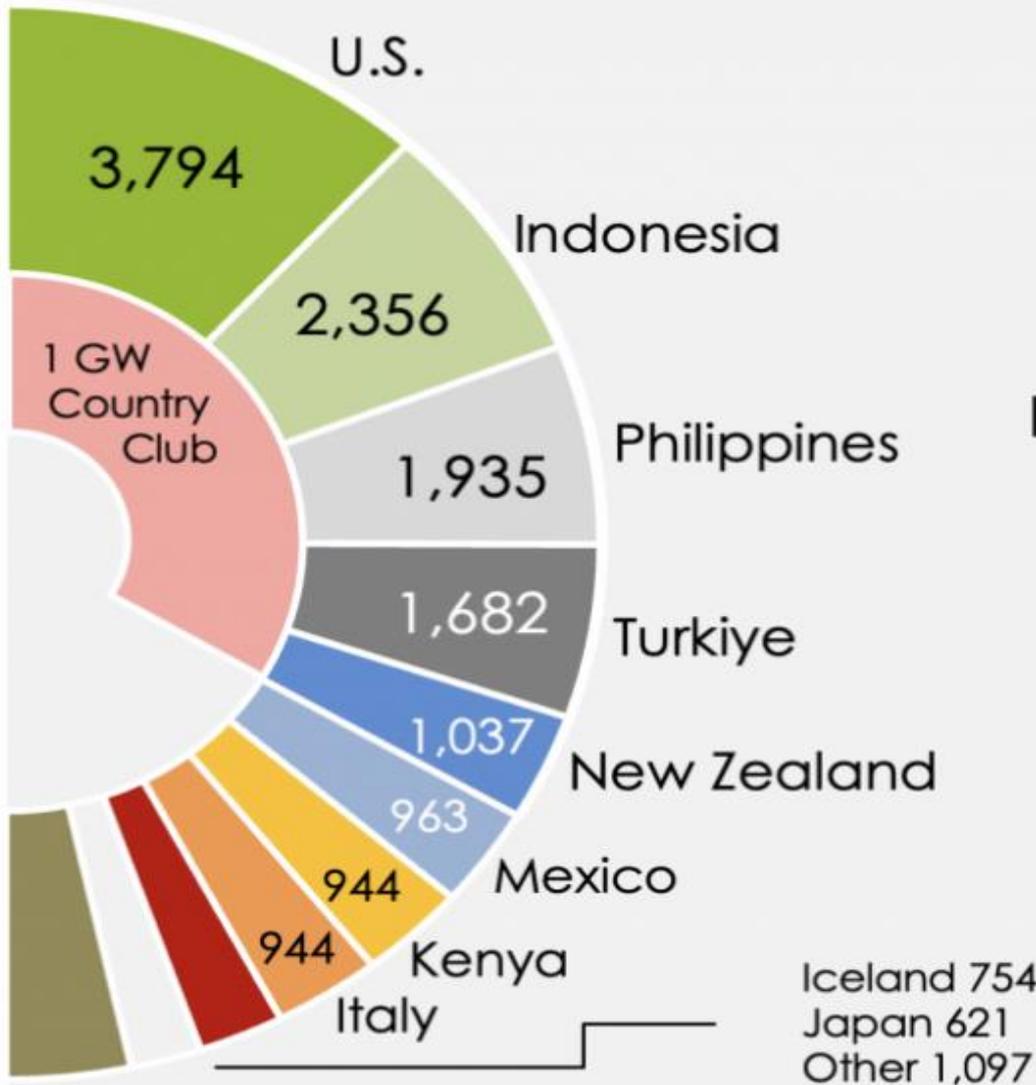
Worldwide: 555 geothermal power plants, 16.1 GW (Jan 2023)

Turkiye: 60 plants, 1.7 GW

Top 10 Geothermal Countries 2022

Installed Capacity in MWe
January 2023

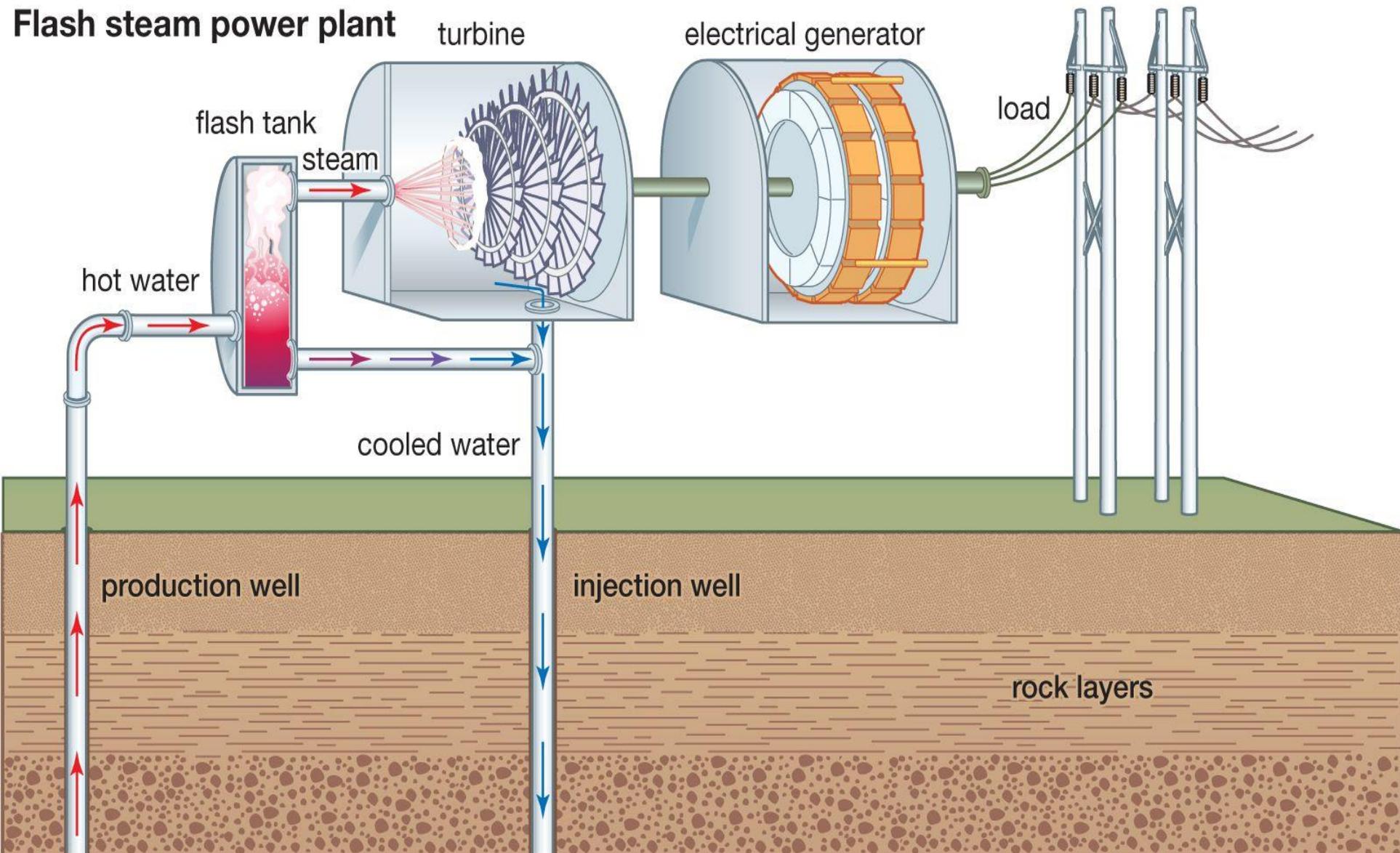
Total 16,127 MW



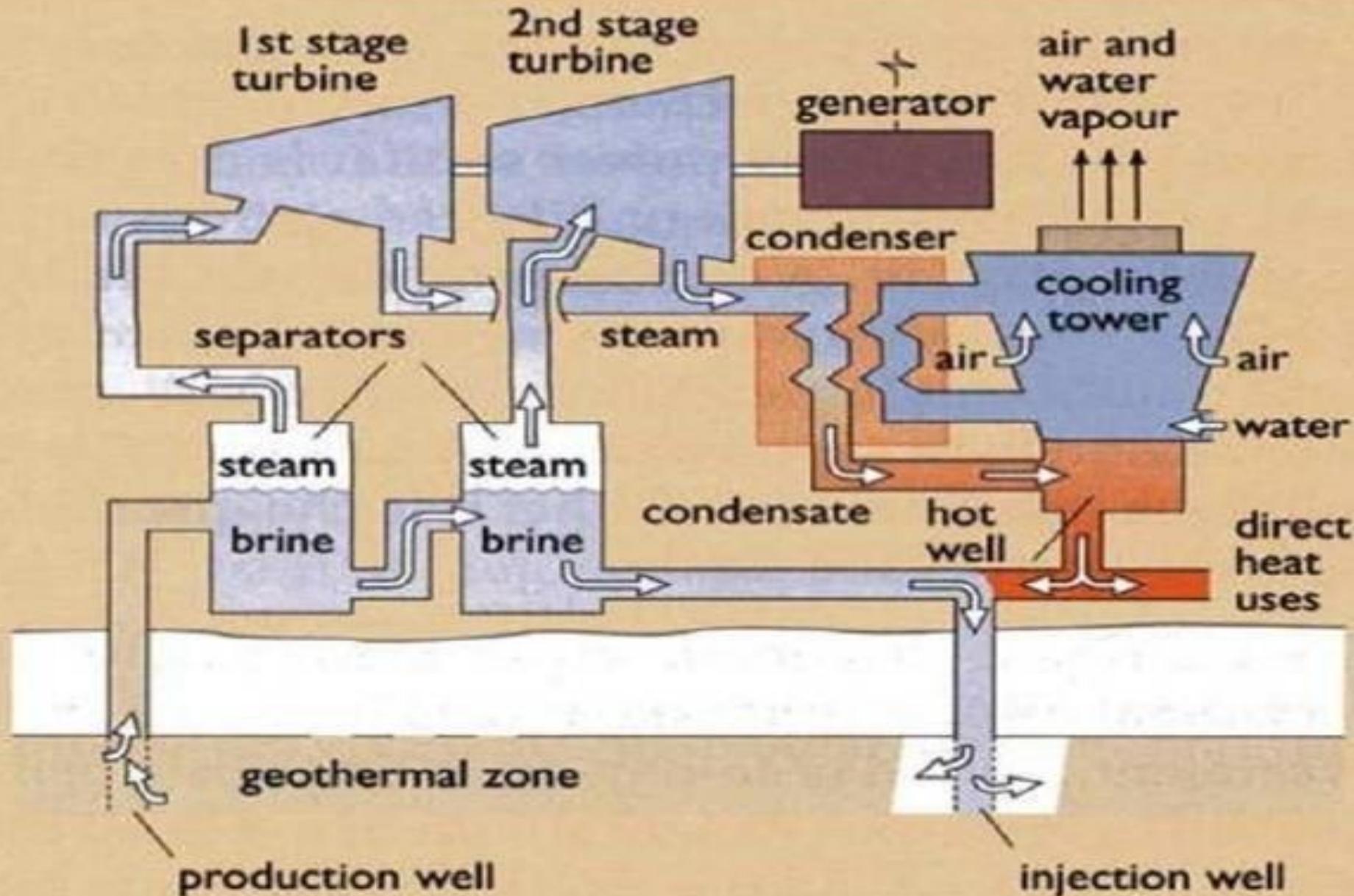
**THINK
GEOENERGY**

Source: ThinkGeoEnergy Research (2023)

Geothermal power plants: Single flash systems (direct expansion)

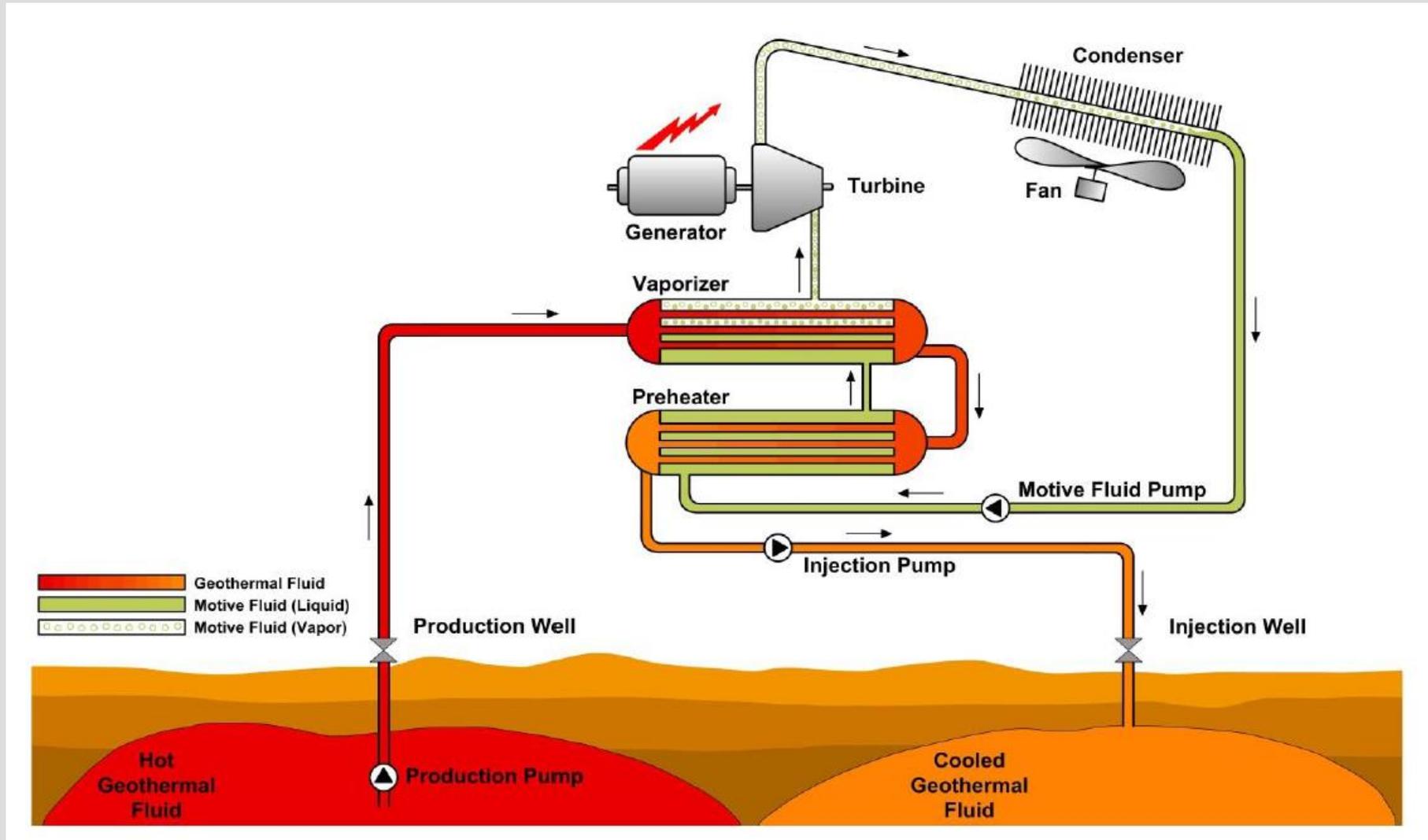


Geothermal power plants: Double flash systems



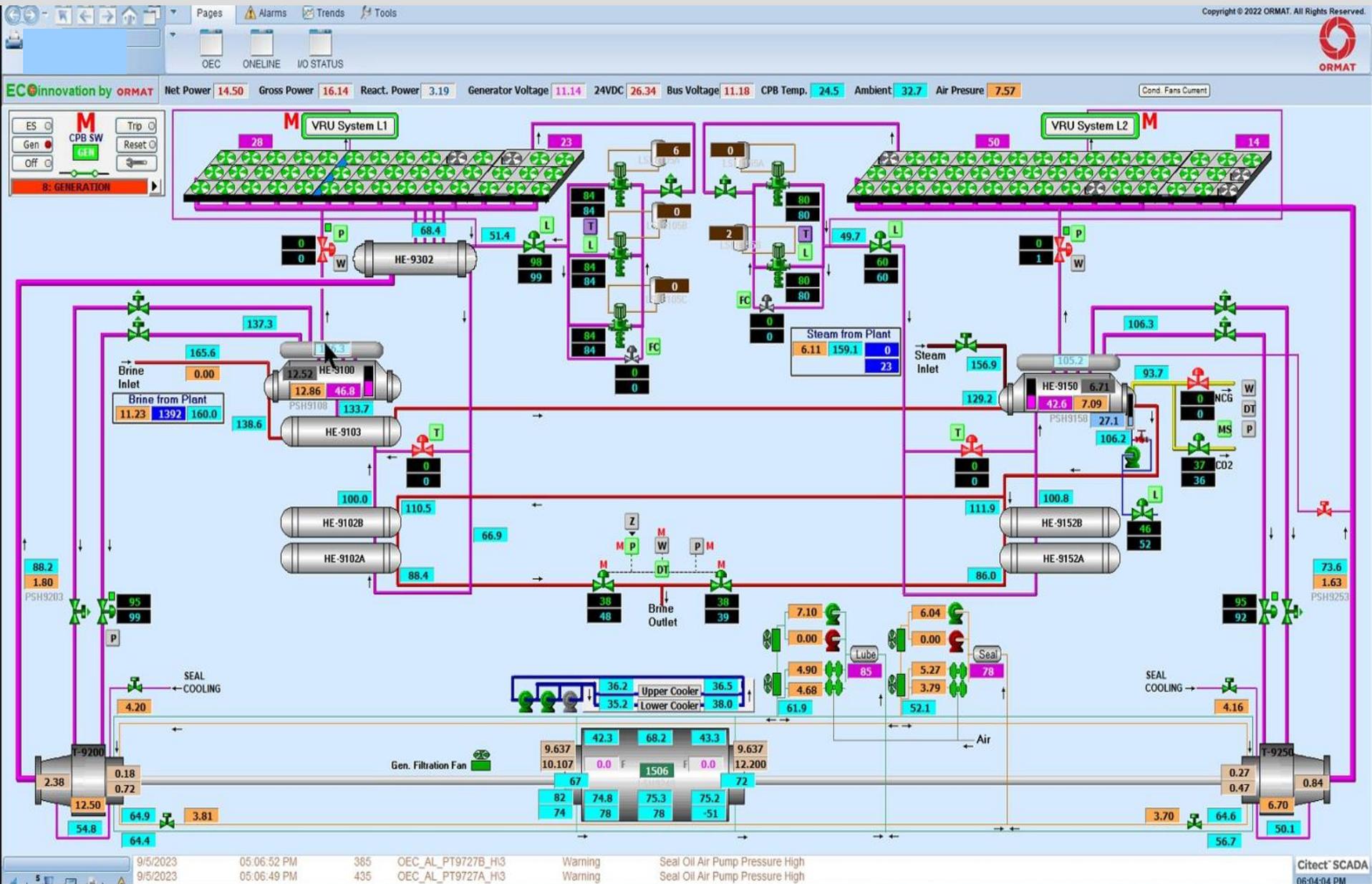
Binary geothermal power plant

(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

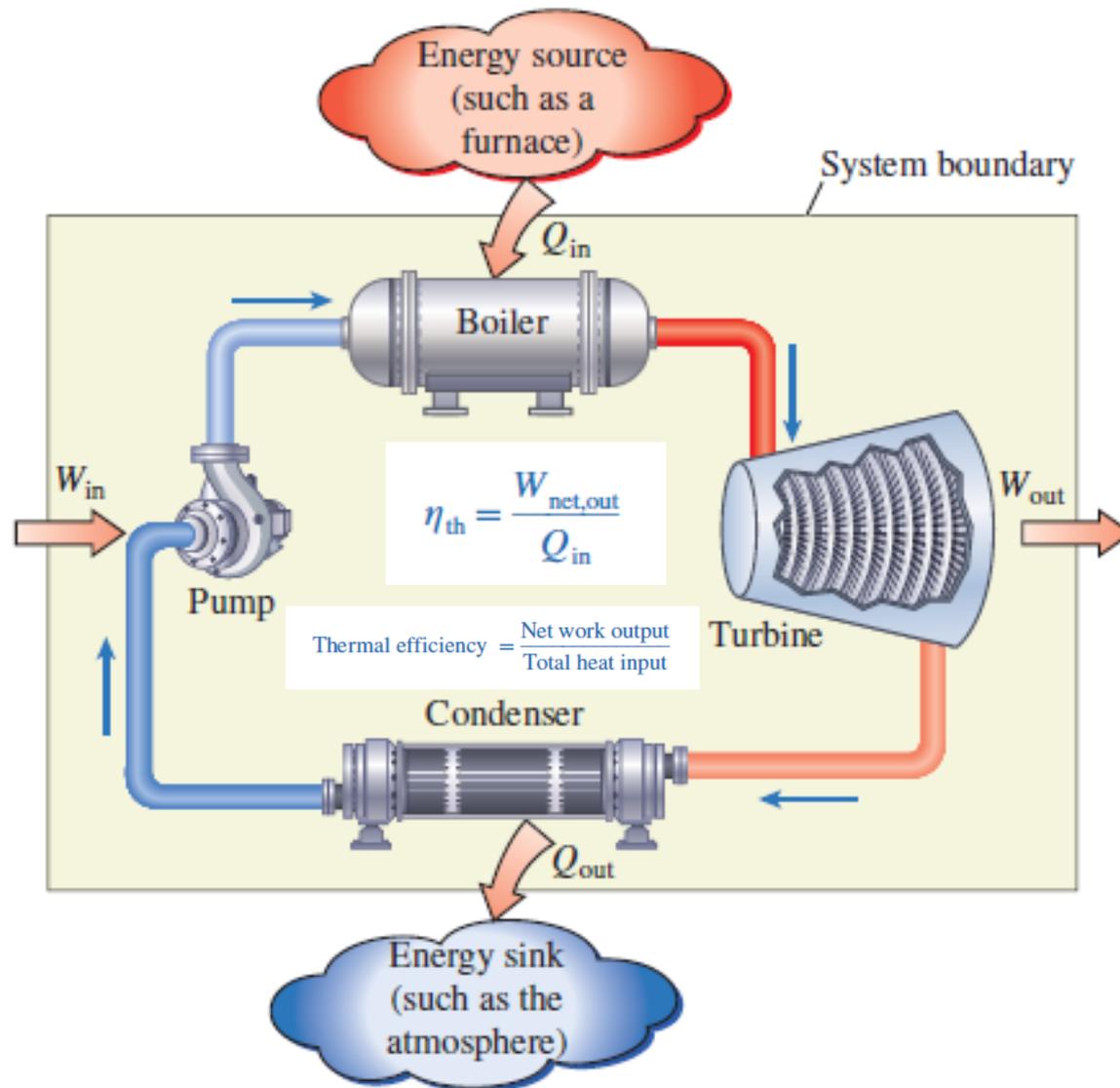
A geothermal power plant in Germencik, Turkiye: A heat exchanger (condenser – Air cooled system)



Photo by Yunus Çengel

A basic closed power cycle:

(Coal, natural gas, geothermal, nuclear, etc. power plants)



'Gross' energy efficiency of a geothermal power plant

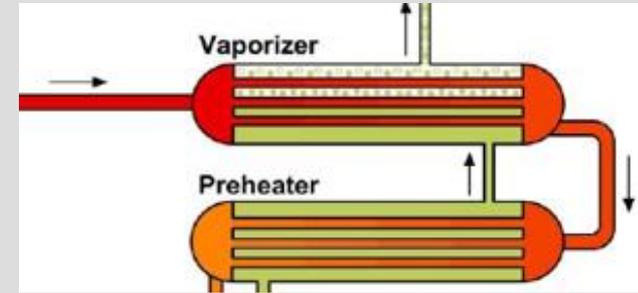
(Based on gross electricity generation)

Geothermal energy consumption in a geothermal power plant:

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

Or:

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



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)

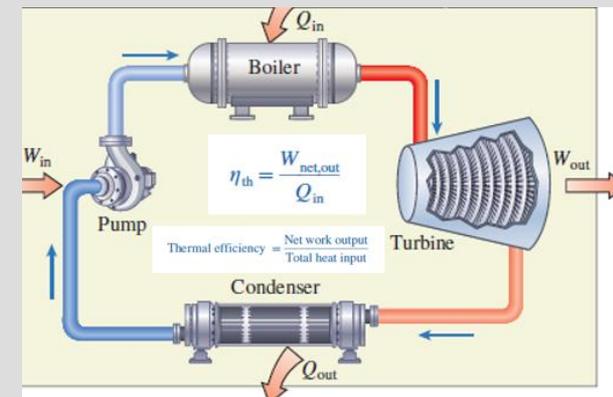
Geothermal energy consumption in a geothermal power plant:

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

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

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

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



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

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

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

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

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

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

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

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

Power plant EXERGY efficiency

(Based on reinjection temperature):

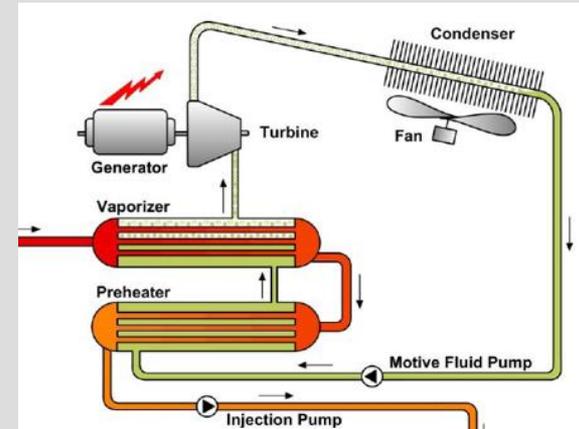
1) **Exergy flow** (brine, steam, or pentane, T_o = ambient temperature in K):

$$\text{Flow exergy: } x = h - T_o s$$

$$\text{Exergy change: } \Delta x = (h_1 - h_2) - T_o (s_2 - s_1)$$

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

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



3) **Exergy efficiency** (based on reinjection and surrounding temperature):

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

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

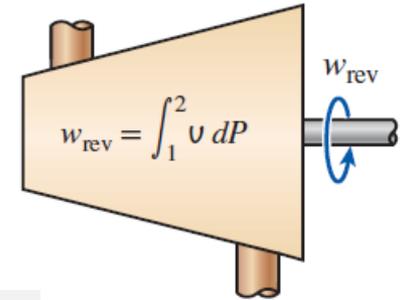
Pump and motor efficiencies

Pump efficiency (reversible):

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

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

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



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

$\Delta P = P_{\text{discharge}} - P_{\text{suction}} = P_{\text{out}} - P_{\text{in}}$: Pressure increase by the pump, kPa

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

Motor:

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

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

Typical **pump efficiency**: 70 – 85%

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

Pump performance curves

(Schlumberger REDA ESP)

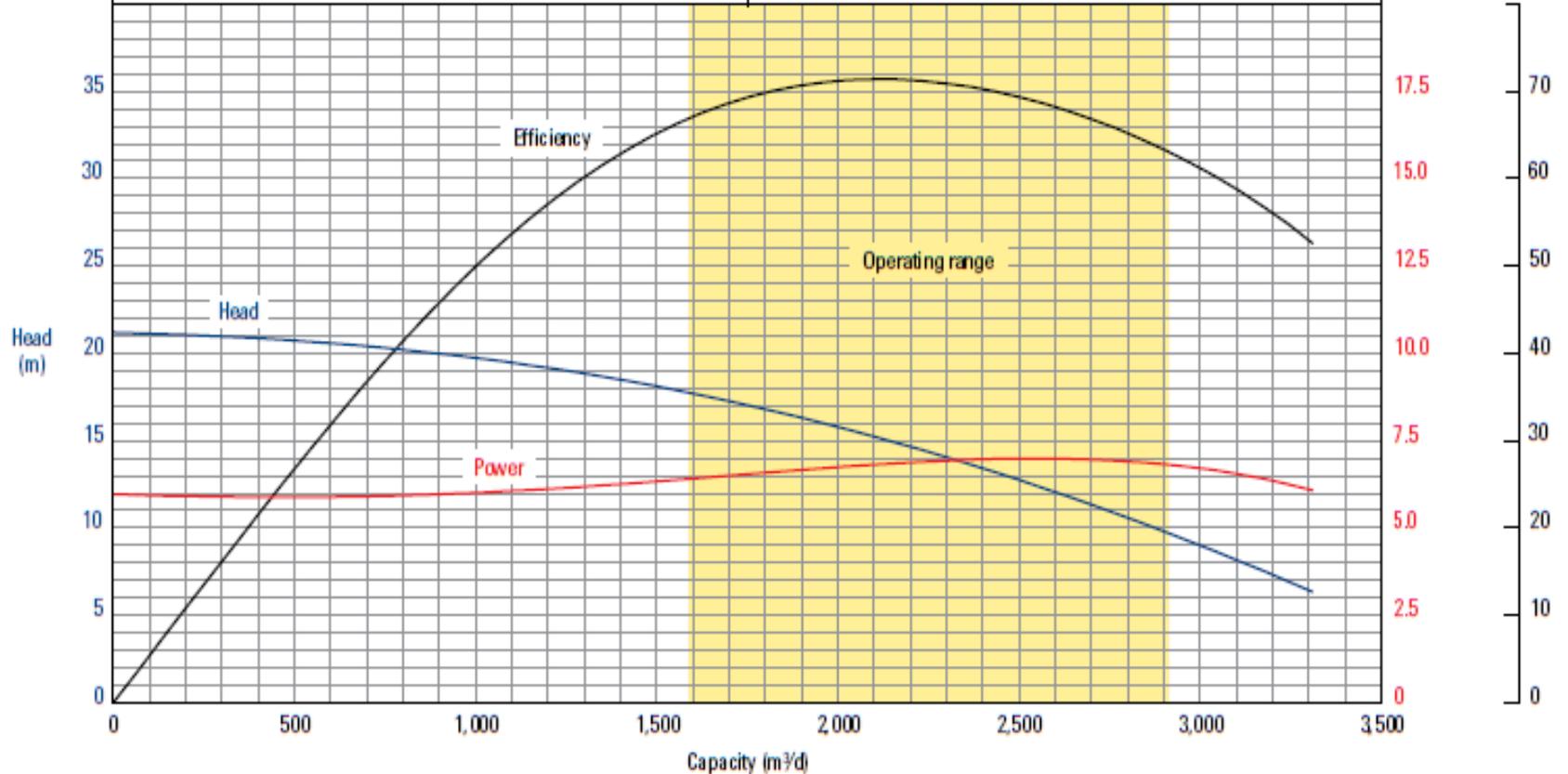
REDA* ESP

M520C Pump Performance Curve

50 Hz, 2,917 rpm

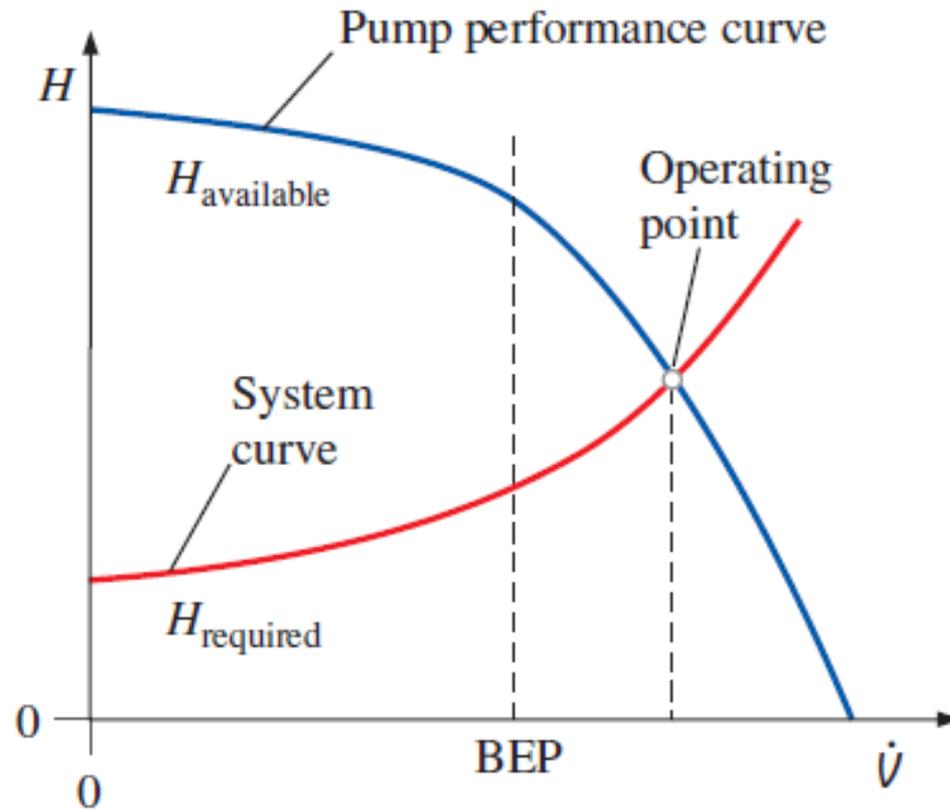
Curve computed for one stage in fluid of 1.00 sg.

Optimum operating range	1,590–2,915 m ³ /d	Shaft brake-power limit	Standard	531 hp
Nominal housing diameter	21.92 cm		High strength	849 hp
Shaft diameter	3.02 cm	Housing burst-pressure limit	Standard	13,790 kPa
Shaft cross-sectional area	7.15 cm ²		Buttress	16,548 kPa
Min. casing size	27.31 cm		Welded	16,548 kPa



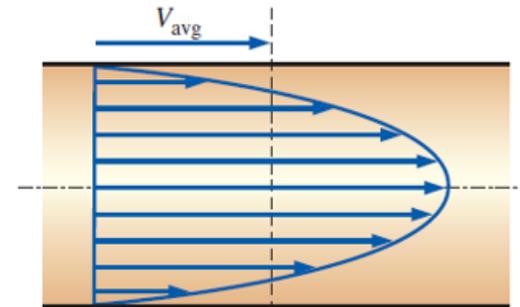
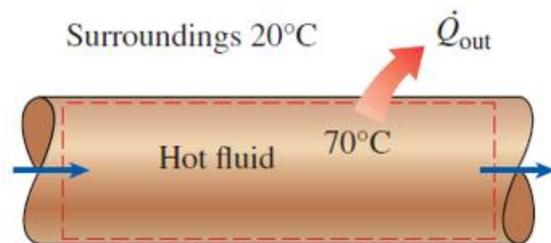
This engineering performance curve represents nominal performance based on actual multistage testing and certification. All pumps supplied by Schlumberger will be tested and certified to perform within the acceptable limits for head, power, and efficiency as defined in the API Recommended Practices (RP11S2) for Electric Submersible Pump Testing.

Operating point of pumps:



Pipe flow/skin friction

(Causes pressure loss; requires pumps to overcome)



Power consumption due to pipe friction (2 wells)

2 KUYUDAN GELIP Y-BAGLANTISI YAPAN 3 BORUDA OLUSAN DEBILER

KUYU 1 (Brine, booster pompa cikisi)

$$T_1 = 174 \text{ [C]}$$
$$P_1 = 11 \text{ [barg]}$$
$$z_1 = 209 \text{ [m]}$$

$$P_{\text{toplam},1} = 29.32 \text{ [barg]}$$

$$V_{1\text{m3saat}} = 669 \text{ [m3/h]}$$
$$m_{1\text{tonsaat}} = 597.2 \text{ [ton/h]}$$

1

Asagidaki bilgiler (mavi) verilince, olusan debiler ve basinclar (kirmizi) hesaplanmaktadir.

- * Booster pompa cikisi kuyu statik basic, kot ve sicaklik degerleri
- * Baglanti noktasi kot degeri (Program sicaklik ve basinc degerlerini hesaplar)
- * Santral (veya ana hat borusu cikis noktasi) statik basinc, kot ve sicaklik degerleri
- * Her bir baglanti ve anahat borusu icin uzunluk, cap ve surtunme katsayisi degerleri
- * (Varsa) hatlardaki tum irtifa pompasi bilgileri (spesifik olarak, sakladiklari basinc veva dusu artisi).
- (Varsa) kisma vanalarinda olusan basinc dususu, negatif pompa basinc artisi olarak girilebilir ($P_{\text{pompa}} = -3$ bar gibi).

$$f_1 = 0.013$$

$$L_1 = 716 \text{ [m]} \quad D_1 = 0.3333 \text{ [m]}$$
$$P_{\text{pompa}_1} = 0 \text{ [bar]}$$

BAGLANTI BORUSU 1

$$P_{\text{kaybi},1} = 0.74 \text{ [bar]}$$

BAGLANTI NOKTASI 11

11

$$f_{11} = 0.012$$

$$L_{11} = 4000 \text{ [m]} \quad D_{11} = 0.4287 \text{ [m]}$$

12

SANTRAL GIRIS veya
ANA HAT CIKIS
NOKTASI (12)

KUYU 2 (Brine, booster pompa cikisi)

$$T_2 = 168 \text{ [C]}$$
$$P_2 = 8 \text{ [barg]}$$
$$z_2 = 235 \text{ [m]}$$

$$P_{\text{toplam},2} = 28.74 \text{ [barg]}$$

$$V_{2\text{m3saat}} = 354 \text{ [m3/h]}$$
$$m_{2\text{tonsaat}} = 318 \text{ [ton/h]}$$

2

BAGLANTI BORUSU 2

$$P_{\text{kaybi},2} = 0.16 \text{ [bar]}$$

$$f_2 = 0.013$$

$$L_2 = 500 \text{ [m]} \quad D_2 = 0.3333 \text{ [m]}$$
$$P_{\text{pompa}_2} = 0 \text{ [bar]}$$

ANAHAT BORUSU 11

$$P_{\text{kaybi},11} = 2.16 \text{ [bar]}$$

$$W_{\text{pump,anahat}} = 82 \text{ [kW]}$$

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

$$T_{11} = 171 \text{ [C]}$$

$$P_{11} = 8.259 \text{ [barg]}$$

$$z_{11} = 231 \text{ [m]}$$

$$P_{\text{toplam},11} = 28.57 \text{ [barg]}$$

$$V_{11\text{m3saat}} = 1021 \text{ [m3/h]}$$

$$m_{11\text{tonsaat}} = 915 \text{ [ton/h]}$$

$$T_{12} = 168 \text{ [C]}$$

$$P_{12} = 10 \text{ [barg]}$$

$$z_{12} = 186 \text{ [m]}$$

$$P_{\text{toplam},12} = 26.41 \text{ [barg]}$$

$$V_{11\text{m3saat}} = 1021 \text{ [m3/h]}$$

$$m_{11\text{tonsaat}} = 915 \text{ [ton/h]}$$

"Ana hatta boru surtunmesini yenmek icin gerekli pompa gucu"

$W_{\text{pump,min,anahat}} = m_{11} \cdot P_{\text{kaybi}}[11] \cdot 100 / \rho_{11}$ "Minimum pompa guc tuketimi, kW"

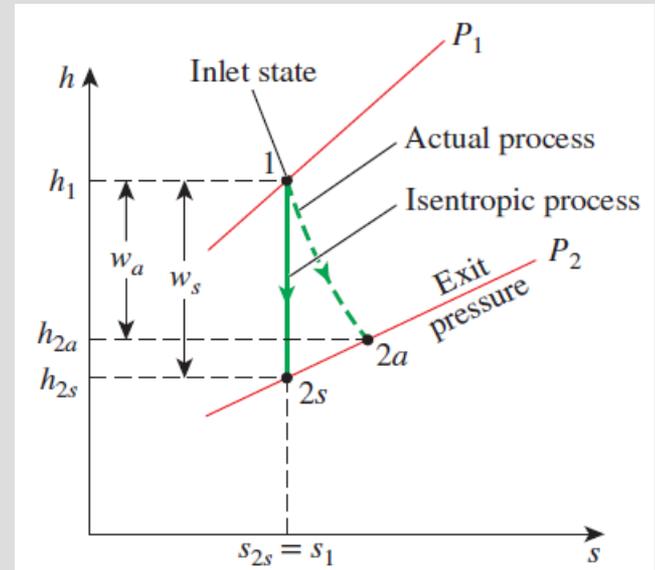
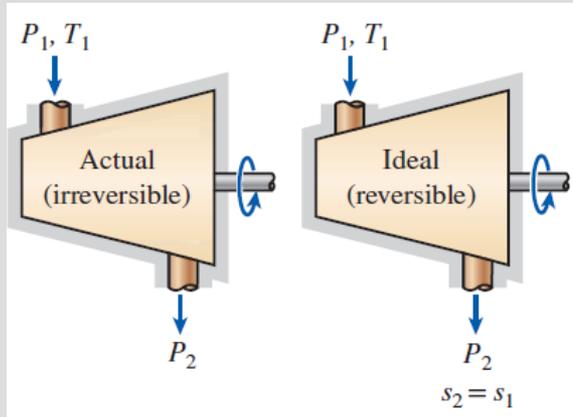
$W_{\text{pump,anahat}} = W_{\text{pump,min,anahat}} / \text{Eta}_{\text{pompa}}$ "Actuak pompa guc tuketimi, kW"

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

Turbine and generator efficiencies

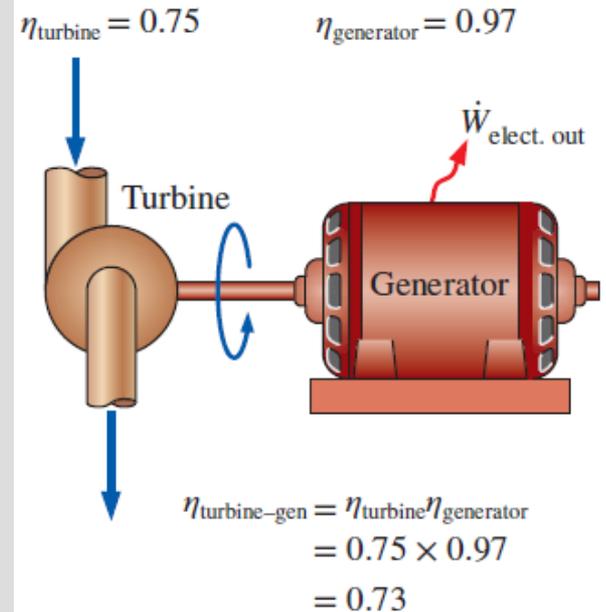
Turbine efficiency (isentropic):

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



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

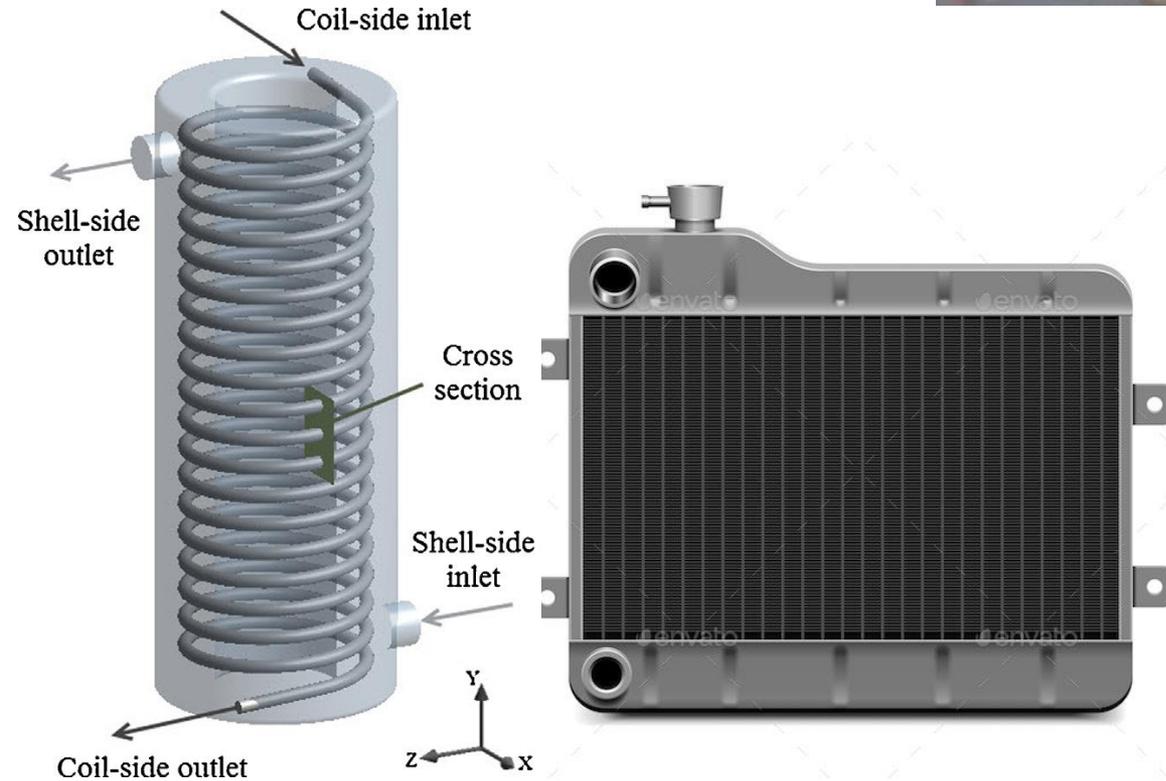
$$\eta_{\text{turbine-gen}} = \eta_{\text{turbine}} \eta_{\text{generator}} = \frac{\dot{W}_{\text{elect, out}}}{\dot{W}_{\text{turbine, e}}} = \frac{\dot{W}_{\text{elect, out}}}{|\Delta \dot{E}_{\text{mech, fluid}}|}$$



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:

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

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

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

Calculation of Q_{max} :

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

or

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

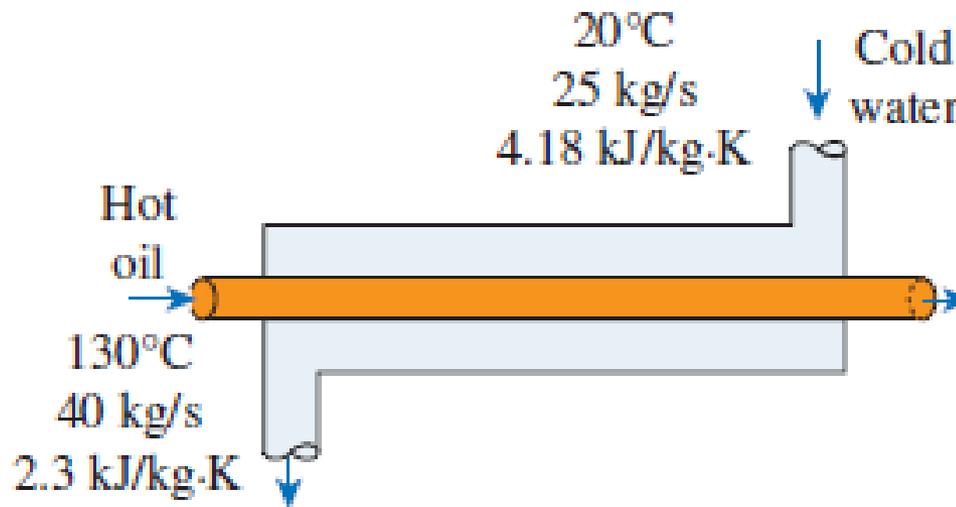
Here:

$C = mC_p$ = Thermal capacity of the fluid

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

Heat exchanger effectiveness-2:

Evaluation of Q_{\max}



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

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

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

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

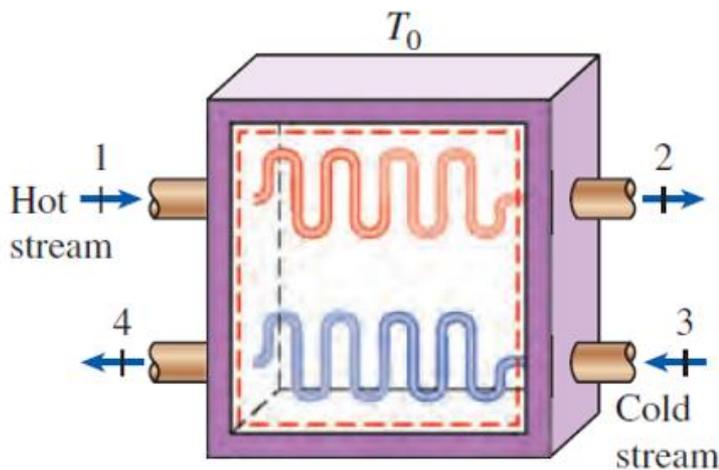
$$\dot{Q}_{\max} = C_{\min} \Delta T_{\max} = 10,120 \text{ kW}$$

Second-Law (exergy) Efficiency of heat exchangers

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

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

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



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.”



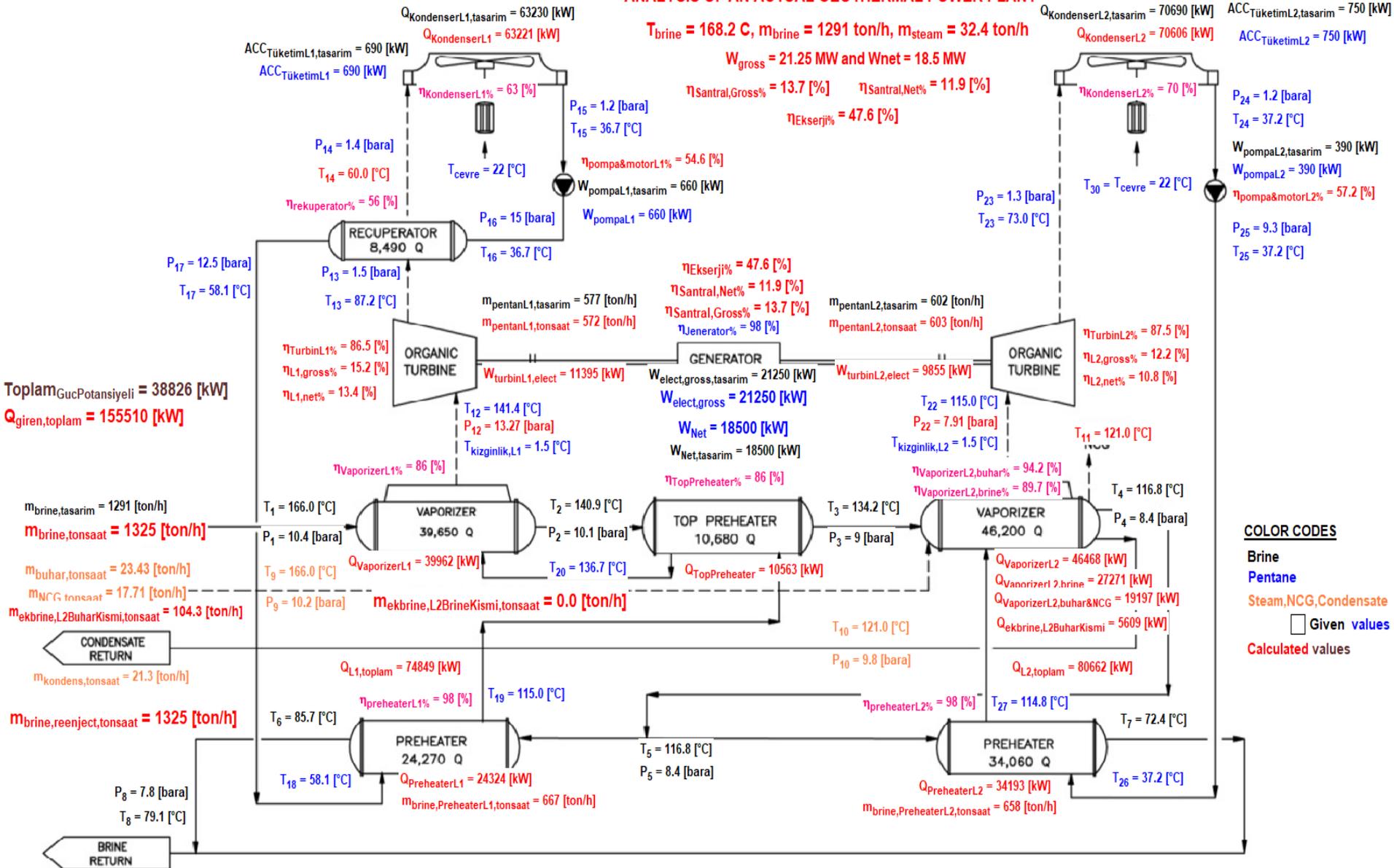
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Example:

Efficiency analysis of a geothermal power plant

Efficiency analysis of a geothermal power plant: Energy&exergy efficiencies of the plant; Effectiveness of HXs

ANALYSIS OF AN ACTUAL GEOTHERMAL POWER PLANT



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 consumption¹	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%	

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

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

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

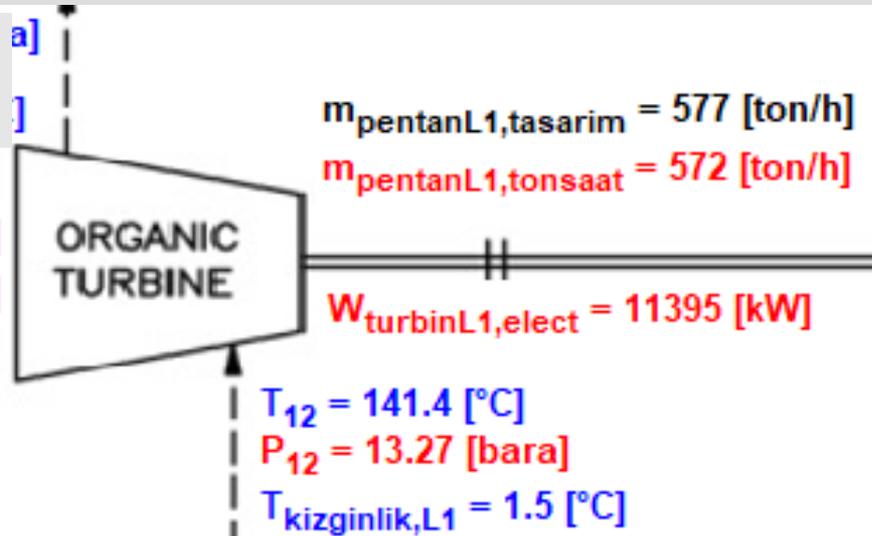
⁴Plant overall efficiency = Electric power sold to utilities (grid)/Geothermal energy consumption

Turbine efficiencies:

High-pressure L1 cycle and low-pressure L2 cycle

High-pressure
L1 cycle

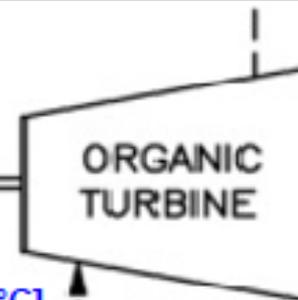
$$\eta_{\text{TurbinL1}\%} = 86.5 \text{ [\%]}$$
$$\eta_{\text{L1,gross}\%} = 15.2 \text{ [\%]}$$
$$\eta_{\text{L1,net}\%} = 13.4 \text{ [\%]}$$



$$m_{\text{pentanL2,tasarim}} = 602 \text{ [ton/h]}$$
$$m_{\text{pentanL2,tonsaat}} = 603 \text{ [ton/h]}$$

$$W_{\text{turbinL2,elect}} = 9855 \text{ [kW]}$$

$$T_{22} = 115.0 \text{ [}^\circ\text{C]}$$
$$P_{22} = 7.91 \text{ [bara]}$$
$$T_{\text{kizginlik,L2}} = 1.5 \text{ [}^\circ\text{C]}$$

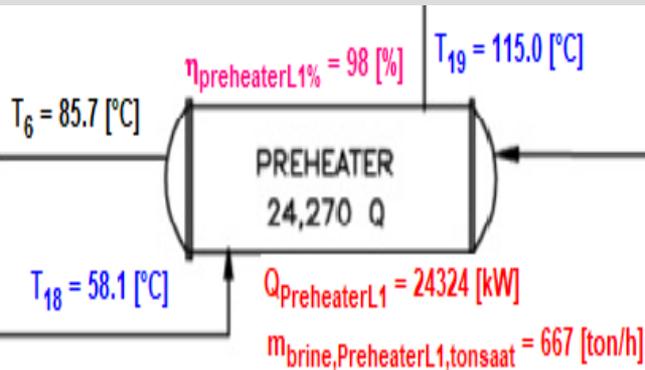


$$\eta_{\text{TurbinL2}\%} = 87.5 \text{ [\%]}$$
$$\eta_{\text{L2,gross}\%} = 12.2 \text{ [\%]}$$
$$\eta_{\text{L2,net}\%} = 10.8 \text{ [\%]}$$

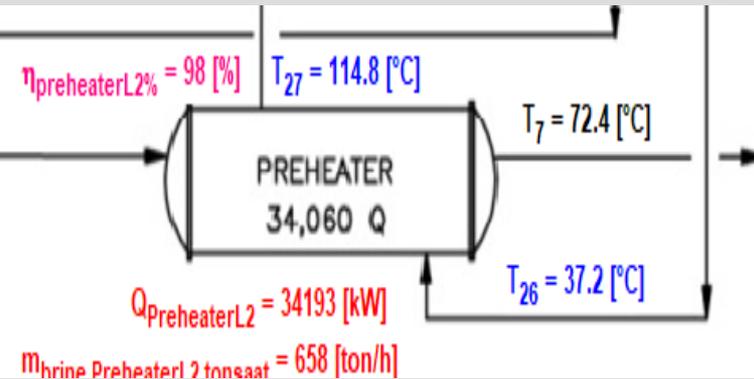
Low-pressure
L2 cycle

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

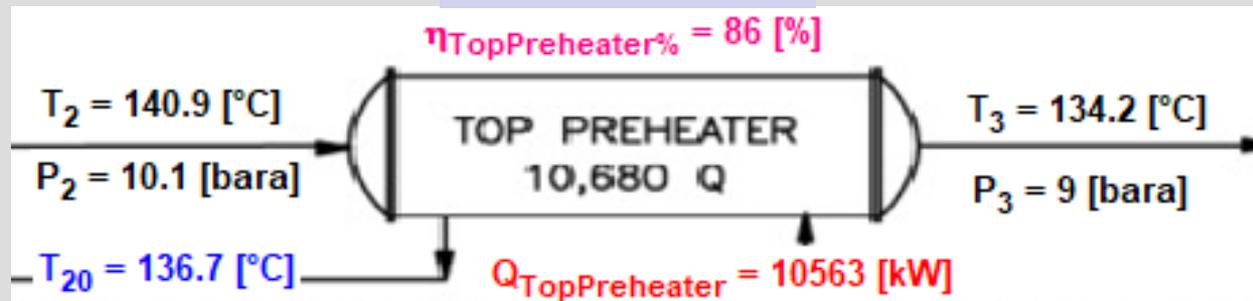
High-pressure
L1 cycle



Low-pressure
L2 cycle

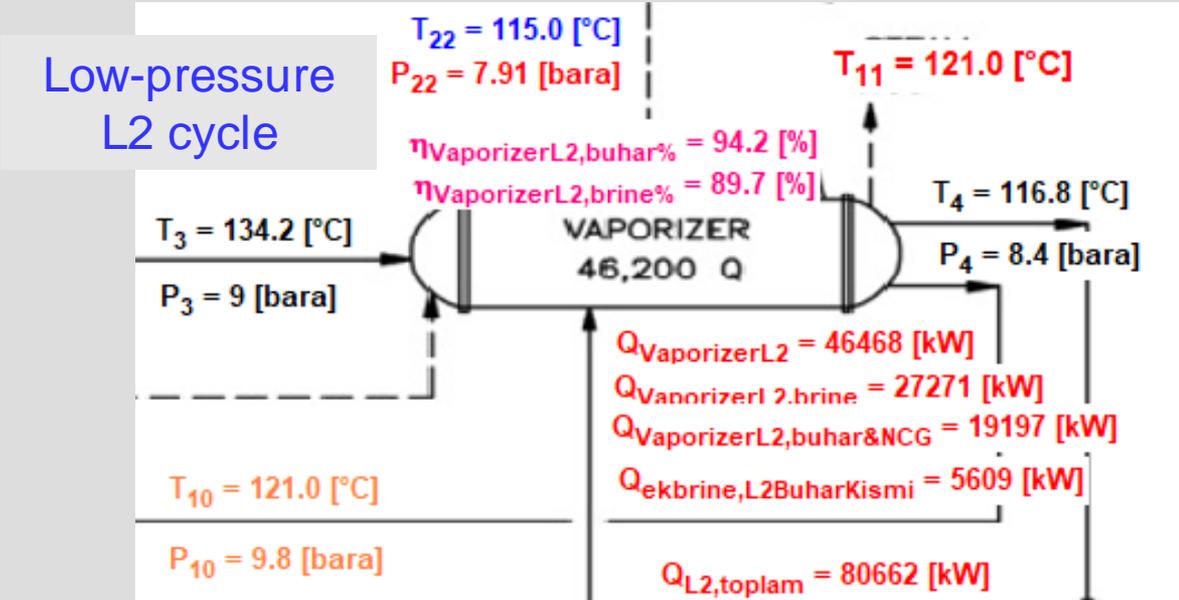
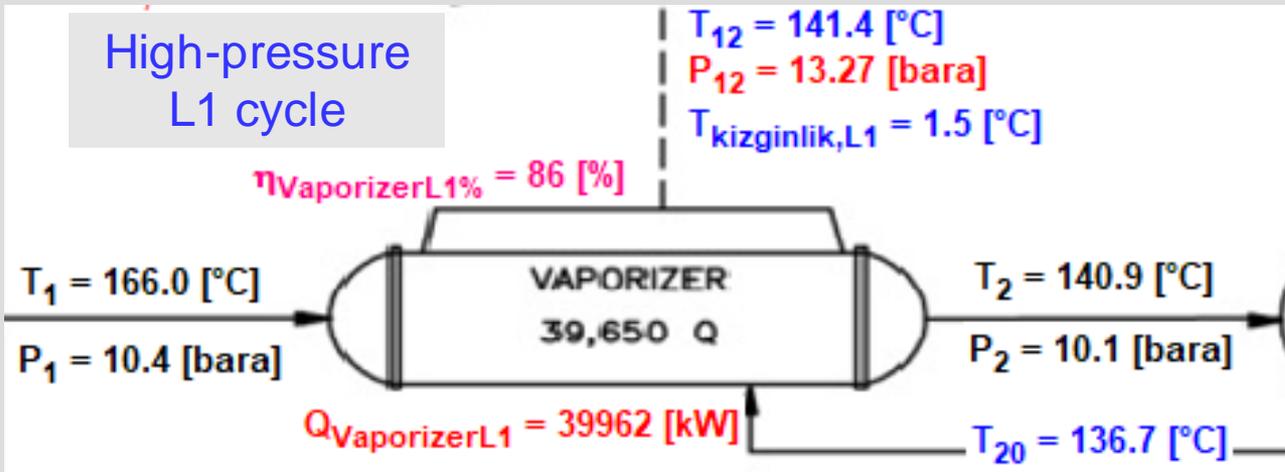


High-pressure
L1 cycle
Top preheater



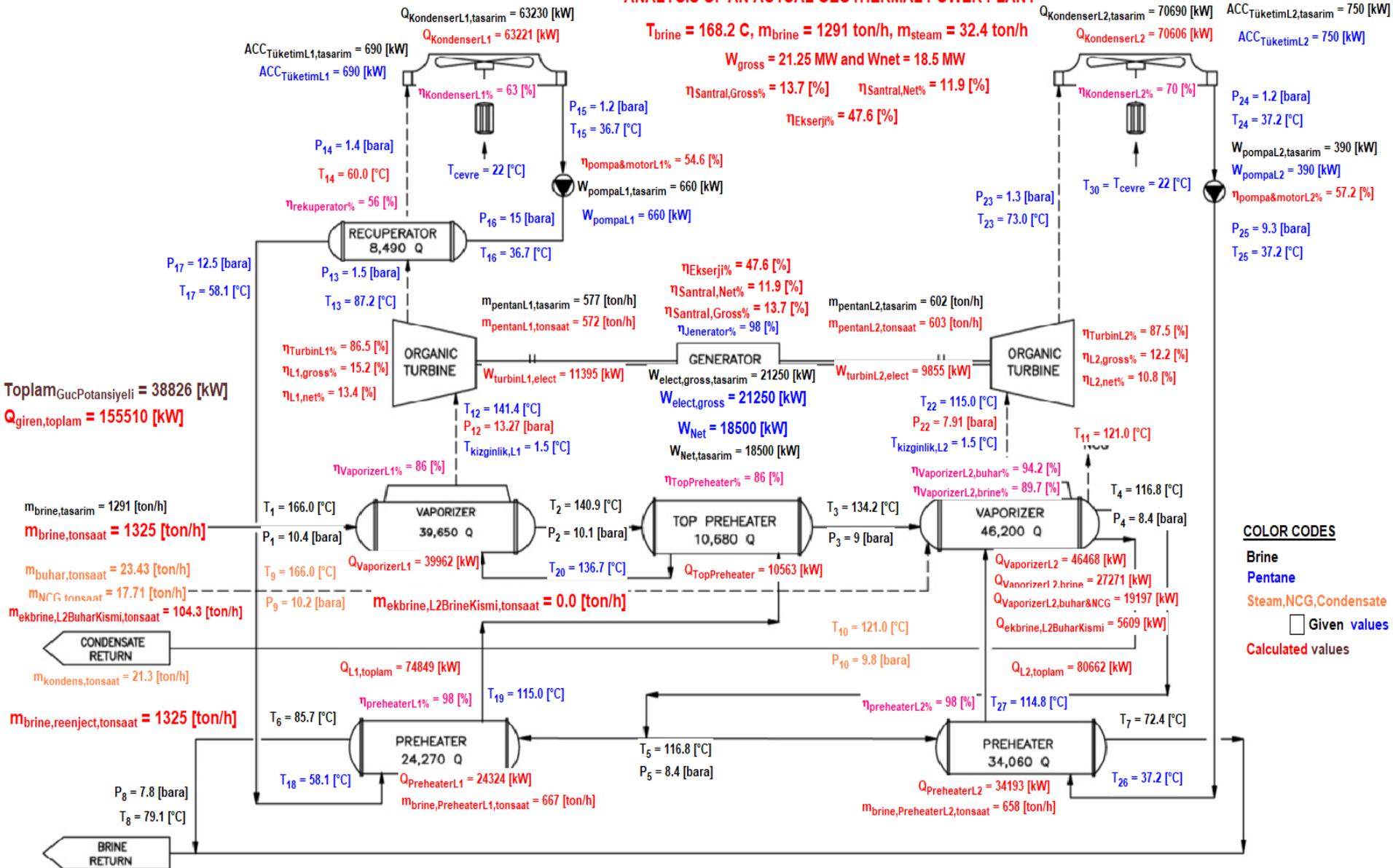
Vaporizer performance:

High-pressure L1 cycle and low-pressure L2 cycle



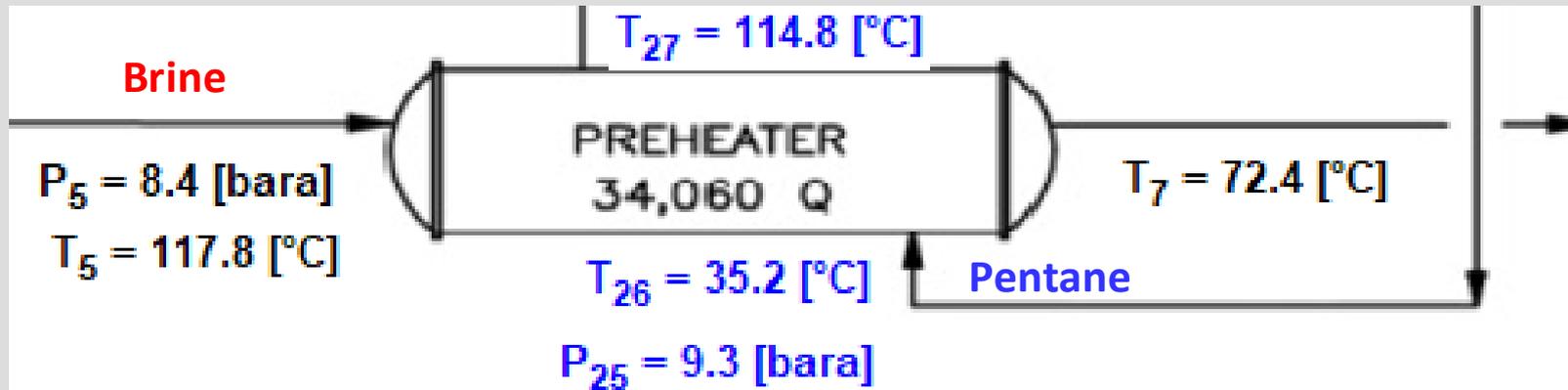
Diagnostics based on analysis: Power production increase when the HXs are washed

ANALYSIS OF AN ACTUAL GEOTHERMAL POWER PLANT



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

What you read is NOT necessarily what it is



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

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