July 9, 10, 16 & 17; 8:00 – 11:00 AM CT

Rita Esuru Okoroafor; Texas A&M University

Fundamentals of Geothermal Reservoir Engineering

Agenda

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Oil and gas well conversions and unconventional geothermal systems

04 Geothermal reserve estimation, system optimization, and future trends

InterPore Academy

Day 1

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

03 Oil and gas well conversions and unconventional geothermal systems

04 Geothermal reserve estimation, system optimization, and future trends

About the Instructor

Rita Esuru Okoroafor, Assistant Professor at TAMU Petroleum Engineering Department

- Ph.D. from Stanford University, B.Eng. University of Port Harcourt, Nigeria
- 15 years of oil and gas industry experience
- Think a lot about sustainable energy
- Main research thrust is numerical modeling of subsurface systems.

Course Organization

INTERPORE

AGENDA FOR FUNDAMENTALS OF GEOTHERMAL RESERVOIR ENERGY VIRTUAL TRAINING

		DATE			
Section	Time	Wednesday	Thursday	Wednesday	Thursday
		9-Jul-25	**10-Jul-25**	**16-Jul-25**	**17-Jul-25**
1	08:00-09:30	Lecture	Lecture	Lecture	Lecture
2	09:30-09:40	Break	Break	Break	Break
3	09:40-11:00	Lecture	Lecture	Lecture	Lecture

Times in CDT

Course Goals – Main Takeaways

1. **Gain foundational knowledge on geothermal energy, including its properties, sources, and production methods.**

2. **Understand the impact of multiphase flow and varying rock properties on geothermal energy production.**

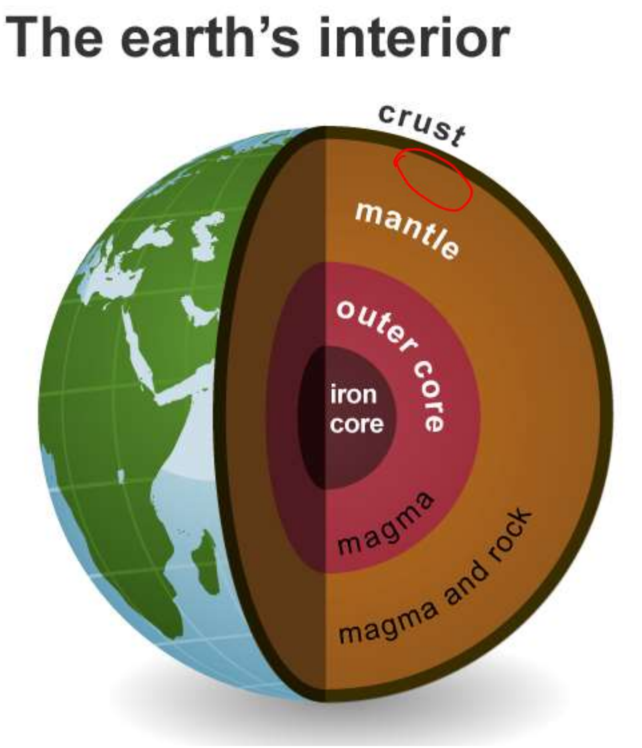
3. **Gain awareness of new generation geothermal energy technologies.**

4. **Be able to apply learnings at work, research, technical meetings, etc.**

Getting To Know You

Share your Background and Course Expectations

What is Geothermal Energy?



Source: Adapted from a National Energy Education Development Project graphic (public domain)

- Geothermal energy is heat within the earth. The word geothermal comes from the Greek words *geo* (earth) and *therme* (heat).
- Geothermal energy is a renewable energy source because heat is continuously produced inside the earth.
- The heat of the Earth is derived from two components: the heat generated by the formation of the Earth, and heat generated by subsequent radioactive decay of elements in the upper parts of the Earth.

Terminology

- **Geothermal Energy** — Geothermal energy is heat within the earth. The word geothermal comes from the Greek words geo (earth) and therme (heat).
- **Energy** — The ability or capacity to do work. Measured in Joules (J) or kilowatt-hour (kWh) or Btu. 1 British thermal unit (Btu) is equivalent to 1,055 J or 0.293 Wh
- **Power** — The rate of doing work or producing or expending energy. Measured in watts (W). One watt is equal to 1 joule (J) per second. A megawatt (MW) is one million watts.
- **Renewable energy** — Electricity supplied from renewable energy sources, such as wind and solar power, geothermal, hydropower, and various forms of biomass. Considered renewable sources because they are continuously replenished on the Earth.

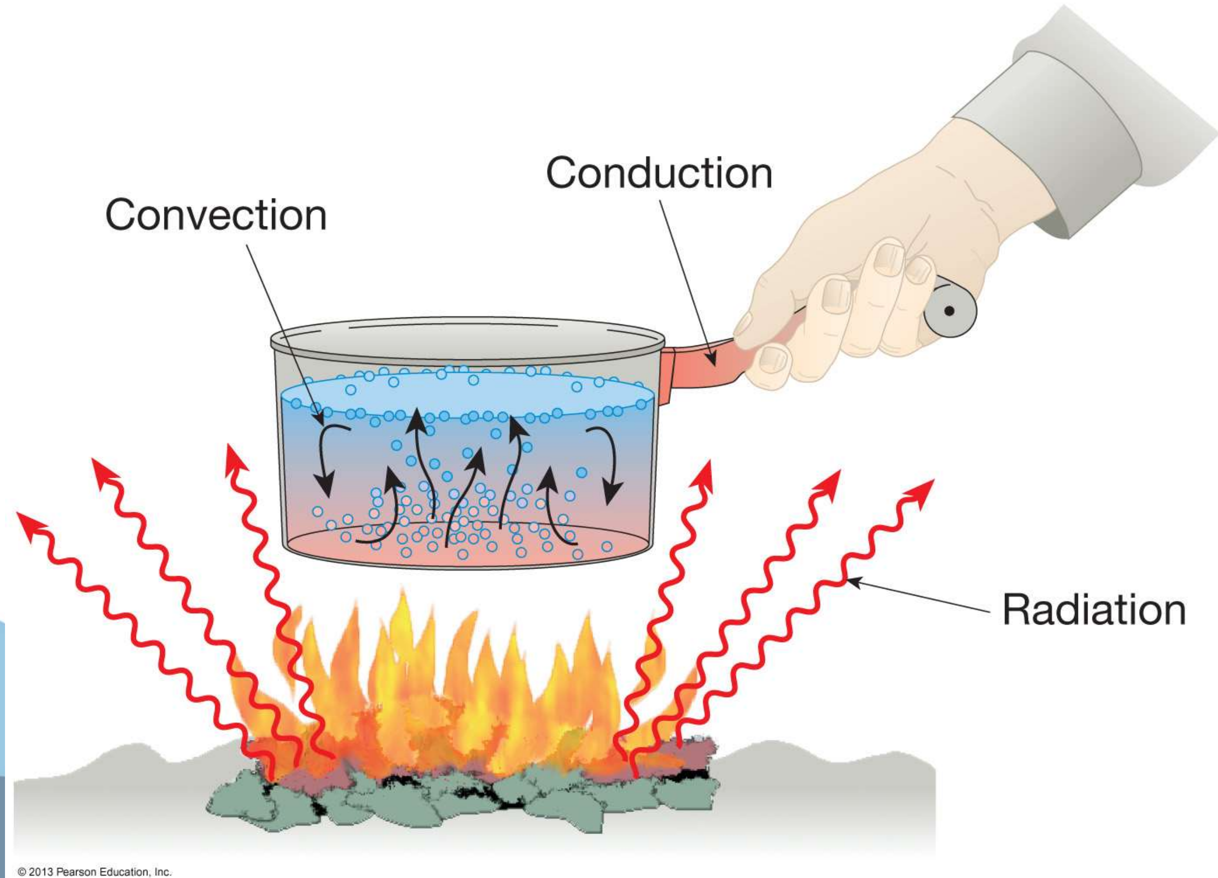
Terminology

- Non-condensable gases (NCG): Gases such as sulfur oxide, carbon dioxide, methane, ammonia, hydrogen sulfide, hydrogen, are the gaseous emissions that are found dissolved in the geothermal water.
- Enthalpy: A thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume.
- Steam quality: Fraction by mass of a given fluid that is steam.
- Capacity factor: The actual energy output from a generating plant over a period of time, usually a year, as a fraction or percentage of the plant's capacity. It reflects how much the plant is used and not shut down for maintenance or malfunction.

Metric Prefixes

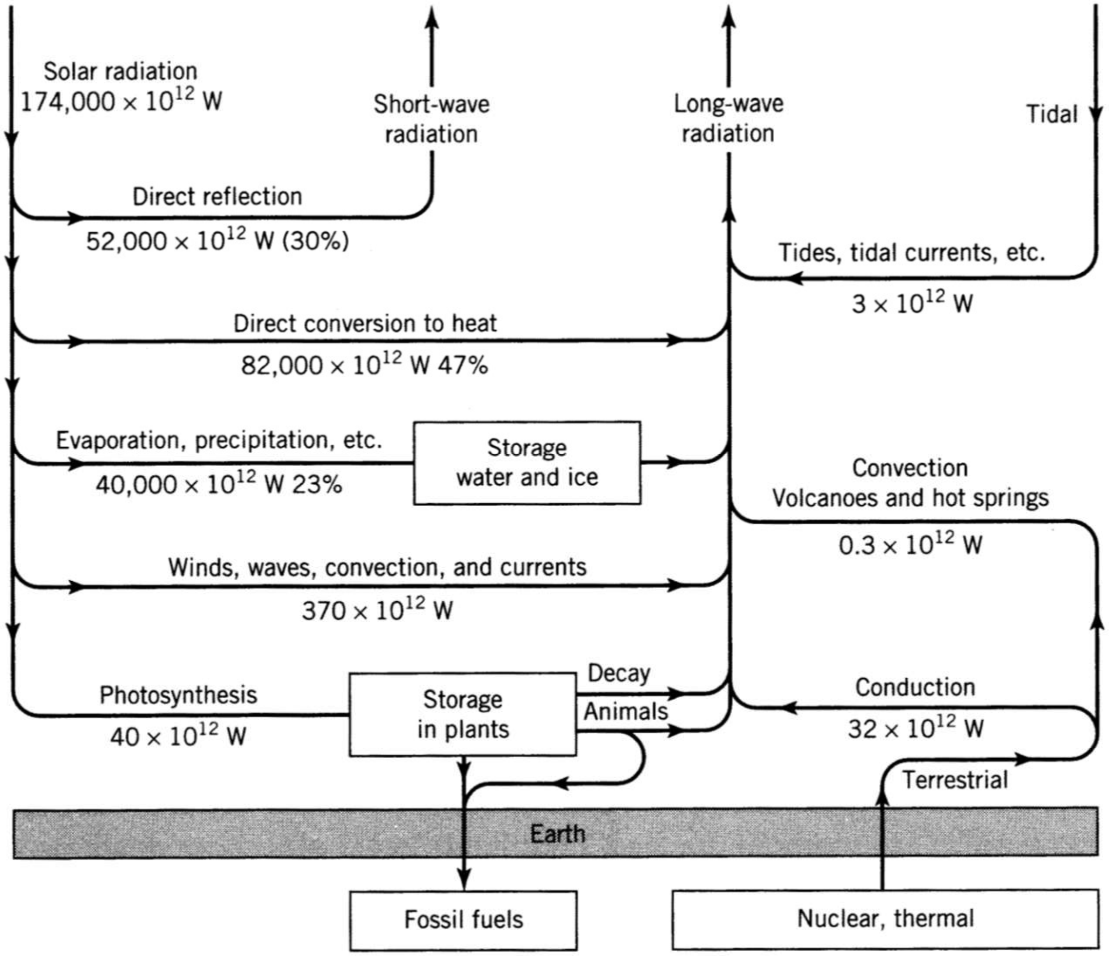
SI PREFIX	SI SYMBOL	SI UNIT CONVERSION FACTOR (STANDARD FORM)	FACTOR (POWER)	FACTOR LANGUAGE
yotta	Y	1 yottametre = 1 000 000 000 000 000 000 000 000 metres	10^{24}	septillion
zetta	Z	1 zettametre = 1 000 000 000 000 000 000 000 metres	10^{21}	sextillion
exa	E	1 exametre = 1 000 000 000 000 000 000 metres	10^{18}	quintillion
peta	P	1 petametre = 1 000 000 000 000 000 metres	10^{15}	quadrillion
tera	T	1 terametre = 1 000 000 000 000 metres	10^{12}	trillion
giga	G	1 gigametre = 1 000 000 000 metres	10^{9}	billion
mega	M	1 megametre = 1 000 000 metres	10^{6}	million
kilo	k	1 kilometre = 1 000 metres	10^{3}	thousand
hecto	h	1 hectometre = 100 metres	10^{2}	hundred
deca	da	1 decametre = 10 metres	10^{1}	ten
		1 metre = 1 metre	$\mathbf{10^{0}}$	**one**
deci	d	1 decimetre = 0.1 metres	10^{-1}	tenth
centi	c	1 centimetre = 0.01 metres	10^{-2}	hundredth
milli	m	1 millimetre = 0.001 metres	10^{-3}	thousandth
micro	µ	1 micrometre = 0.000 001 metres	10^{-6}	millionth
nano	n	1 nanometre = 0.000 000 001 metres	10^{-9}	billionth
pico	p	1 picometre = 0.000 000 000 001 metres	10^{-12}	trillionth
femto	f	1 femtometre = 0.000 000 000 000 001 metres	10^{-15}	quadrillionth
atto	a	1 attometre = 0.000 000 000 000 000 001 metres	10^{-18}	quintillionth
zepto	z	1 zeptometre = 0.000 000 000 000 000 000 001 metres	10^{-21}	sextillionth
yocto	y	1 yoctometre = 0.000 000 000 000 000 000 000 001 metres	10^{-24}	septillionth

Heat Transfer Methods



- Conduction: heat transfer by direct contact of two materials at different temperatures.
- Convection: heat transfer within fluids of different temperatures and densities.
- Radiation: heat transfer by electromagnetic waves.

How Great is Renewable Geothermal Energy?



Source: Hubbert, M. K., Man's Conquest of Energy: It's Ecological and Human Consequences," in the Environmental and Ecological Forum, U. S. A.E.C. TID–25857, 1972

Let's compare to the current world energy consumption

- World consumes about 500 EJ/year
- Convert to Watts:
- $(500 \times 10^{18} J/yr)(1\ yr/365\ d)(1\ d/24hr)(1hr/3600s)$
- $= 1.6 \times 10^{13}$ J/s
- $= 16 \times 10^{12}$ J/s $= 16 \times 10^{12}$ W

- Or world power demand is about 16/32 = ½ of renewable geothermal energy

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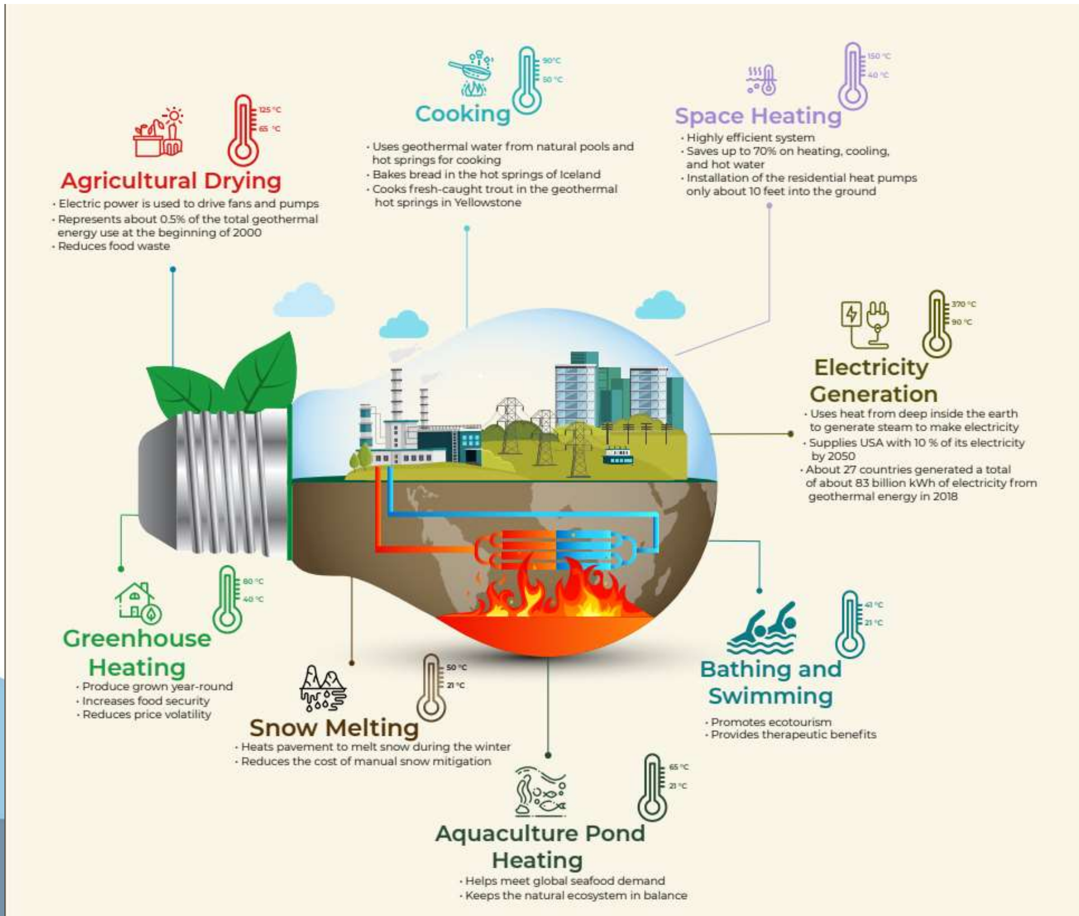
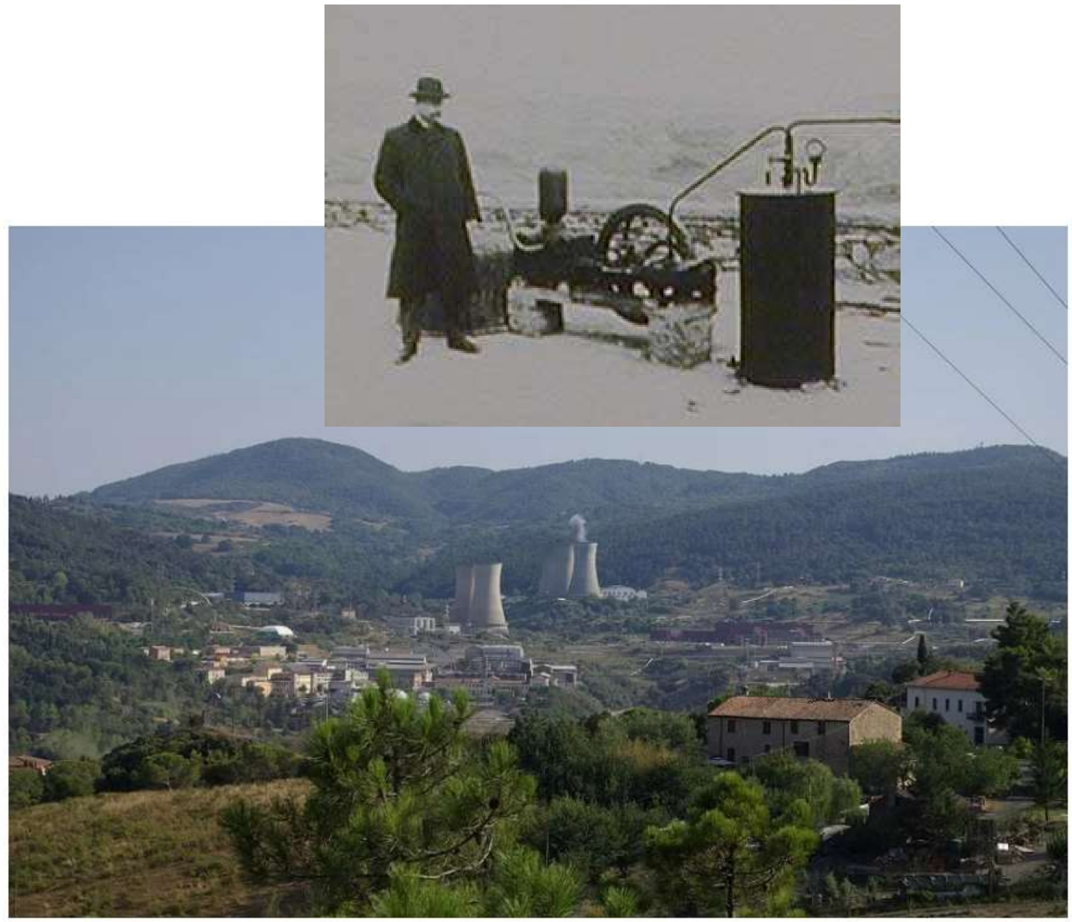


- Geothermal Uses:
- Electricity
- Heating
- Direct Use

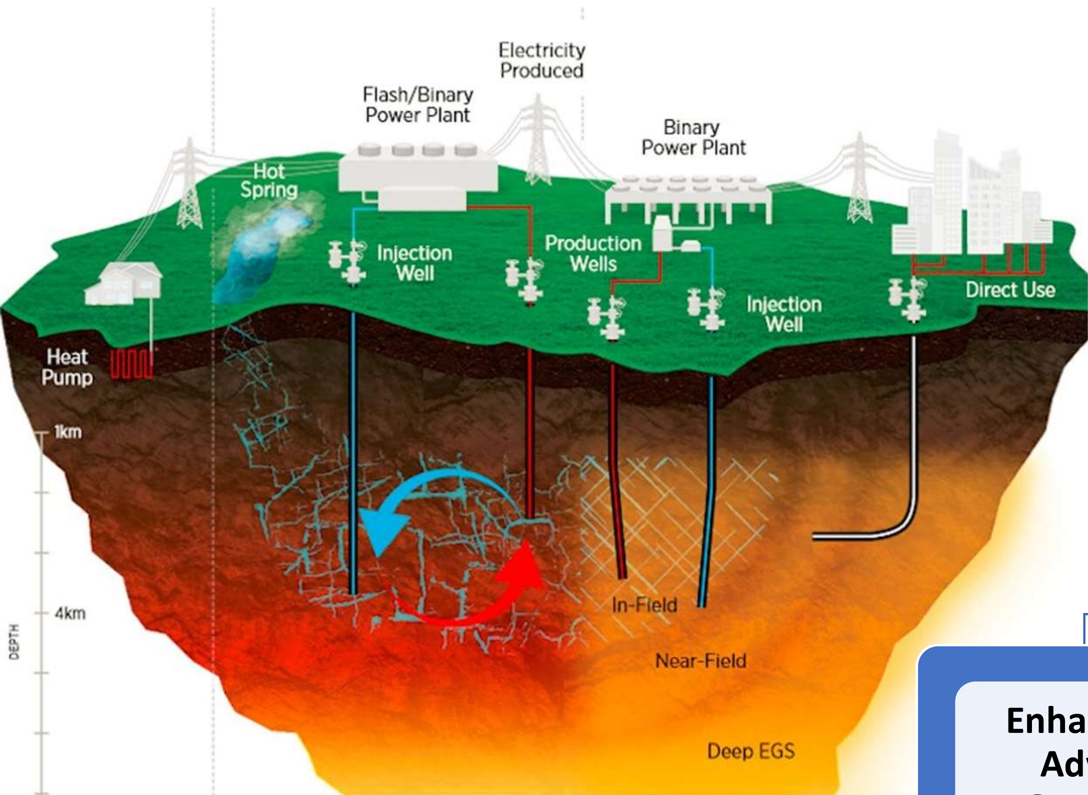
Early Development

- 1904 – Larderello, Italy
- First experimental work by Prince Piero Ginori Conti
- 5 light bulbs from 10 kWe indirect cycle dynamo
- Later, in 1911, the world's first commercial geothermal power plant was built there.



Larderello geothermal power plant in Tuscany, Italy.

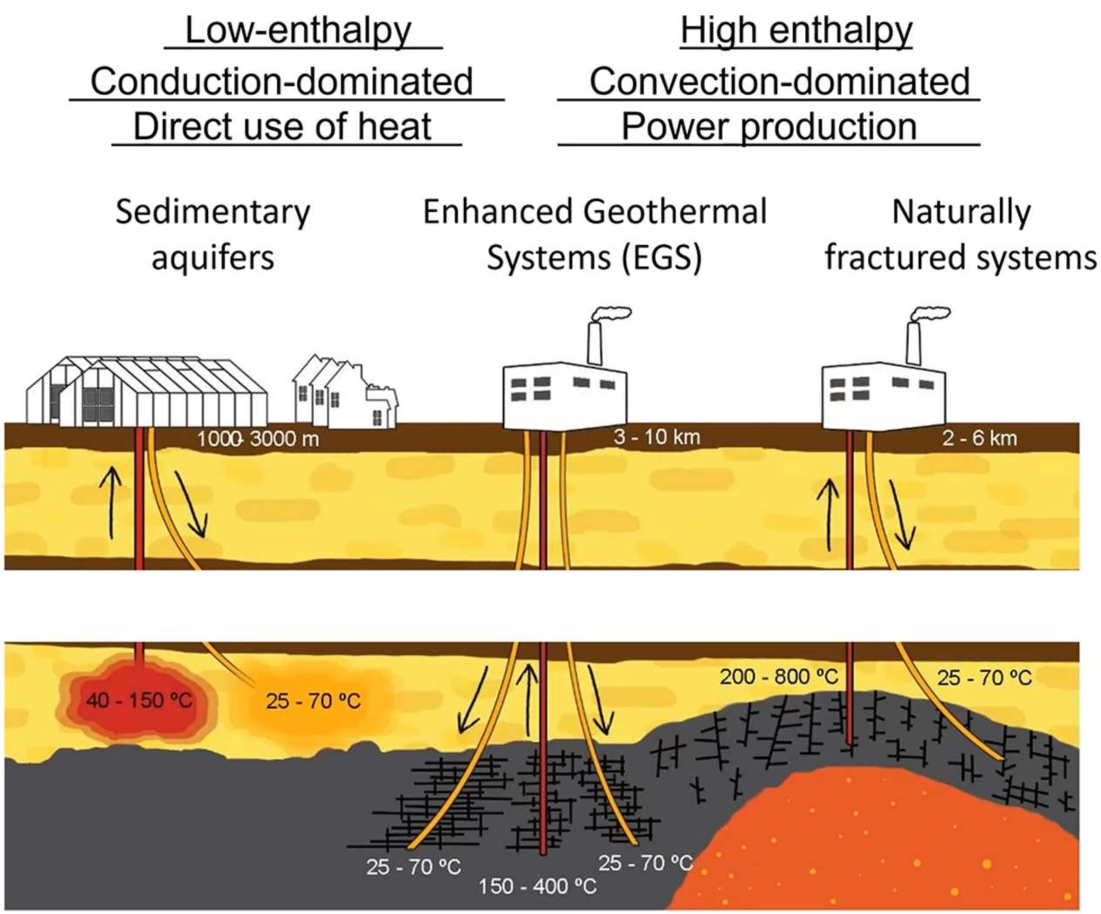
Introduction: About Geothermal Energy



Source: GeoVision report by the U.S. DOE (2019)

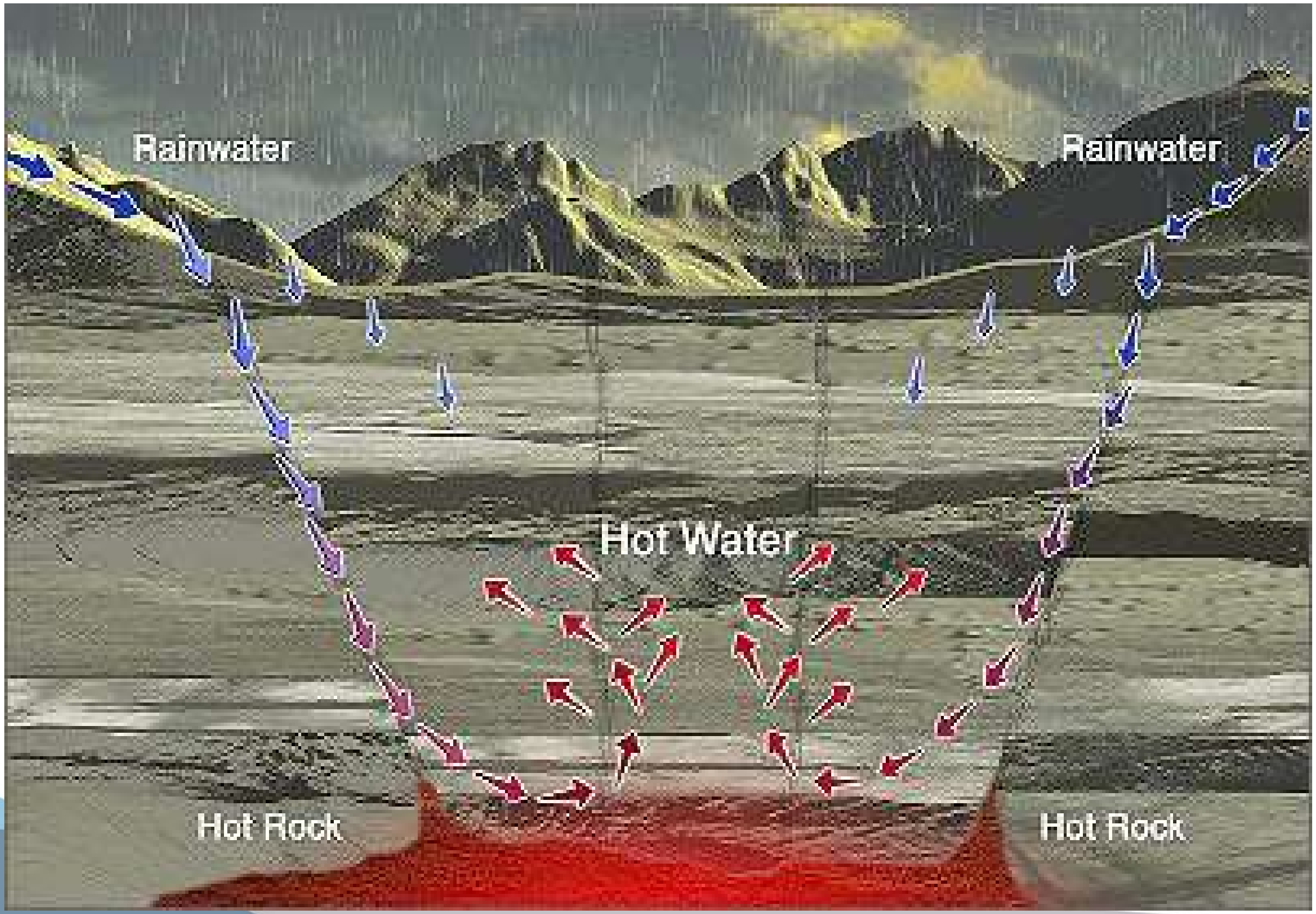
- **Geothermal Resources**
  - **Unconventional**
    - **Enhanced and Advanced Geothermal Systems**
    - **Low-Temperature / Coproduced Fluids**
  - **Conventional**
    - **Hydrothermal**

Overview of Geothermal Systems



- High temperature or enthalpy (T>180 to 200 °C)
- Medium temperature or enthalpy (100 to 180 °C)
- Low temperature or enthalpy (T<100°C)

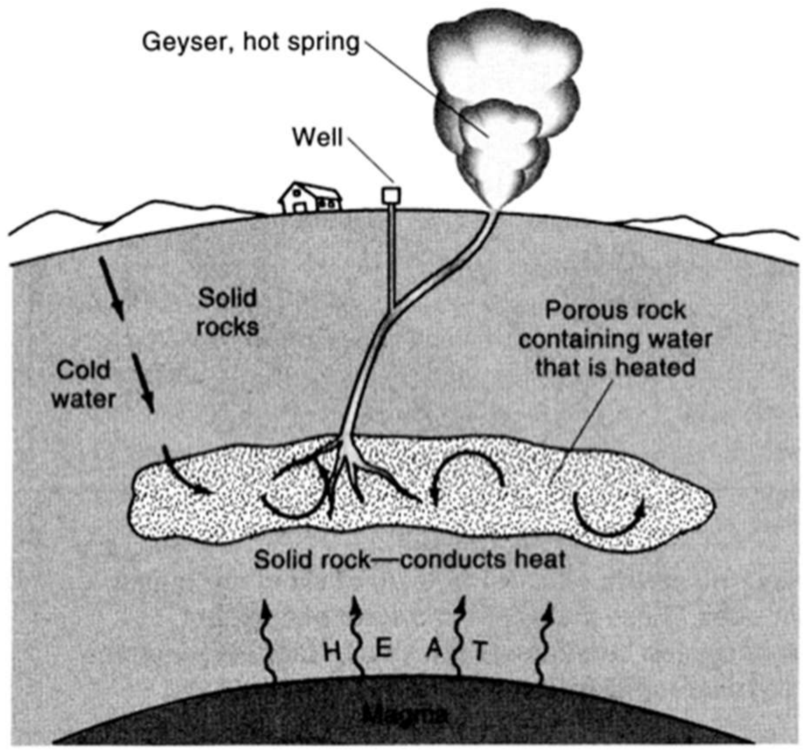
Conventional Hydrothermal System



DOE's Office of Energy Efficiency and Renewable Energy (DOE, 2010)

Necessary Elements for a Geothermal Reservoir

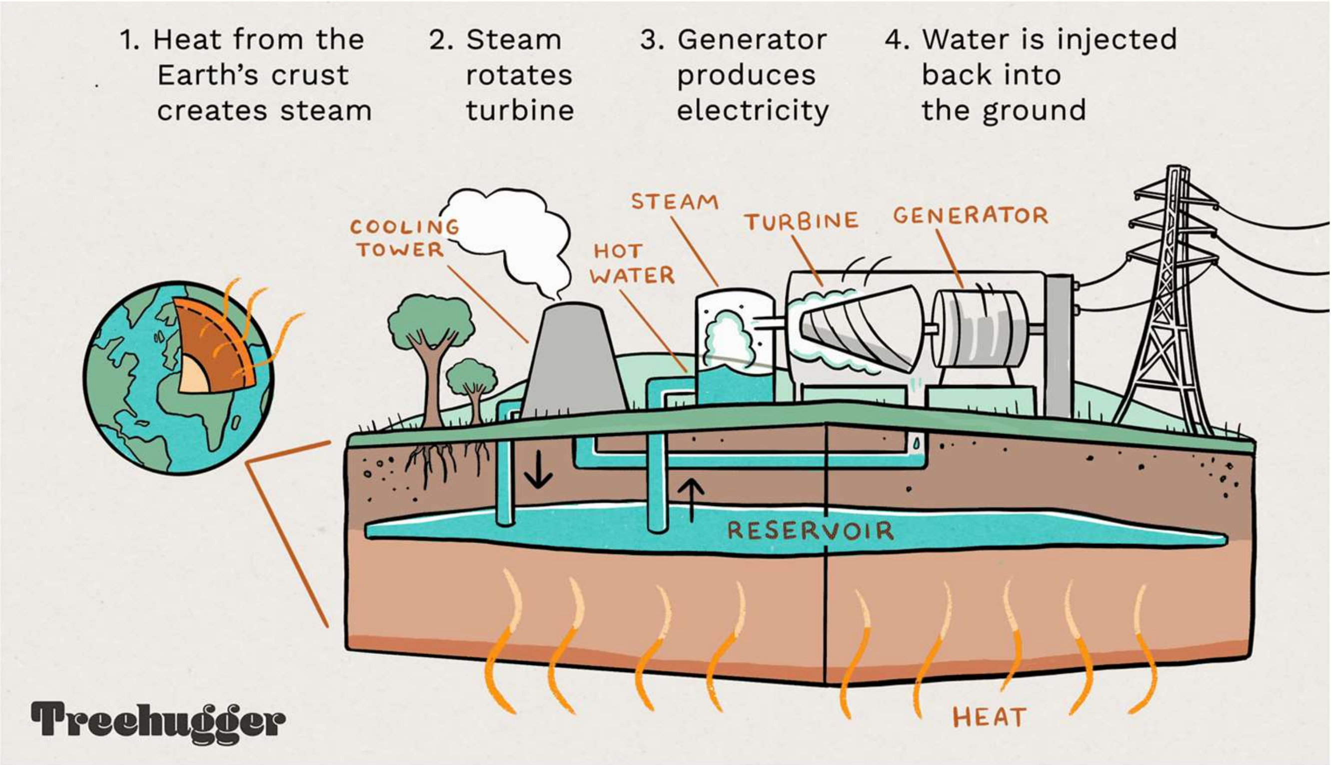
- Heat source–e.g., volcanic heat
- A reservoir– porous and permeable rock
- Fluid–heat transfer fluid (working fluid) such as water or steam
- Caprock or Seal – to contain the fluid



Source: Hinricks and Kleinbach, Energy Its Use and the Environment, 2002.

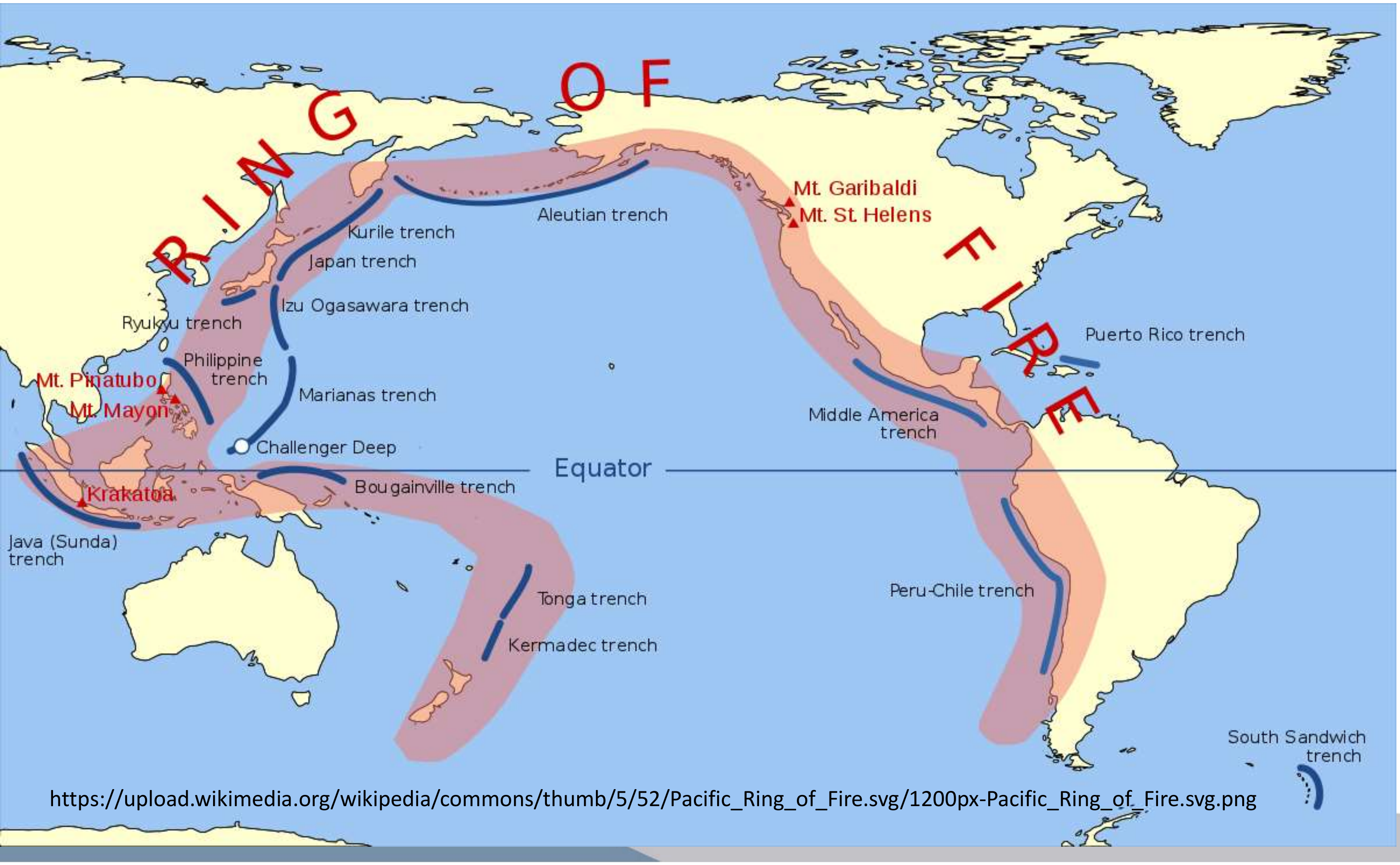
Geothermal Electricity

- From reservoir to ….power plant
  - energy stored in rock
  - heat transfer from rock to fluid
  - flow through porous media to well
    - fracture and matrix flow
  - power cycles (heat to electricity)
    - vapor dominated
    - liquid dominated
    - binary
  - reinjection



- Say that you are a geothermal prospector, where on earth do you go to find "hot" rocks?

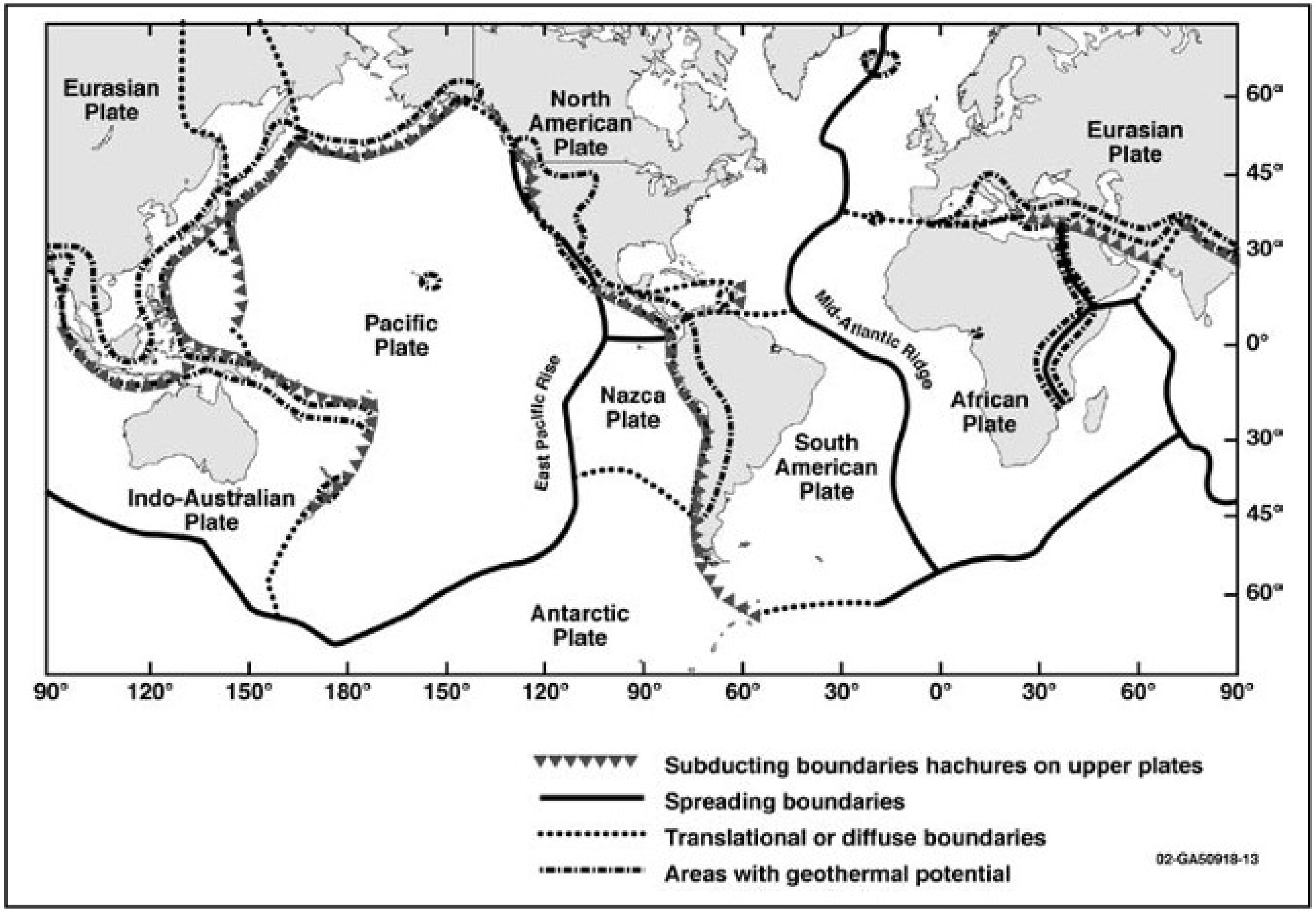
Ring of Fire



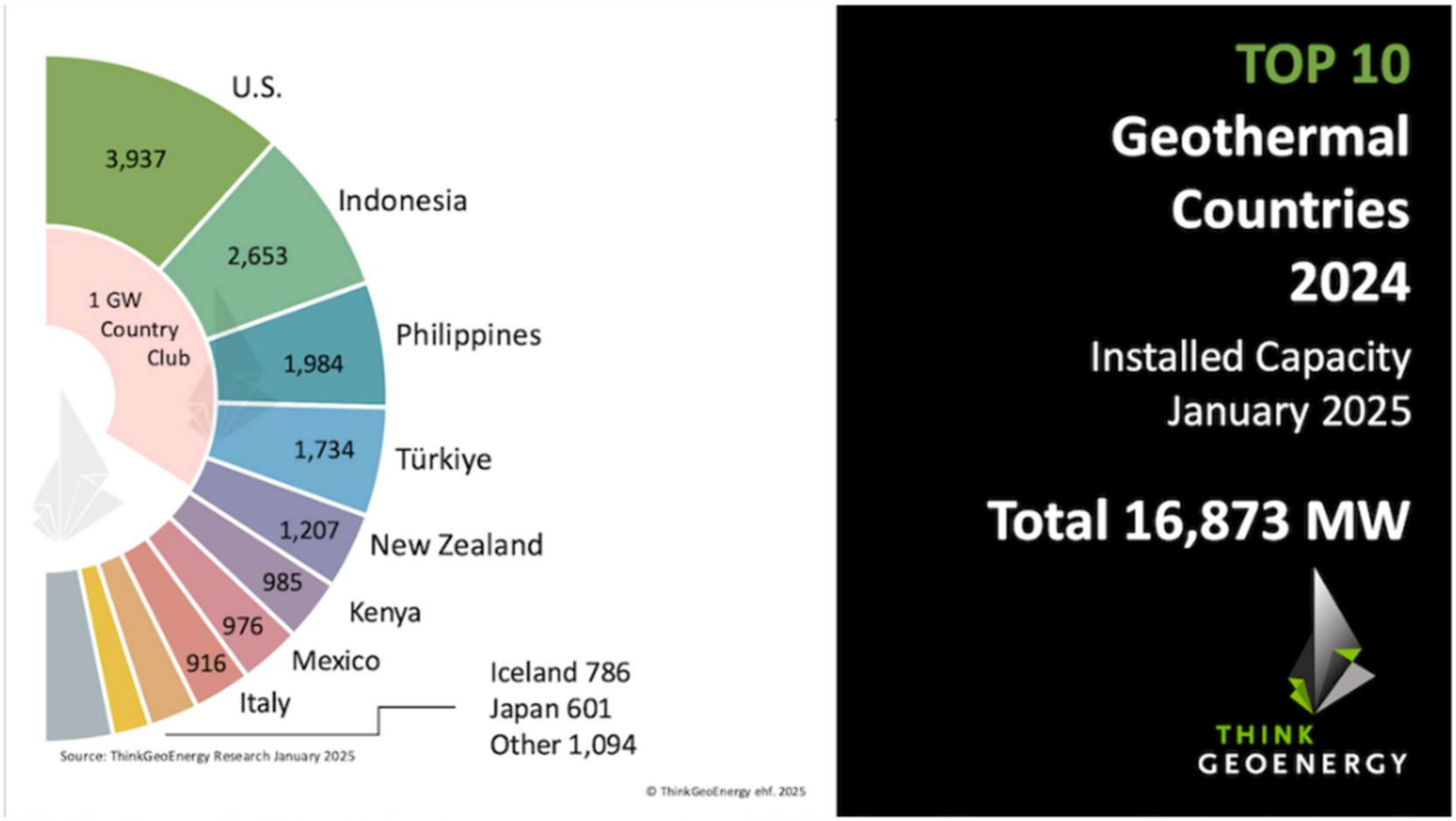
https://upload.wikimedia.org/wikipedia/commons/thumb/5/52/Pacific_Ring_of_Fire.svg/1200px-Pacific_Ring_of_Fire.svg.png

- Generally along the Ring of Fire, plate boundaries, and other locations where heat can migrate upward from deep in the earth.

Areas with Geothermal Potential



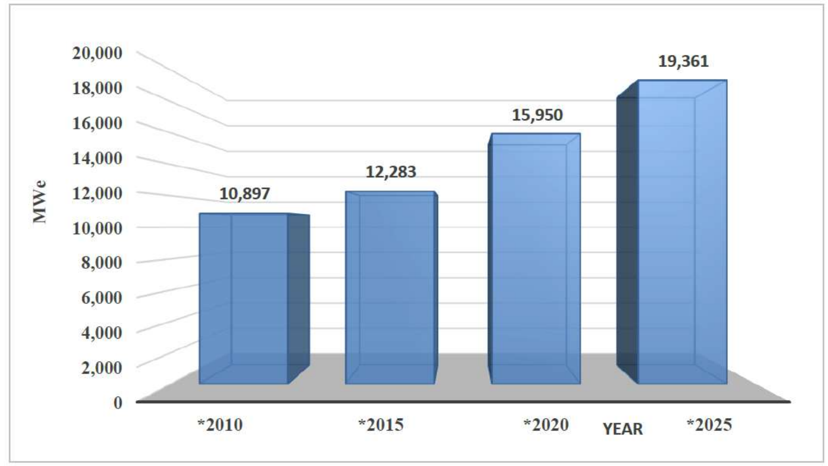
Geothermal Energy Globally



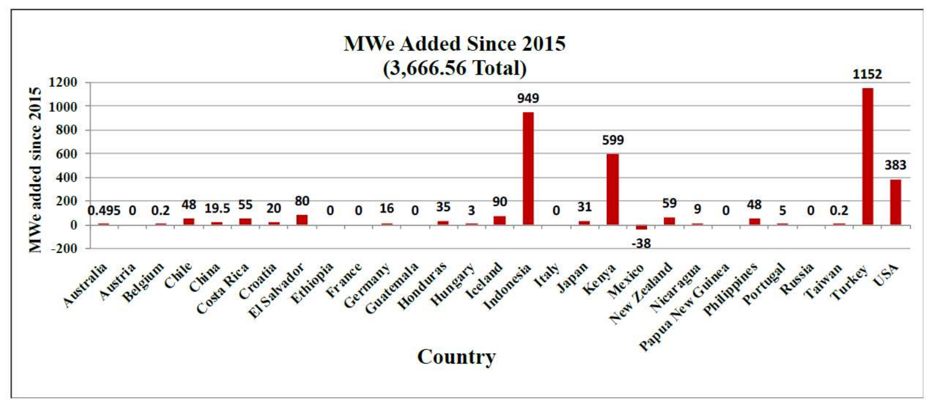
ThinkGeoEnergy 2024 Top 10 Geothermal Countries - Installed Geothermal Power Generation Capacity (copyright: ThinkGeoEnergy)

Geothermal Energy Globally

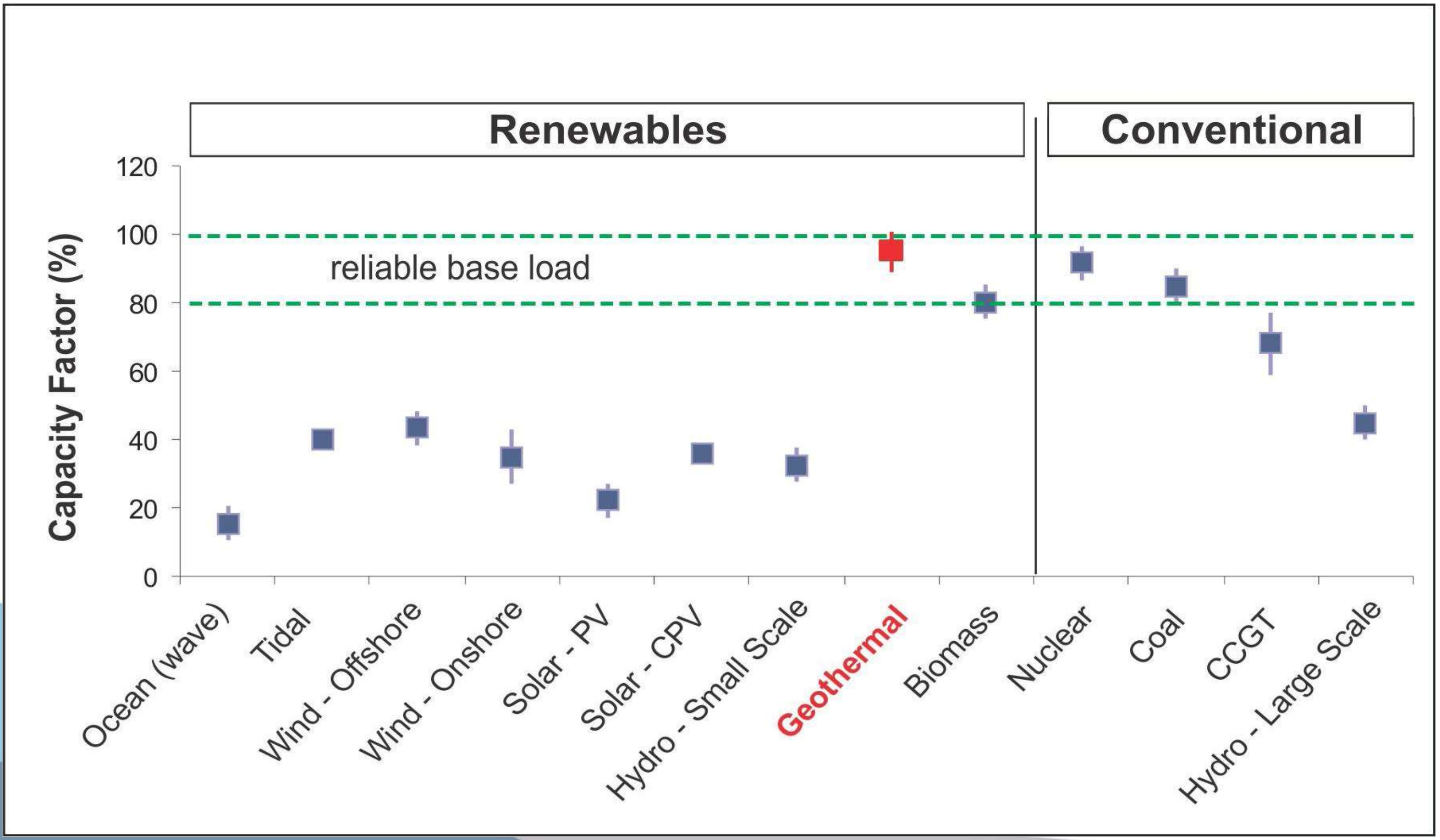
- Geothermal Power Generation in the World 2015-2020 Update Report (Huttrer,2020)
  - Geothermal installed capacity is increasing
  - Five countries (Belgium, Chile, Croatia, Honduras and Hungary) generated geothermal power for the first time



- Direct Utilization of Geothermal Energy 202 Worldwide Review (Lund and Toth, 2020)
  - Uses of Geothermal Energy beyond power generation is growing
  - Energy savings, reduction in CO_2 emissions



A key advantage for geothermal

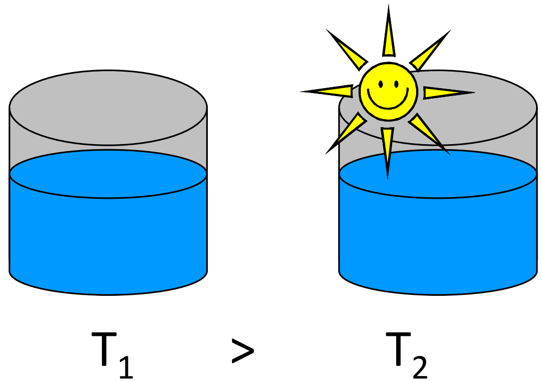


- Baseload: the amount of power made available by an energy producer (such as a power plant) to meet fundamental demands by consumers.

Source: Emerging Energy Research (2009)

Work and Heat Interactions

- Heat = Q

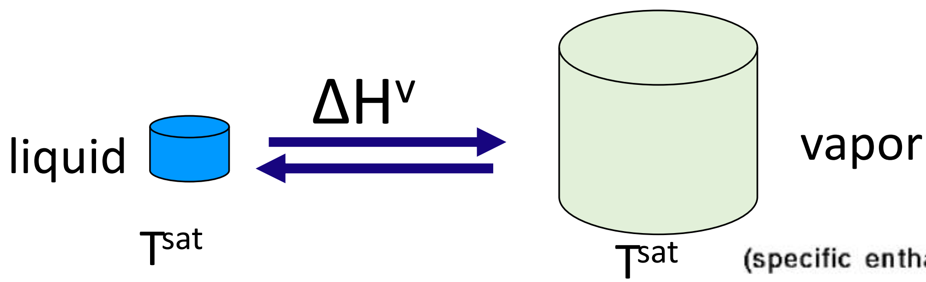


$$Q = mC_p(T_1 - T_2)$$

	C_p (J/kg°C)	C_p BTU/lb°F
water	4189	1
concrete	960	0.23
brick	840	0.2
oak	2390	0.57
pine	2800	0.67

source: Kreith and Black, Basic Heat Transfer (1980)

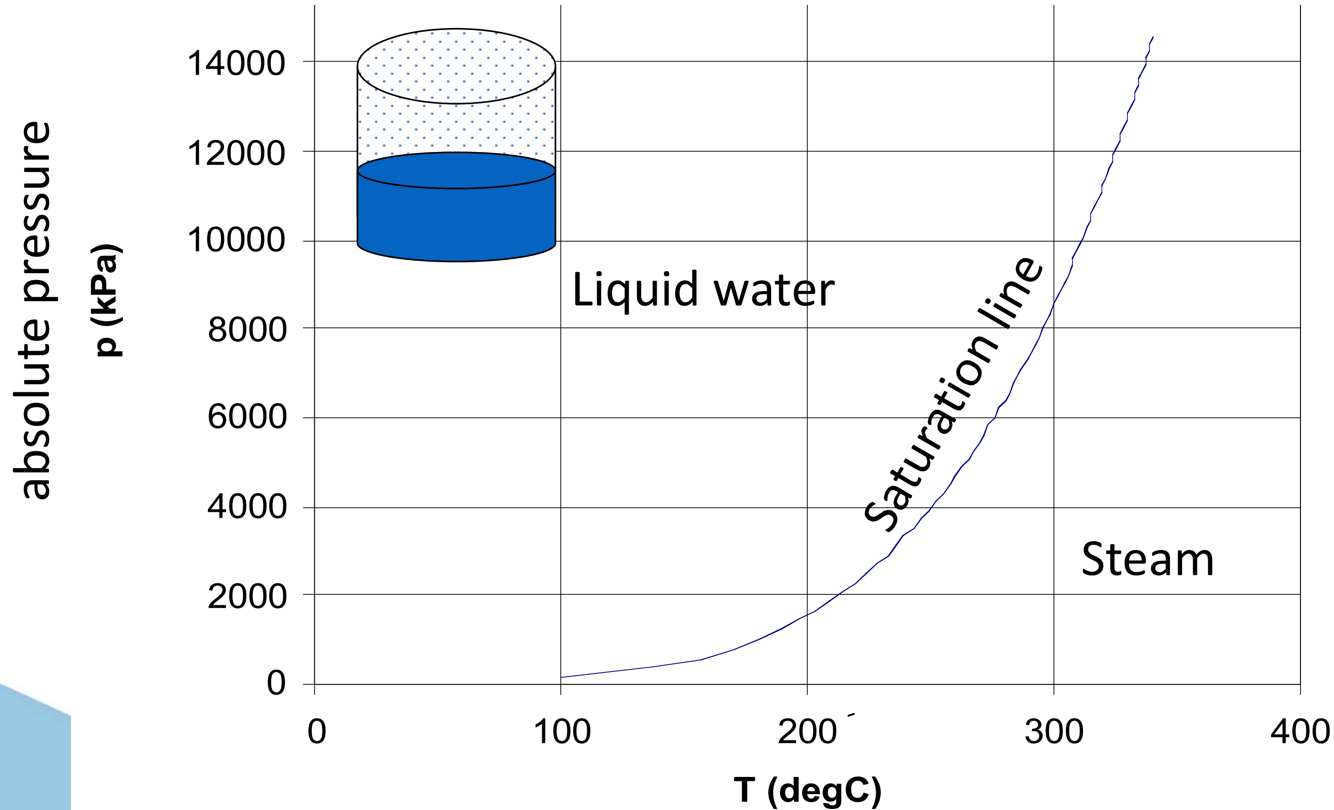
- Phase change = ΔH^v, latent heat of vaporization



(specific enthalpy) $(h_2 - h_1)_p = c_p (T_2 - T_1)_p$

- Enthalpy = H = U + PV, internal energy + PV energy

Properties of Water



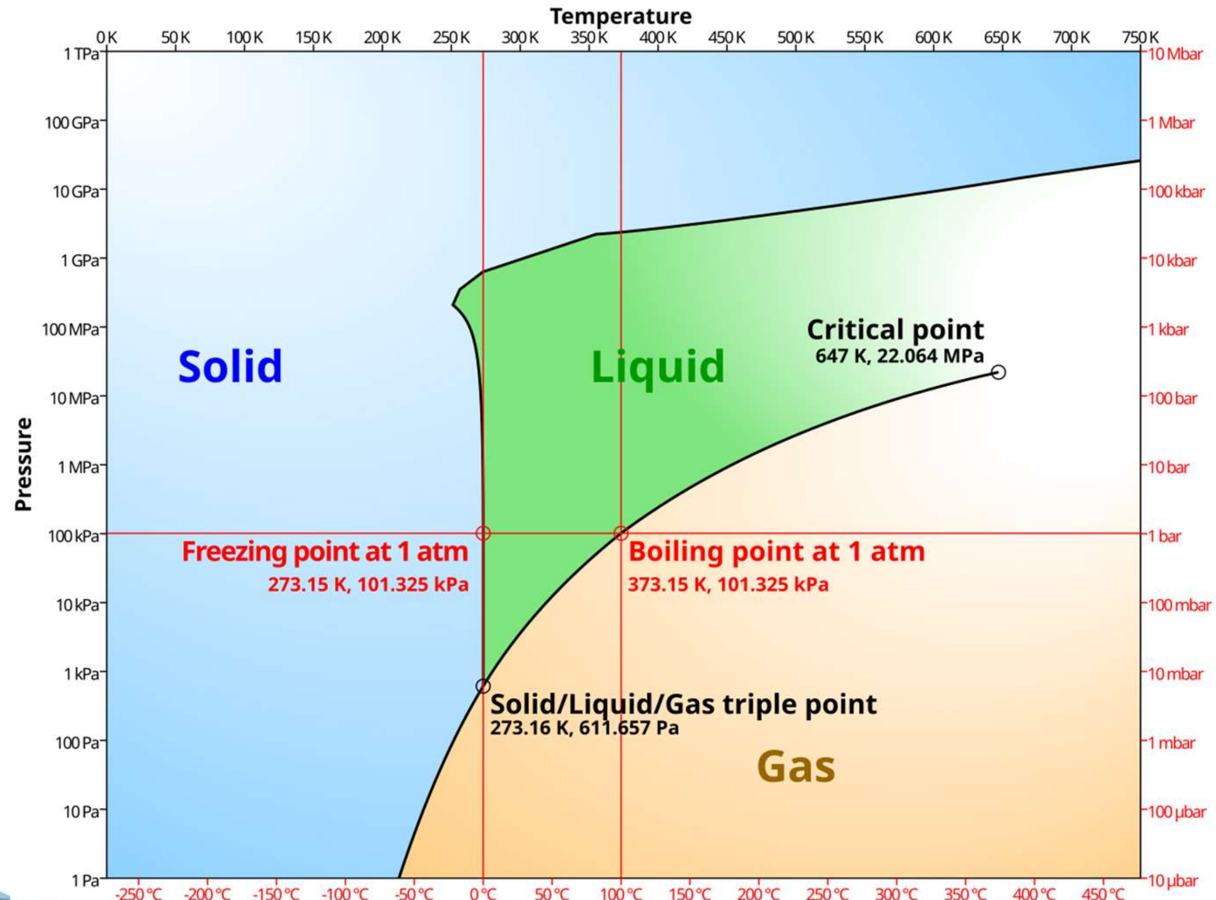
1 atm = 101.325 kPa

Saturated is a mixture of steam and water at a constant T

Only need the P or T to specify the state (vapor, saturated, liquid) of the system

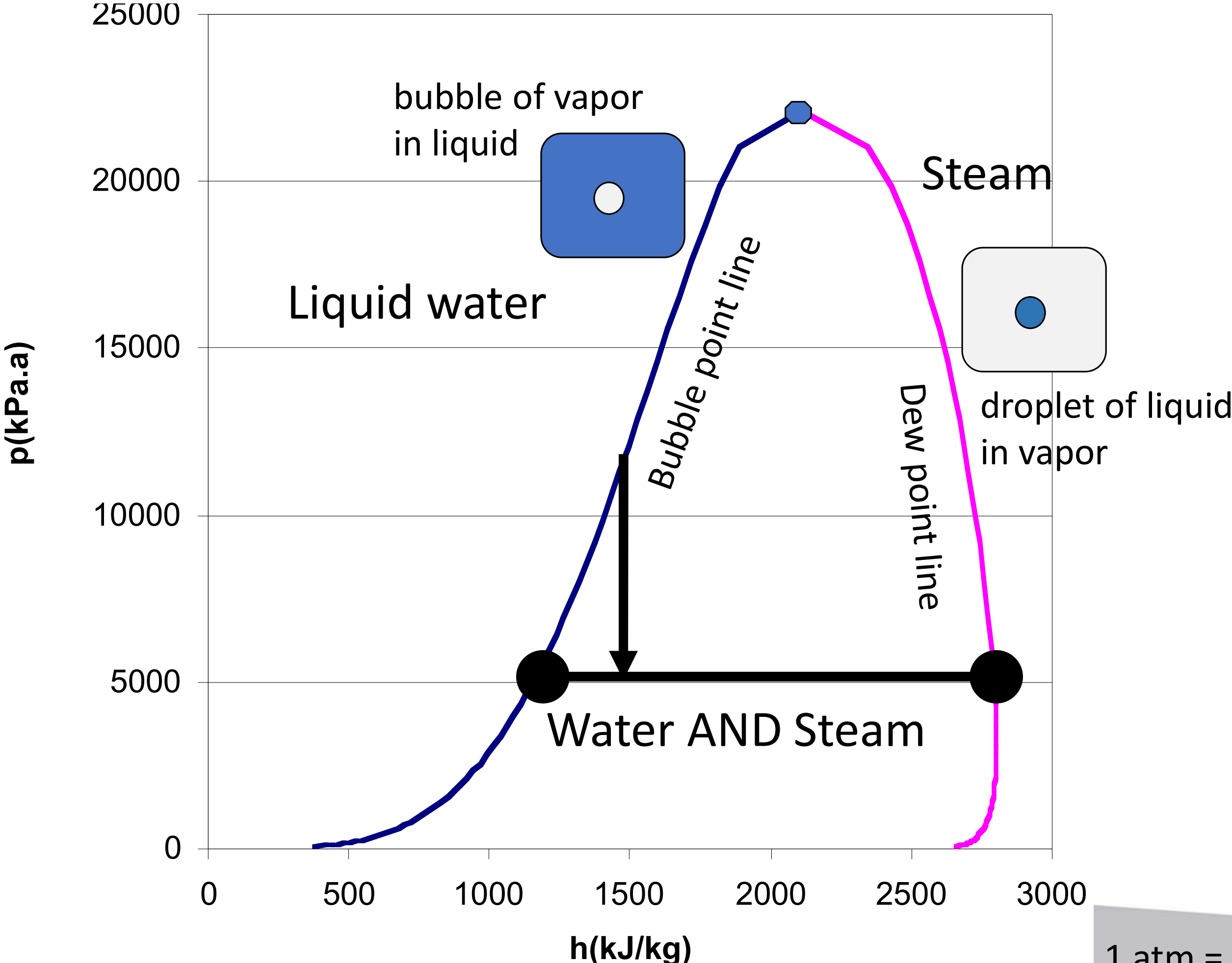
If saturated, the quality (X) is the fraction of the mixture that is steam by mass

Properties of Water



1 atm = 101.325 kPa

Properties of Water



$$\text{Quality} = X = \frac{h(P,T) - h_{\text{liquid}}}{h_{\text{steam}} - h_{\text{liquid}}}$$

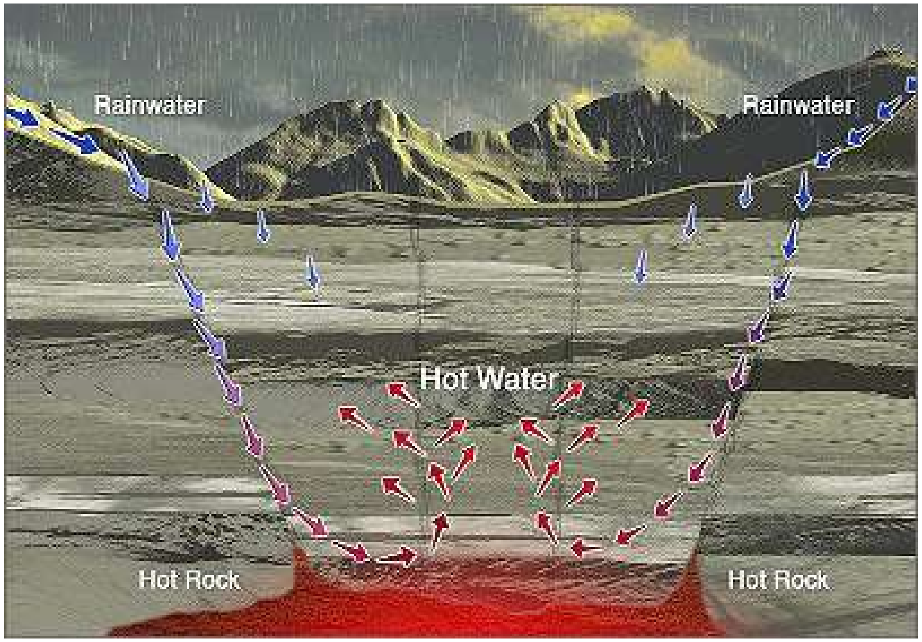
1 atm = 101.325 kPa

Hydrothermal Systems

- Functional Definitions
  - dry steam
  - wet steam (0<X<1)
  - hot water (X=0)

  - high T or enthalpy (T>180 to 200 °C)
  - medium T or enthalpy (100 to 180 °C)
  - low T or enthalpy (T<100° C)

- Conversion efficiency (heat to electricity)
- Carnot Efficiency
  - $\eta = 1 - T_c/T_h$
  - Temperatures are absolute (T[K] = T[°C] + 273.15), where K denotes units of Kelvin.



DOE's Office of Energy Efficiency and Renewable Energy (DOE, 2010)

Steam Tables (e.g., https://www.efunda.com/materials/water/steamtable_sat.cfm)

- During a test at a geothermal site, a mixture of saturated steam and water is produced. The mixture has a temperature of 300 C and an enthalpy of 2539 kJ/kg. What is the quality?
- Steam tables give
- h_w =1345.1kJ/kg and h_s = 2751 kJ/kg

$$\text{Quality} = X = \frac{h(P,T) - h_{liquid}}{h_{steam} - h_{liquid}}$$

T (C)	p (kPa.a)	Vw(m3/kg)	Vs(m3/kg)	hw(kJ/kg)	hs(kJ/kg)
185	1123.3	0.0011344	0.17386	785.26	2780.4
190	1255.1	0.0011415	0.15632	807.52	2784.3
195	1398.7	0.0011489	0.14084	829.88	2787.8
200	1554.9	0.0011565	0.12716	852.37	2790.9
205	1724.3	0.0011644	0.11503	874.99	2793.8
210	1907.7	0.0011728	0.10424	897.73	2796.2
215	2106	0.0011811	0.09463	920.63	2798.3
220	2319.8	0.00119	0.08604	943.67	2799.9
225	2550	0.0011992	0.07835	966.88	2801.2
230	2798	0.0012087	0.07145	990.27	2802
235	3063	0.0012187	0.06525	1013.83	2802.3
240	3348	0.0012291	0.05965	1037.6	2802.2
245	3652	0.0012399	0.05461	1061.58	2801.6
250	3978	0.0012513	0.05004	1085.78	2800.4
255	4325	0.0012632	0.0459	1110.23	2798.7
260	4694	0.0012756	0.04213	1134.94	2796.4
265	5088	0.0012887	0.03871	1159.93	2793.5
270	5506	0.0013025	0.03559	1185.23	2789.9

Find the quality

- During a test at a geothermal site, a mixture of saturated steam and water is produced. The mixture has a temperature of 300 C and an enthalpy of 2539 kJ/kg. What is the quality?
- Steam tables give
- h_w =1345.1kJ/kg and h_s = 2751 kJ/kg
- X=(2539-1345.1)/(2751-1345.1)=0.85
- The answer means that we have 85% steam and 15% liquid

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Subsurface Temperature Conditions

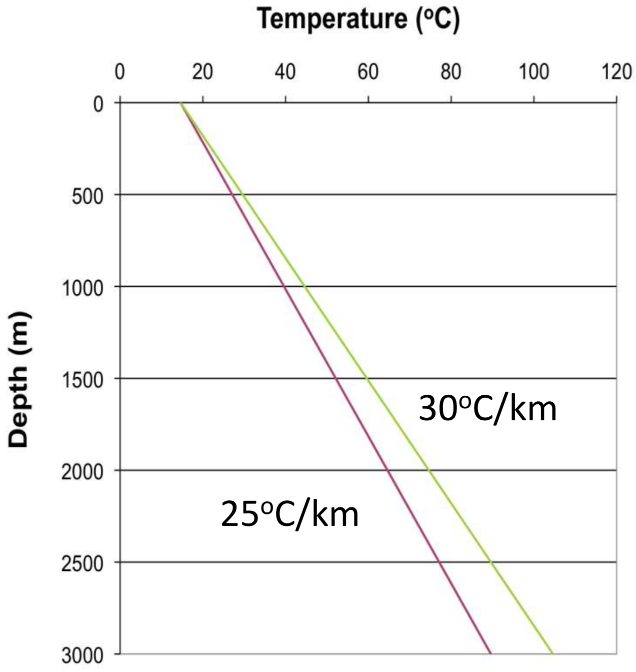
Geothermal Gradient

- Temperature increases with depth below the ground surface
  - dT/dz ~ 25^{o} to 30^{o} C/km (average geothermal gradient)

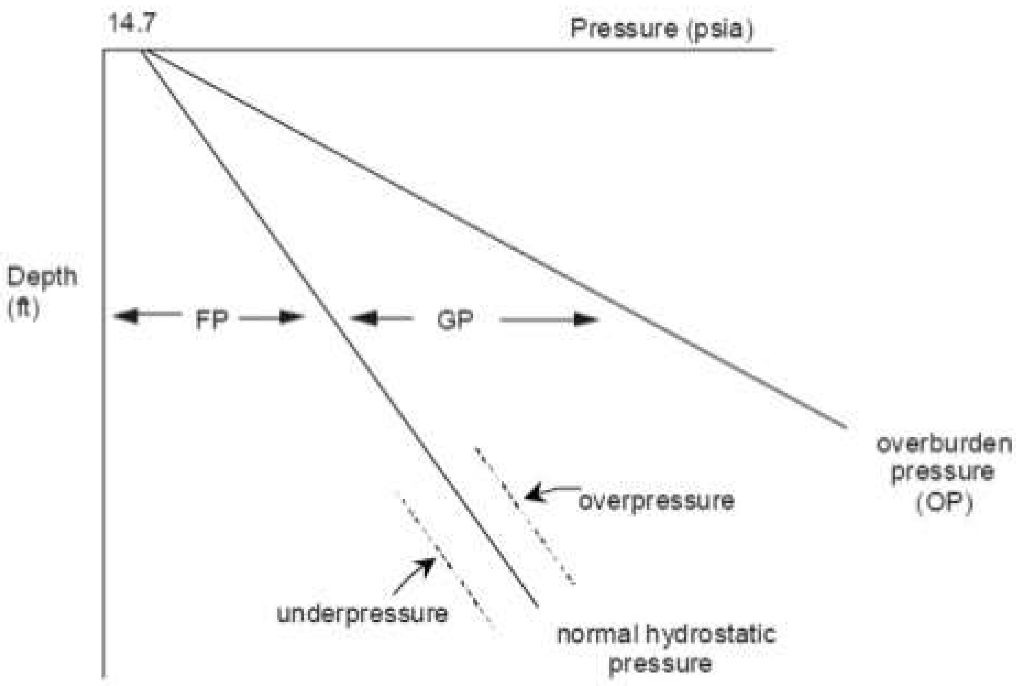
- $T(z) = T_s + \int_0^z \frac{dT}{dz} dz \;=\; T_s + \frac{dT}{dz} \cdot z$

  T_s = mean annual ground surface temperature (^{o}C) ~ 14.6^{o}C

  z = depth below ground surface (m)



Pore & Overburden Pressure



The total pressure at any reservoir depth, due to the weight of overlying fluid saturated rock column, is called the overburden pressure, P_{ov}

The total pressure at any depth is the sum of the overlaying fluid-column pressure P_f and the overlaying grain or matrix column pressure P_m

Overburden pressure as the combined effect of grain and fluid columns pressure

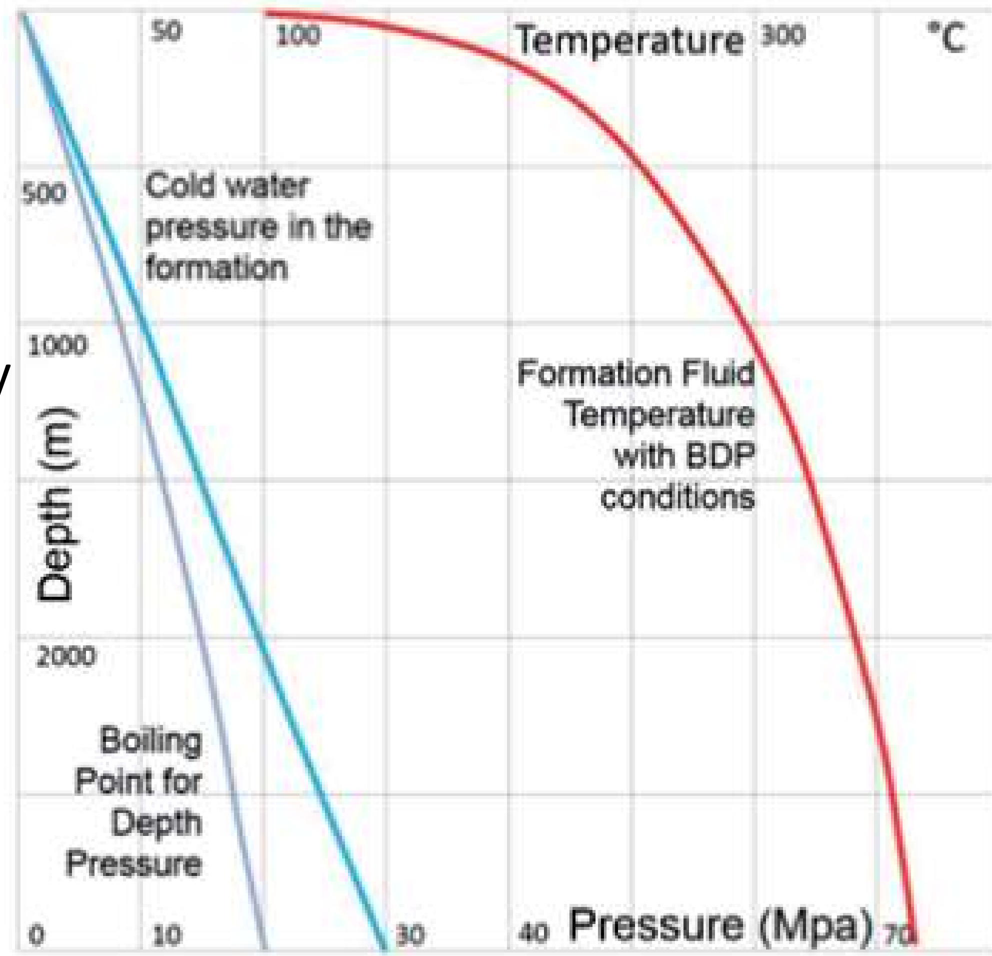
$$P_{ov} = P_f + P_m$$
$$P = \rho \times g \times h$$

Boiling Point for Depth (BPD)

- Fluid movement allows fluids to arrange themselves in a stable state described by the boiling point for depth (BPD) curve.

$$\frac{\partial p}{\partial z} = \rho_w g$$

$$\rho_w = \rho_w[T_{sat}(p)]$$



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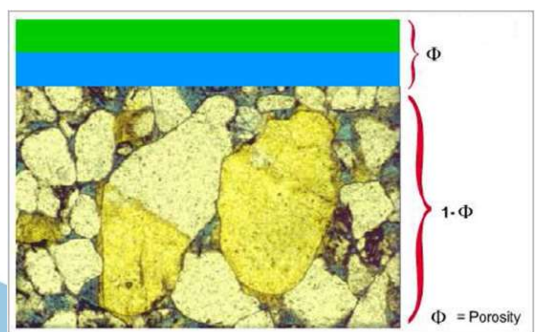
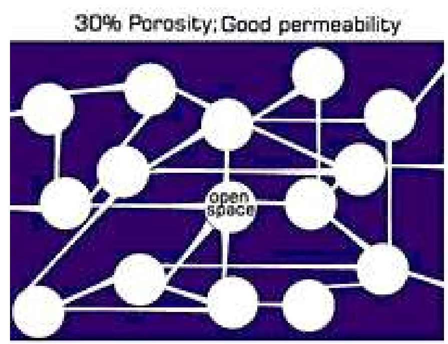
Porosity

- Subsurface fluids are stored in the non-solid fraction of the reservoir rock. This volume is called the porosity of the rock. The porosity of a rock is then the fraction of a unit volume of rock that is filled by fluids i.e., the space available in the rock for fluid storage.

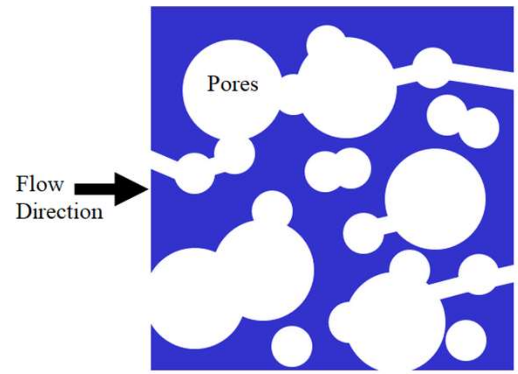
It is denoted by ϕ and defined by $\phi = \dfrac{\textbf{void volume}}{\textbf{total volume}} \textbf{ x 100 \%}$



Porosity



Connected Pore Spaces



Absolute vs. Effective Porosity

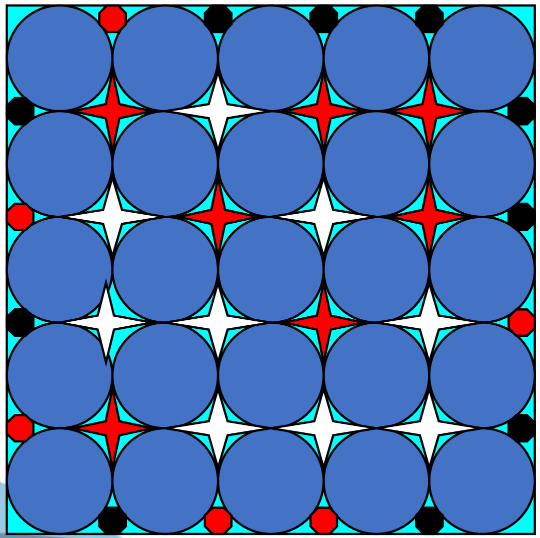
Permeability

- Permeability is a property of the porous medium that measures the capacity and ability of the formation to transmit fluids.

- The rock permeability, k, is a very important rock property because it controls the directional movement and the flow rate of the reservoir fluids in the formation.

Fluid Saturations

Grain Water Gas Oil



- Water saturation: $S_w = \frac{V_w}{V_p}$
- Oil saturation: $S_o = \frac{V_o}{V_p}$
- Gas saturation: $S_g = 1.0 - S_o - S_w$

Rocks

- Density $\rho \sim 2.65 \times 1000\ kg/m^3$
- Heat capacity (the amount of energy required to change the temperature of a body by 1ºC) $C_p \sim 1$ kJ/kg-ºC
- Thermal conductivity (the ability for a material to transmit heat) K ~ 2 W/m -ºC
- Thermal diffusivity (a measure of how easily a material exchanges heat with the surrounding) $\alpha = K/\rho C_p$
- Porosity $\phi \sim 5 – 20\%$ (in fractures)

$$K = \frac{Qd}{A\Delta T}$$

K = thermal conductivity
Q = amount of heat transferred
d = distance between the two isothermal planes
A = area of the surface
ΔT = difference in temperature

Fluids

- Heat capacity c_p (kJ/kg-ºC):
- – Rock ~ 1
- – Water ~ 4.5
- – Steam ~ 2.5
- – Oil ~ 2
- – Gas ~ 1
- – Air ~ 1

$$Q = mc\Delta T$$

Q = heat energy
m = mass
c = specific heat capacity
ΔT = change in temperature

Thermal Conductivity K (W/m-ºC):

- Water is 0.598 W/m·K at 20 °C

Gases	
Air (dry)	0.026
Argon (gas)	0.016
Carbon dioxide (gas)	0.0146
Helium	0.15
Hydrogen	0.18
Krypton (gas)	0.0088
Methane (gas)	0.03
Nitrogen (gas)	0.024
Steam, saturated	0.0184
Xenon (gas)	0.0051

Fluids

Water

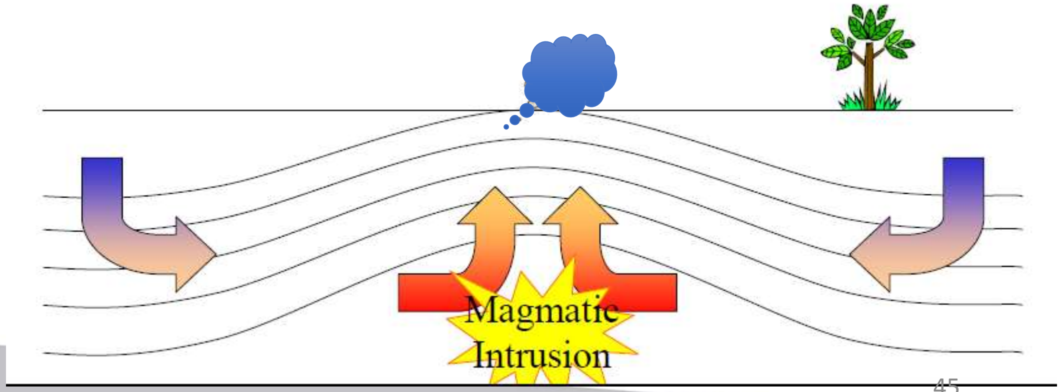
- Global average gradient is 30ºC/km, can be up to 60ºC/km.
- Typical conductivity K is around 2/W/m-ºC.
- Typical natural discharge from geothermal reservoirs is around 40 W/m^2.
- Q=KA$\frac{\partial T}{\partial Z}$ implying that $\frac{Q}{A}$ =K$\frac{\partial T}{\partial Z}$

  $= 2\times \frac{30}{1000} = 0.06$ W/m^2
- What might this mean?

Steam

- Fluids are driven upwards by buoyancy

  e.g., 250ºC water at 2 km depth, assume surroundings at 120ºC i.e., surface temperature of 20ºC and gradient of 50ºC/km
- $\rho_{w,250}$=800 kg/m^3
- $\rho_{w,120}$=943 kg/m^3
- Buoyancy force $\Delta\rho$ = 143 kg/m^3.



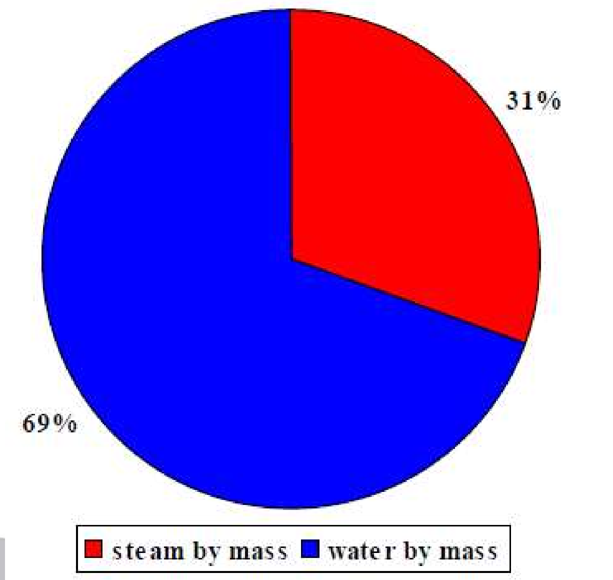
Energy In Place

- Given a well that has the following properties:
  - Temperature 270 ºC
  - Enthalpy 1675 kJ/kg (of the produced fluid measured at surface)
  - Pressure 5506 kPa
  - hw 1185.23 kJ/kg
  - hs 2789.90 kJ/kg
  - vw 0.001303 m^3/kg
  - vs 0.035600 m^3/kg
- Estimate the energy in place by mass, energy and volume

Energy In Place (Mass)

- Recall: In thermodynamics, vapor (steam) quality, X, is the **mass** fraction in a saturated mixture that is vapor (steam)

- X=0.31
- imply mass fraction of steam=0.31
-   mass fraction of water = 0.69

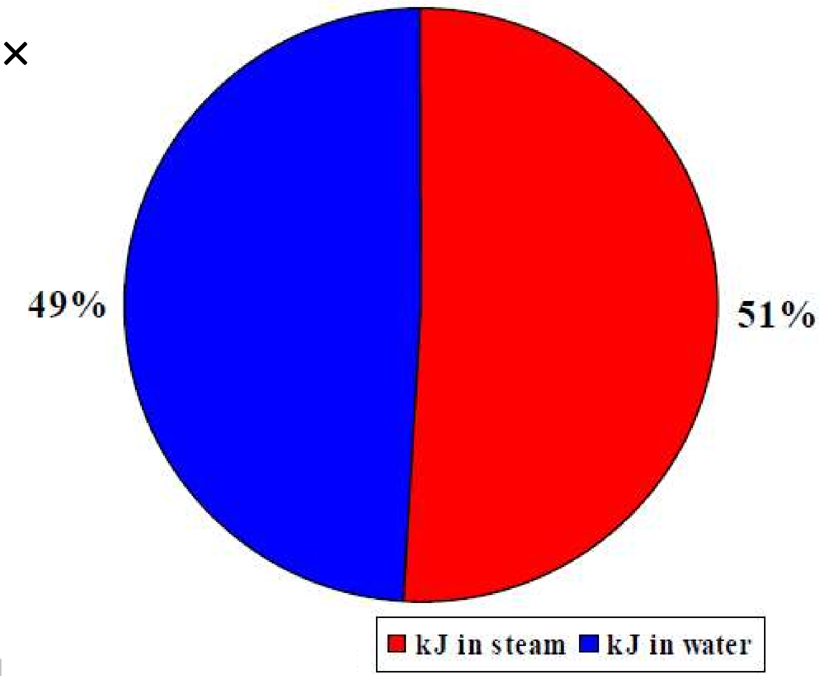


$$\text{Quality} = X = \frac{h(P,T) - h_{liquid}}{h_{steam} - h_{liquid}}$$

Energy In Place (Energy)

- The specific enthalpy is in units of KJ/kg
- The energy contained in 1 kgm of reservoir fluid
- =mass fraction of the fluid × specific enthalpy (× 1kg)

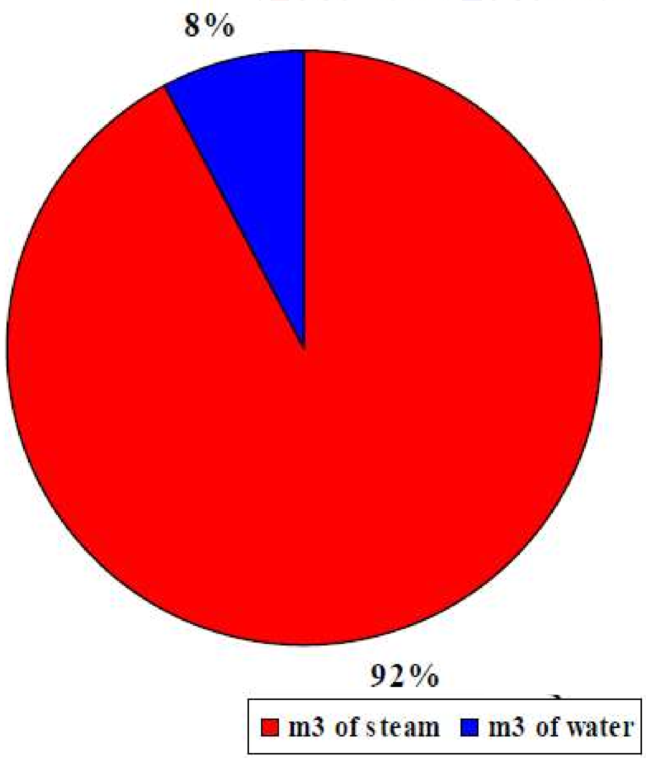
- Energy in steam =x*hs= 864.87 KJ
- Energy in water = (1-X)*hw=817.81 KJ



Energy In Place (Volume)

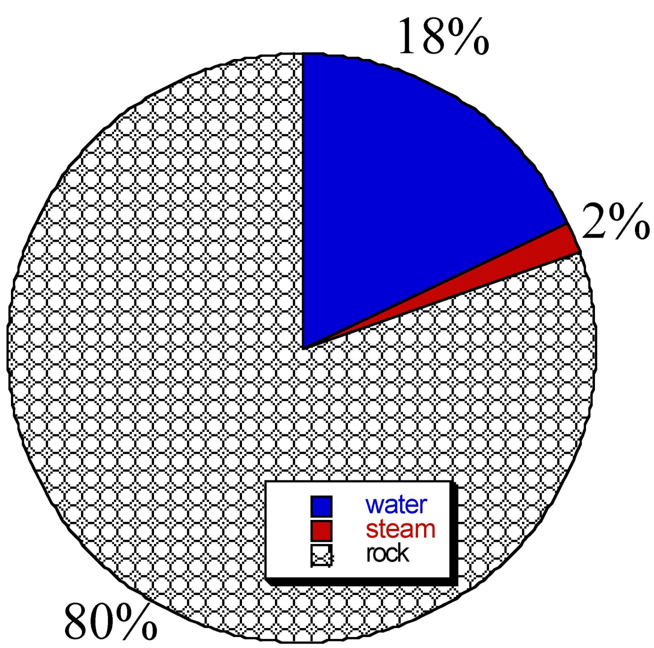
- The specific volume is in units of m^3/kg
- The volume contained in 1 kgm of reservoir fluid
- =mass fraction of the fluid × specific volume (× 1kg)

- Volume of steam =x*vs= 0.011 m^3
- Volume of water= (1-X)*vw=0.0009 m^3



Energy Density (/m^3 of substance)

- Assuming the reservoir has a porosity of 10%, rock specific gravity of 2.65, and will be produced until an abandonment temperature of 100 ºC
  - rock energy = $(1\text{-}ø)\rho_r\, c_{pr}\,(270 – 100)$
  - = 0.9•2650•1•170 = 405,450 kJ/m^3
  - steam = $ø h_s/v_s$
  - =0.1•2789.9/0.03559 = 7840 kJ/m^3
  - water = $ø h_w/v_w$
  - =0.1•1185.23/0.0013025 =90996 kJ/m^3



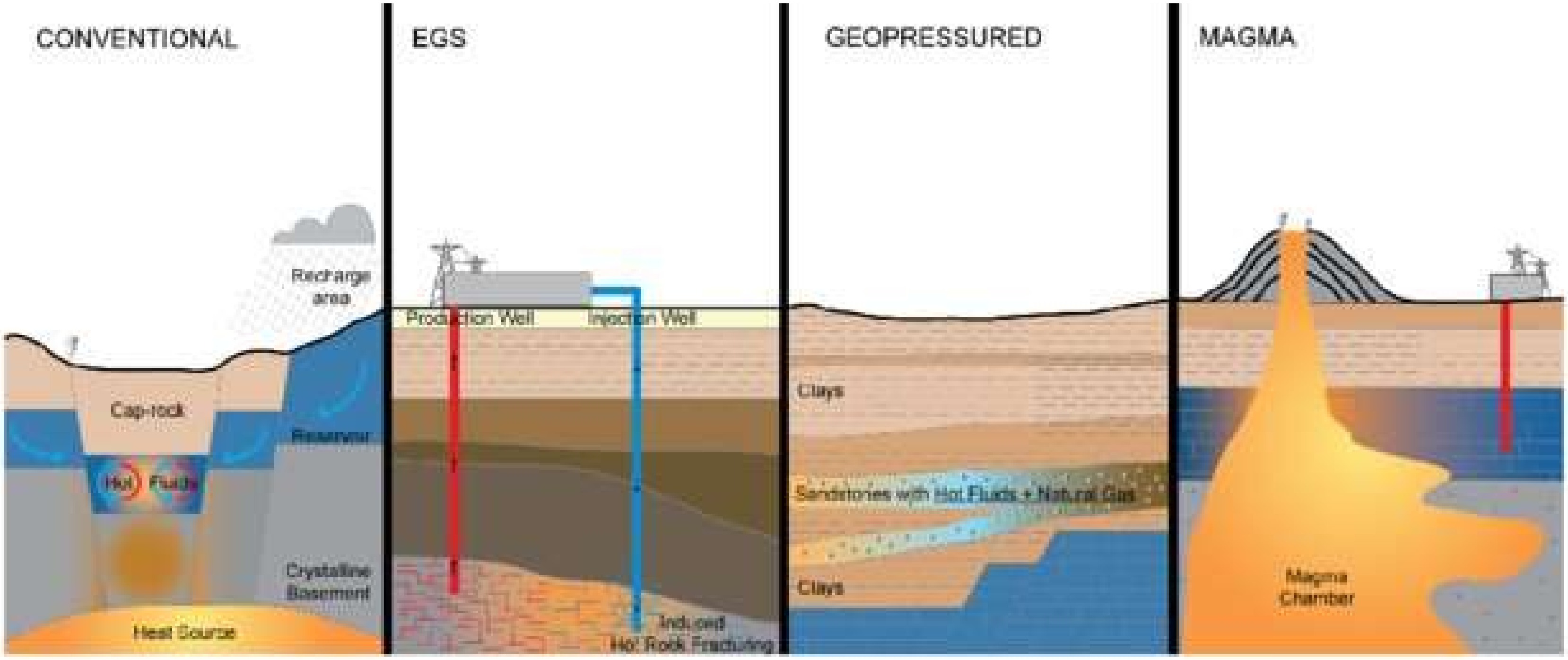
Types of Geothermal Systems

1) Hydrothermal Systems
   Vapor Dominated
   Liquid Dominated

2) Enhanced Geothermal System

3) Geopressured Systems

4) Magmatic Systems



Procesi, M., Cantucci, B., Buttinelli, M., Quattrocchi, F., & Saponaro, A. (2013). Strategic use of the underground for an energy mix plan, synergies among CO2 and CH4 Geological Storage and Geothermal Energy: Italian Energy review and Latium case study. *Applied Energy, 110*, 125-136.

Day 1

01 Foundations of geothermal energy, heat and flow properties

02 Multiphase flow, reservoir properties and energy conversion

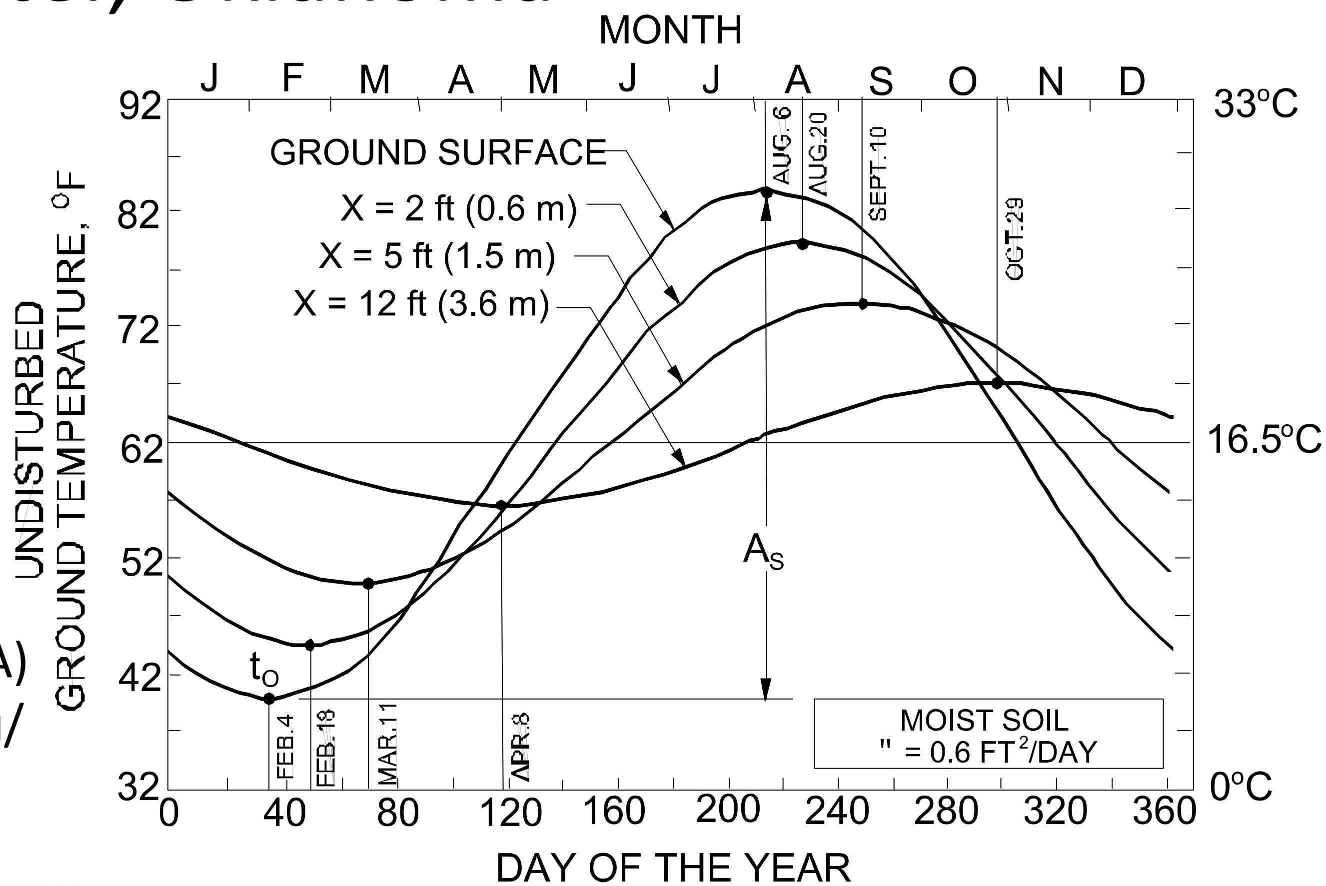
03 Oil and gas well conversions and unconventional geothermal systems

04 Geothermal reserve estimation, system optimization, and future trends

Annual Soil Temperature Variations, Stillwater, Oklahoma

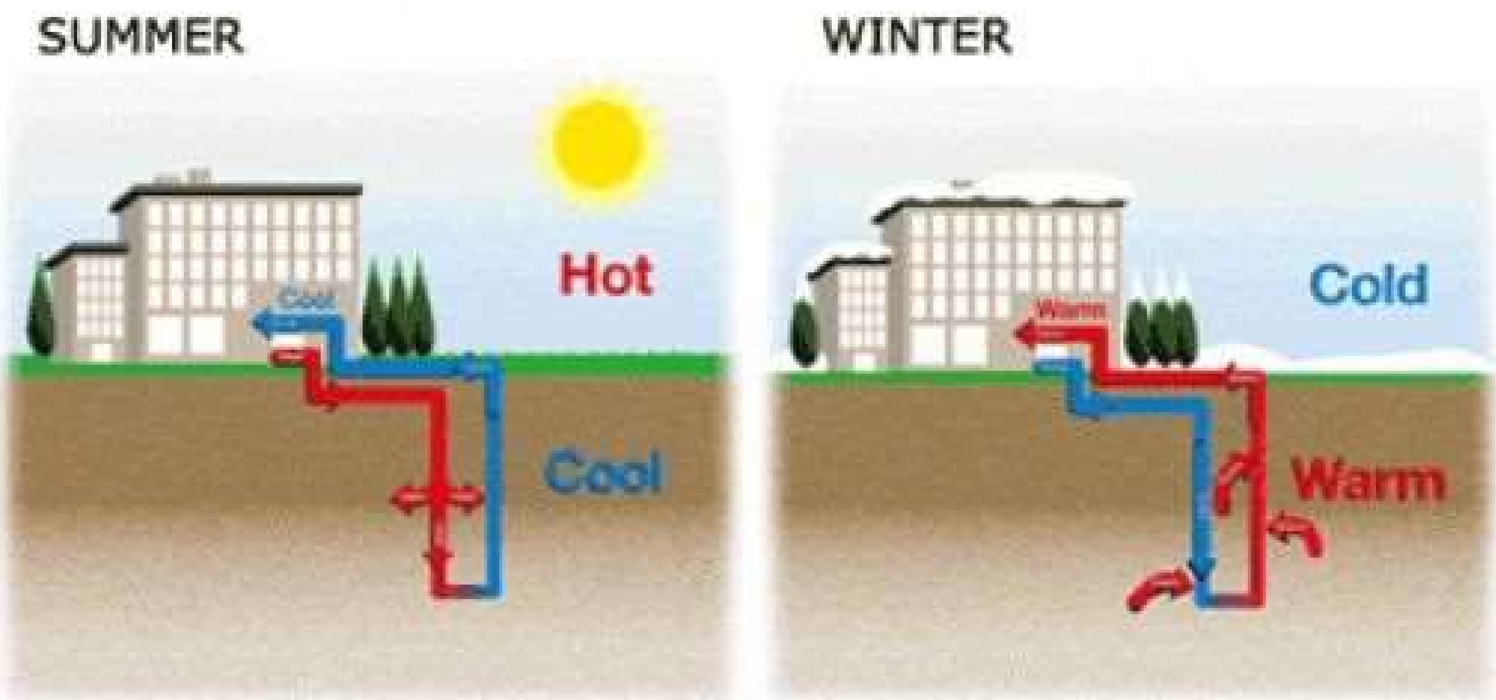
Why Stillwater, Oklahoma?

Because it is the home of the International Ground Source Heat Pump Association (IGSHPA) http://www.igshpa.okstate.edu/



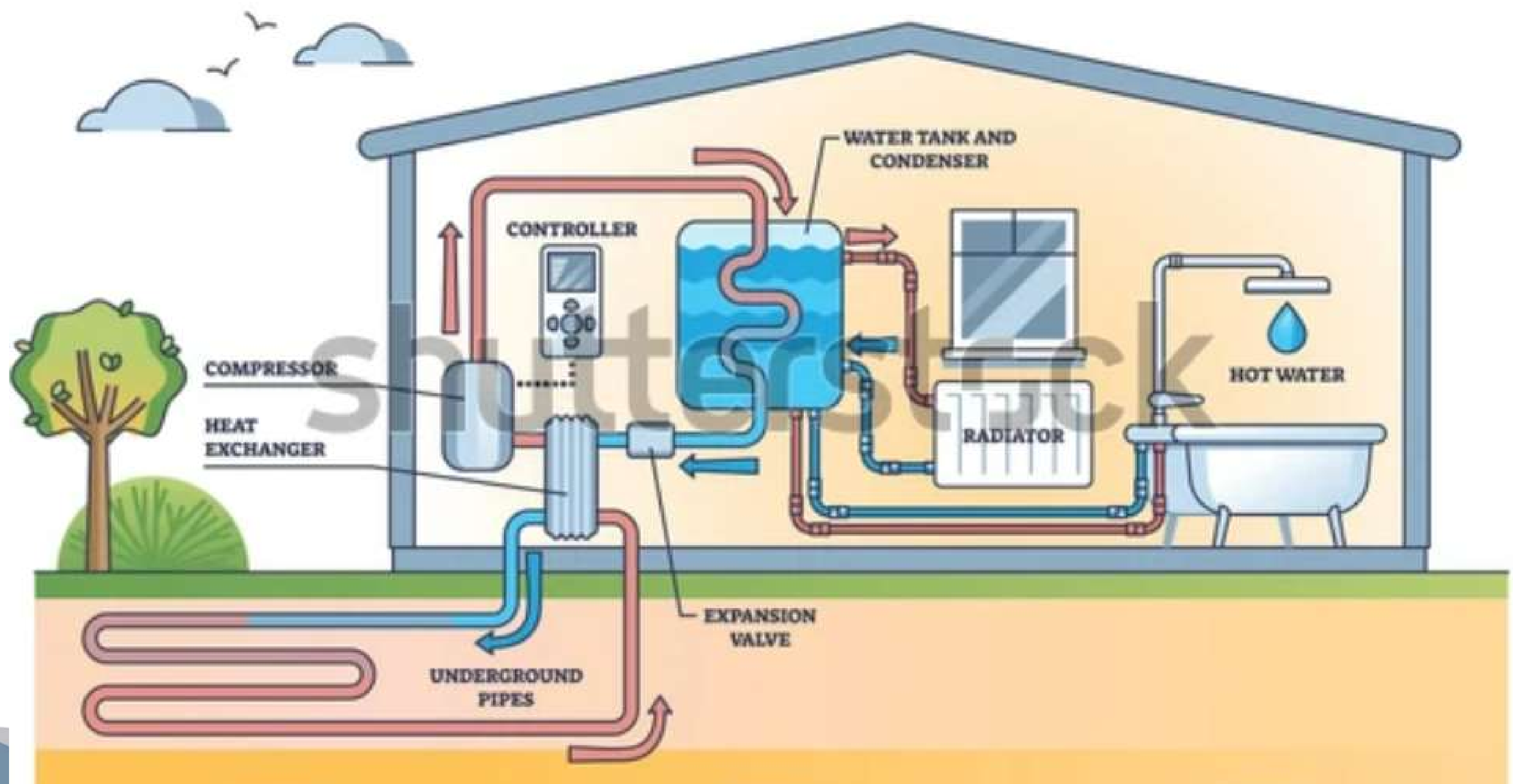
It's a hybrid. Near surface combines solar and geothermal energies!

Ground Source Heat Pump - Principle

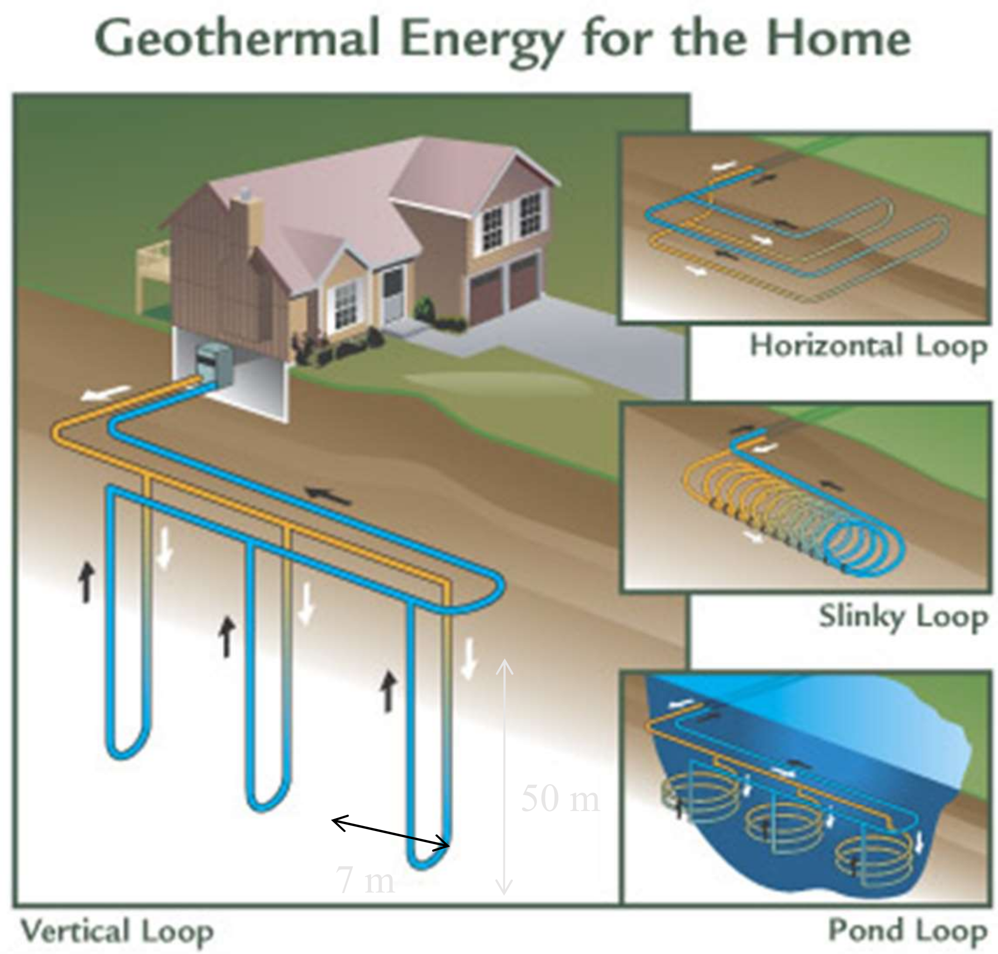


Ground Source Heat Pump - Components

The three main parts consist of the geothermal unit, the underground piping system (open or closed loop), and the ductwork.

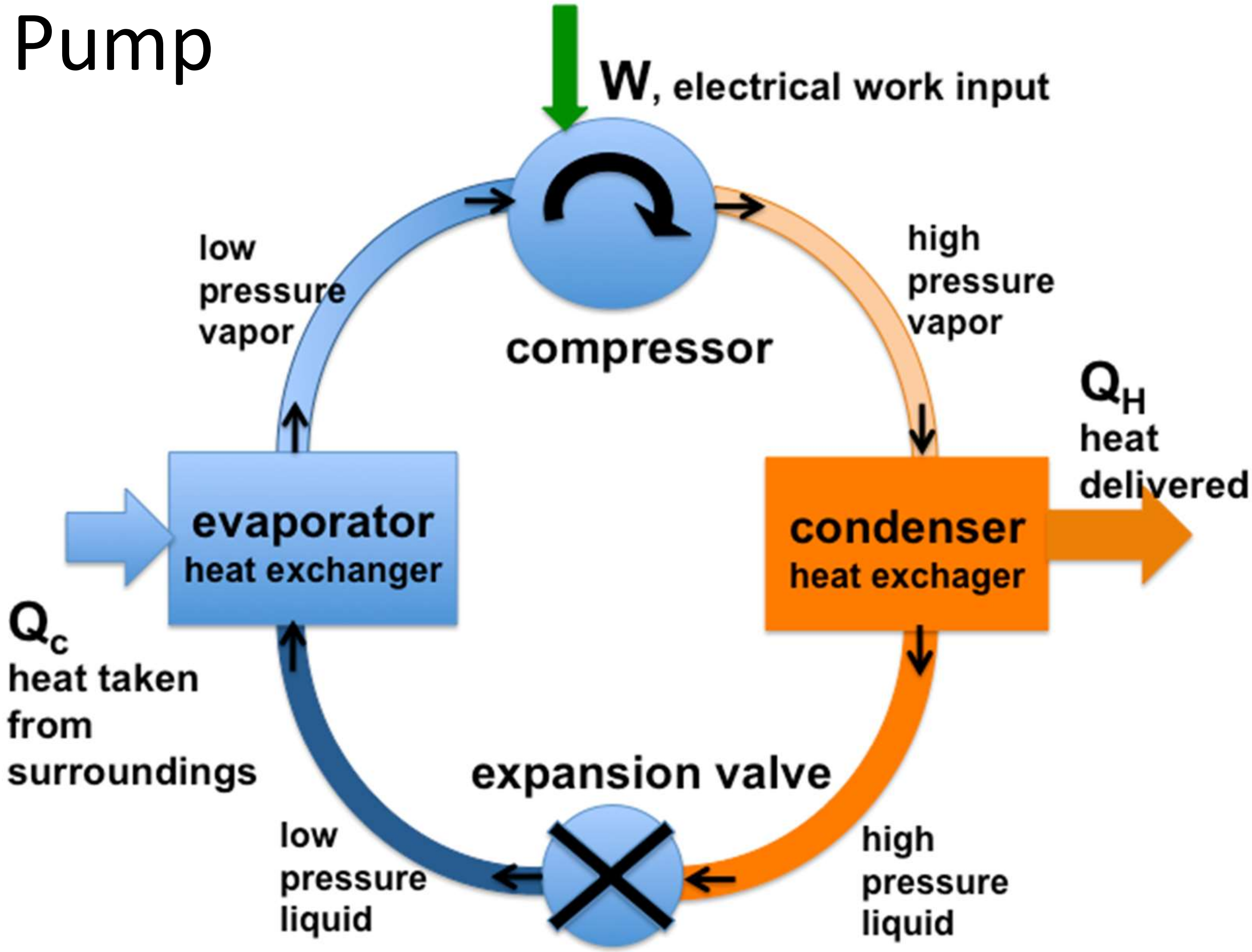


Ground Source Heat Pump – Different Configurations



Heat Pump

The biggest benefit of GHPs is that they use 25% to 50% less electricity than conventional heating or cooling systems.



Heat Pump Jargon and Definition

- Heat Pump = machine causes heat to flow “uphill” From lower to higher temperature
- Work done – “pump” used to compress and move refrigerant, not converted directly to heat.
- Refrigeration unit – reversible
- Heat absorbed = “source”
- Heat delivered = “sink”
- Coefficient of Performance (COP) = The system’s heating efficiency. The higher the COP, the more efficiently the system heats. The rating is a ratio of heat produced over electrical energy input. Simply stated, it indicates how much home heating you get for the amount of electrical energy the system uses to concentrate that heat. Geothermal heat pumps typically have COPs of 3 to 5.
- Energy Efficiency Ratio (EER) = The system’s cooling efficiency. A higher number means greater efficiency. The number is a ratio of the heat removed over the amount of electricity the system uses. The average geothermal system has an EER of between 13 and 18.

Hot Topics in Geothermal Energy

- Superhot and Supercritical Geothermal
- Geothermal Direct Use
- Enhanced Geothermal Systems
- Lithium Extraction from Geothermal Brines
- Oil and Gas Wells Conversion for Geothermal Energy
- Advanced Geothermal Systems
- Machine Learning in Geothermal Development