Green and Sustainable Technologies: 2 Credits
Geothermal Energy

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What we have discussed so far?

- Introduction to sustainability
- Sustainable Development Goals: A Brief Introduction
- The Blue-Green Economic Policy: The Creator of New Prospects in the Economy
- What is green technology?
- Importance of green technology
- Evolution of green technology
- Emerging green technologies
- Why is Green Technology Necessary?
- Principles of Green Engineering and principles of green chemistry
- Introduction to the concept of energy, Types and forms of energy, Energy sources, flow, Power, Energy losses and efficiency, Energy demand, Rising of renewables
- Introduction to renewable energy
- **Solar energy**
- **Wind Energy**
- **Tidal Energy**

Today’s Outline

- What is geothermal energy?
- Identify the source of geothermal energy and appreciate issues around its sustainability.
- Identify requirements for geothermal energy to be potentially useful for electricity generation and understand why suitable locations are geographically restricted.
- Appreciate potential for more geographically widespread use of geothermal energy for thermal applications.
- Understand operating principles of ground source heat pumps.

What is Geothermal Energy?

- The word geothermal comes from the Greek words geo (earth) and therme (heat).
- So, geothermal energy is heat from within the earth.
- We can use the steam and hot water produced inside the earth to heat buildings or generate electricity.
- Geothermal energy is a renewable energy source because the water is replenished by rainfall and the heat is continuously produced inside the earth.

Energy Inside the Earth

- Geothermal energy is the thermal energy within the earth’s interior.
- It is a renewable energy source because heat is continuously transferred from within the earth to the water recycled by rainfall.
- The origin of geothermal energy is earth’s core and it is about 6500 km deep/ below the surface.
- Temperatures hotter than the sun's surface are continuously produced inside the earth by the slow decay of radioactive particles, a process that happens in all rocks. The earth has a number of different layers:

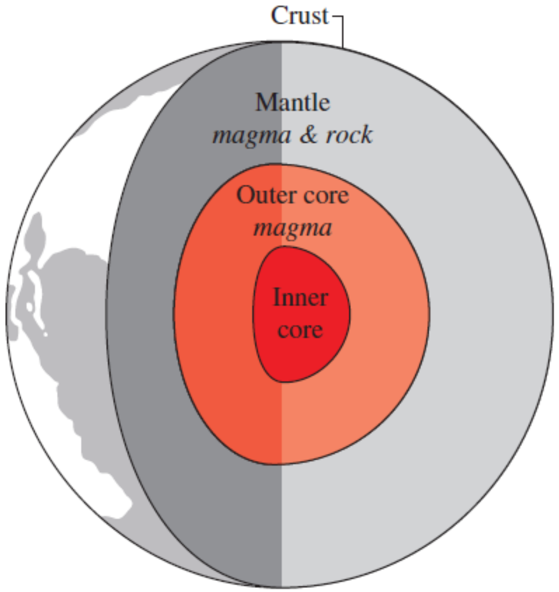
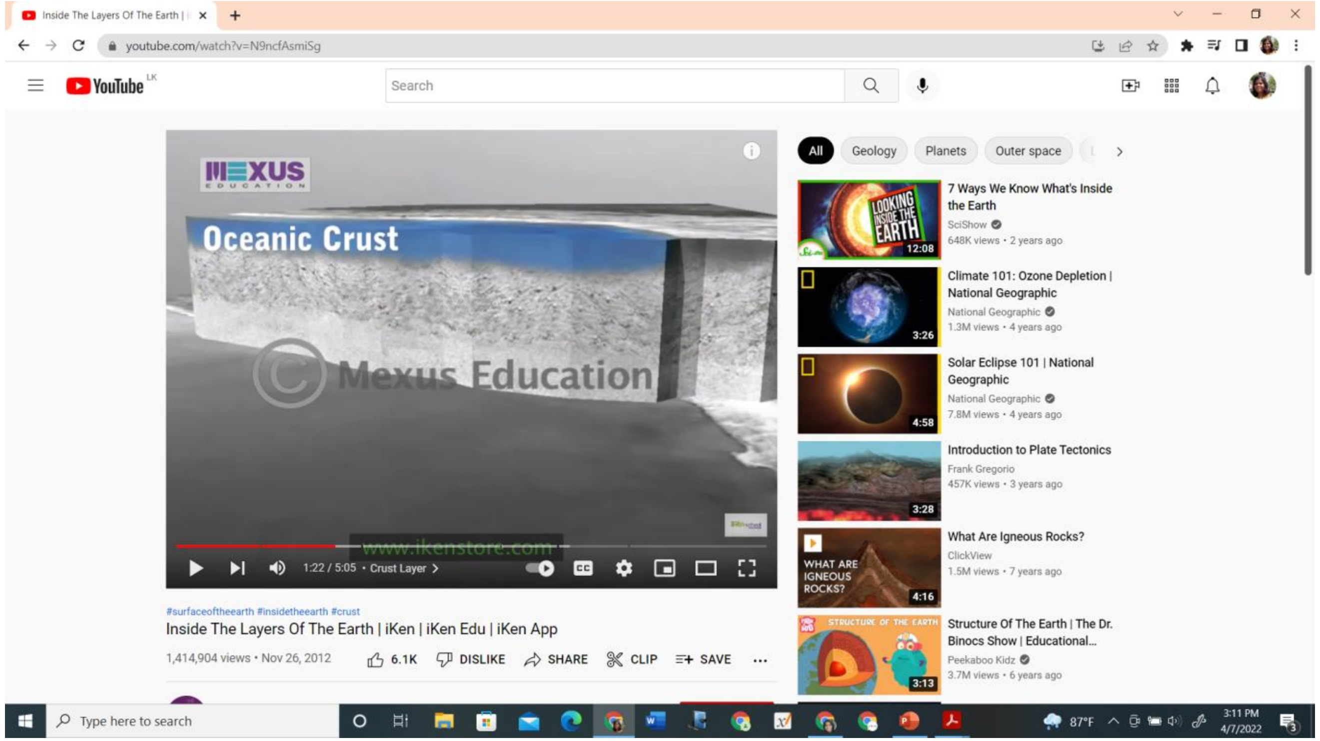


Fig. 1 The interior of the earth (*The NEED Project*)

- The earth has a number of different layers:
- The core itself has two layers: a solid iron core and an outer core made of very hot melted rock, called magma.
- The mantle which surrounds the core. It is made up of magma and rock.
- The crust is the outermost layer of the earth, the land that forms the continents and ocean floors.

Inside the Layers of the Earth



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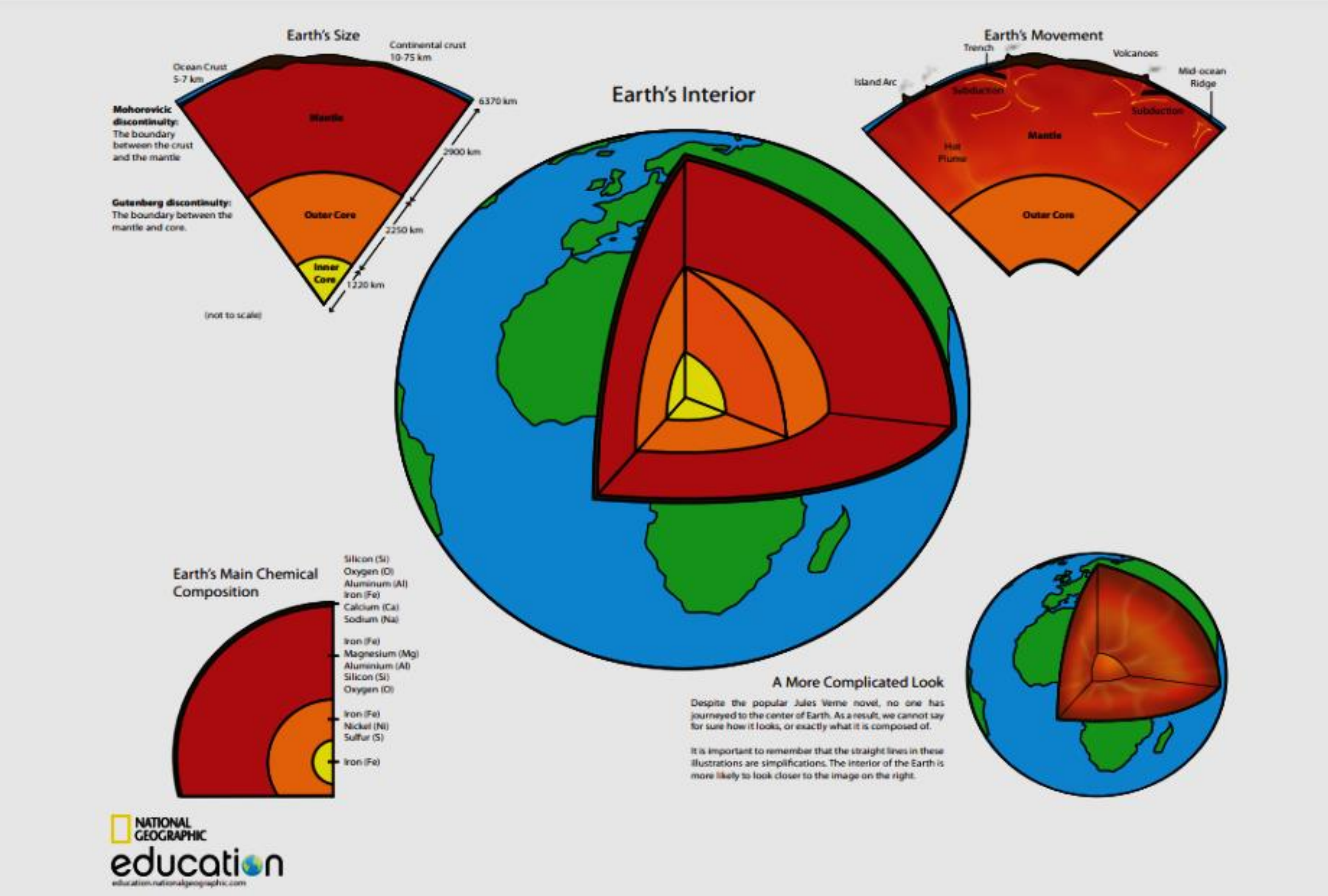


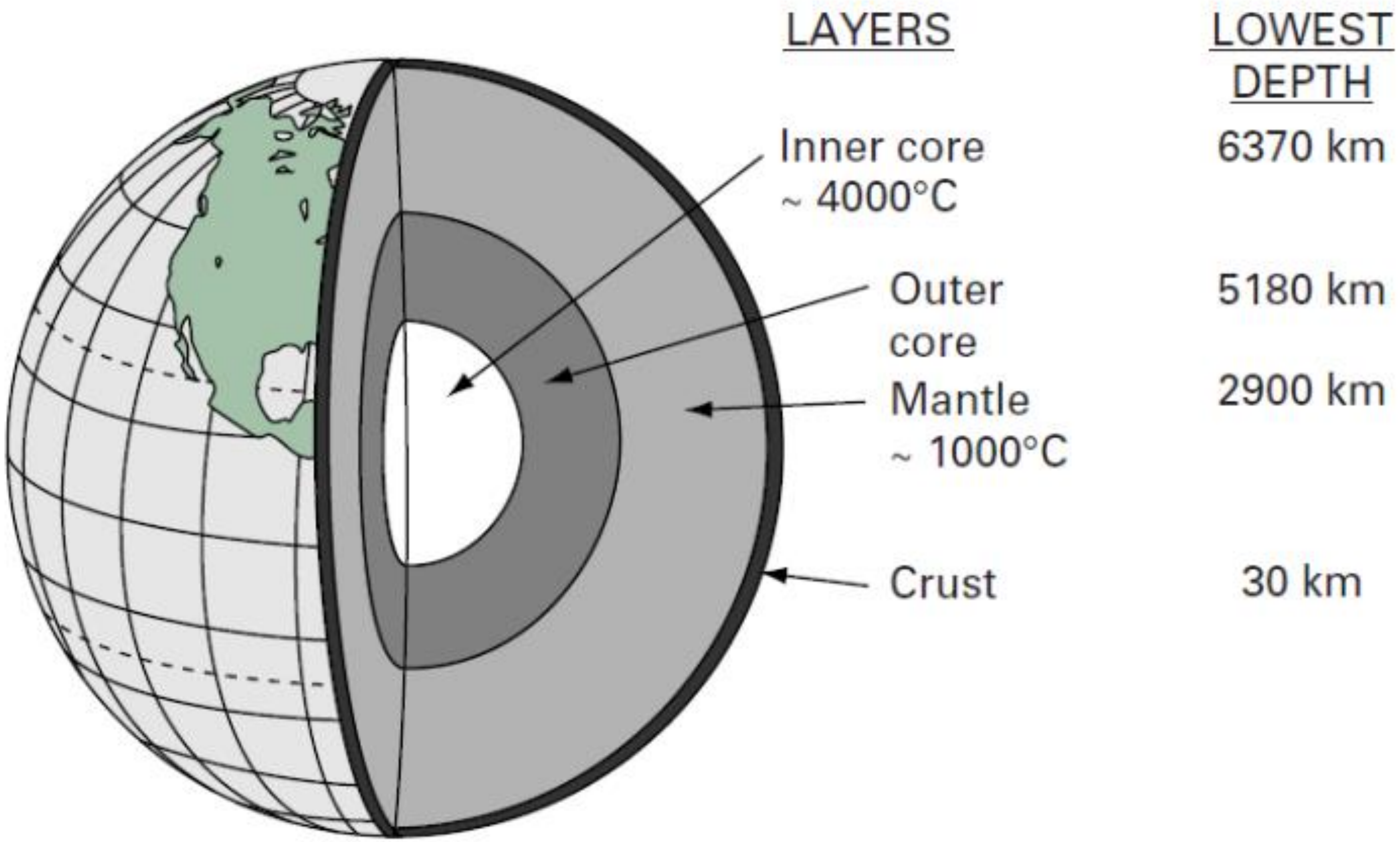
Fig. 2 https://media.nationalgeographic.org/assets/file/Earth_Interior_Poster.pdf

Core:
The core extends out to half the Earth's radius (6400 km) and is made mostly of iron (80%) and nickel (20%), whose inner half (by radius) is solid and whose outer half is liquid. This iron and nickel core is the source of the Earth's magnetic field, which is believed to be created by electric currents in the core.

• *Mantle*:
The mantle makes up most of the rest (83%) of the Earth's volume and made mostly of rocky material, whose inner part is semirigid and whose outer and cooler part is plastic and, therefore, can flow (think lava).

• *Crust*:
The crust is the outermost thin layer (1% of the Earth's volume), whose average thickness is 15 km. The crustal thickness ranges from a high of 90 km under continental mountains to as little as 5 km under some parts of the oceans. On a scale where the Earth is the size of a soccer ball, the crust would be a mere 0.25 mm thick.

- The earth's crust is broken into pieces called plates.
- Magma comes close to the earth's surface near the edges of these plates.
- This is where volcanoes occur.
- The lava that erupts from volcanoes is partly magma. Deep underground, the rocks and water absorb the heat from this magma.
- The temperature of the rocks and water get hotter and hotter as you go deeper underground.
- People around the world use geothermal energy to heat their homes and to produce electricity by digging deep wells and pumping the heated underground water or steam to the surface.
- Or, we can make use of the stable temperatures near the surface of the earth to heat and cool buildings.



Geothermal structure of the Earth, showing average lower depths of named layers. The crust has significant variation in composition and thickness over a local scale of several kilometres.

At the plate boundaries there is active convective thermal contact with the Mantle, evidenced by seismic activity, volcanoes, geysers, fumaroles and hot springs – the so-called ‘ring of fire’.

The geothermal energy potential of these regions is very great, owing to increased anomalous temperature gradients (to ~100 ºC/km) and to active release of water as steam or superheated liquid, often at considerable pressure when tapped by drilling.

Therefore it is no coincidence that each of the eight largest producers of geothermal electricity have experienced locally a major earthquake and/or volcanic eruption in the past 100 years

(i.e. ‘now’ in geological terms).

There are three classes of global geothermmal regions:

1 *Hyperthermal*:

- Temperature gradient 80 $^oC/km$. These regions are usually on tectonic plate boundaries. The first such region to be tapped for electricity generation was in 1904 at Larderello in Tuscany, Italy. Nearly all geothermal power stations are in such areas.

2 *Semithermal*:

- Temperature gradient ~40 $^oC/km$ to 80 $^oC/km$.
- Such regions are associated generally with anomalies away from plate boundaries. Heat extraction is from harnessing natural aquifers or fracturing dry rock.
- A well-known example is the geothermal district heating system for houses in Paris.

3. Normal

- Temperature gradient < 40 $^{o}C/km$.
- These remaining regions are associated with average geothermal conductive heat flow at ~0.06 W/m^2.
- It is unlikely that these areas can ever supply geothermal heat at prices competitive to present (finite) or future (another renewable) energy supplies.

In each class it is, in principle, possible for heat to be obtained by the following:

- *Natural hydrothermal circulation,* in which water percolates to deep aquifers to be heated to dry steam, vapor/liquid mixtures, or hot water.
- Emissions of each type may be observed in nature.
- If pressure increases by steam formation at deep levels, spectacular geysers may occur, as at the geysers near Sacramento in California and in the
- Wairakei area near Rotorua in New Zealand.
- Note, however, that liquid water is ejected, and not steam.

Hot igneous systems associated with heat from semi-molten magma that solidifies to lava. The first power plant using this source was the 3 MW station in Hawaii, completed in 1982.

Dry rock fracturing. Poorly conducting dry rock (e.g. granite) stores heat over millions of years with a subsequent increase in temperature.

Artificial fracturing from boreholes enables water to be pumped through the rock, so that (in principle) the heat can be extracted.

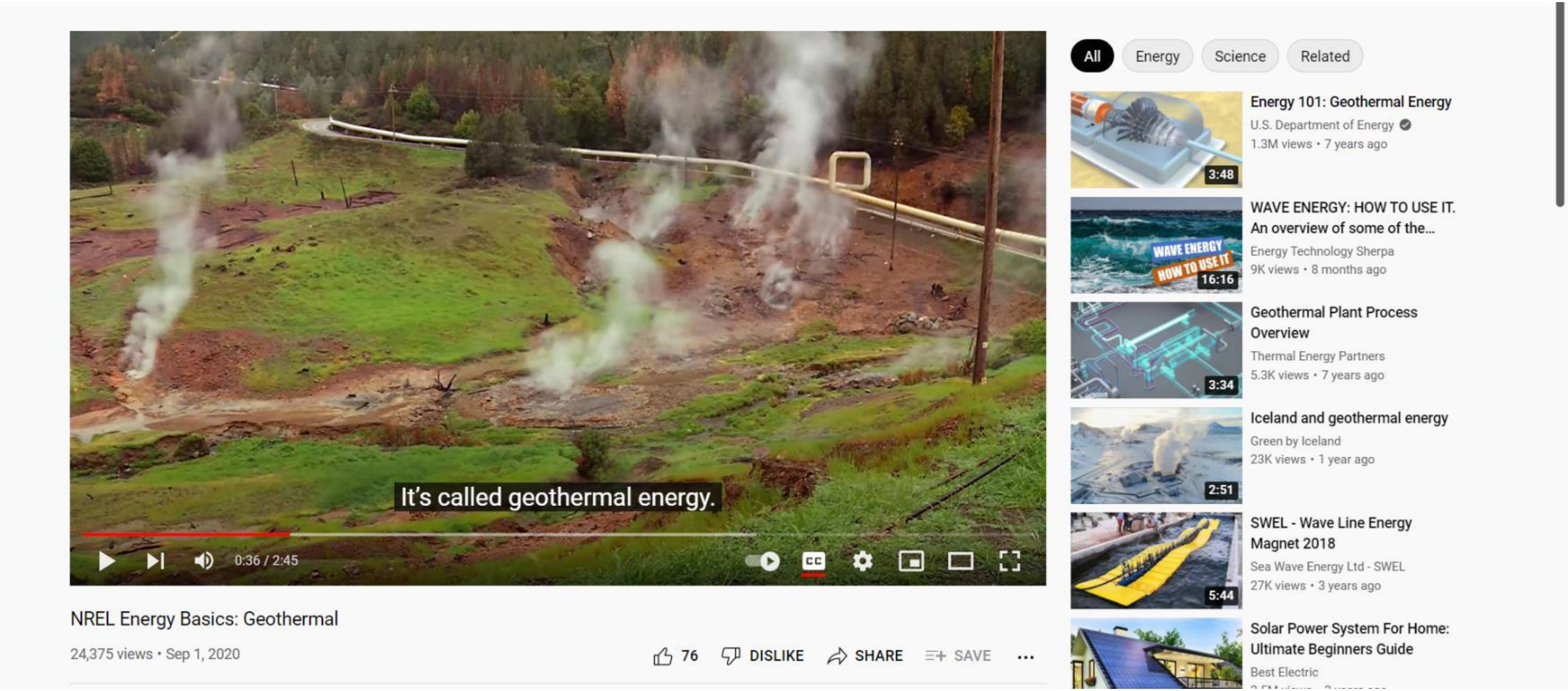
In practice, geothermal energy plants in *hyperthermal* regions are associated with natural hydrothermal systems;

- in *semithermal* regions both hydrothermal and (perhaps) hot rock extraction may be developed; *normal* areas have too small a temperature gradient for commercial interest,
- except for near-surface heat pumps.

Where is Geothermal Energy Found ?

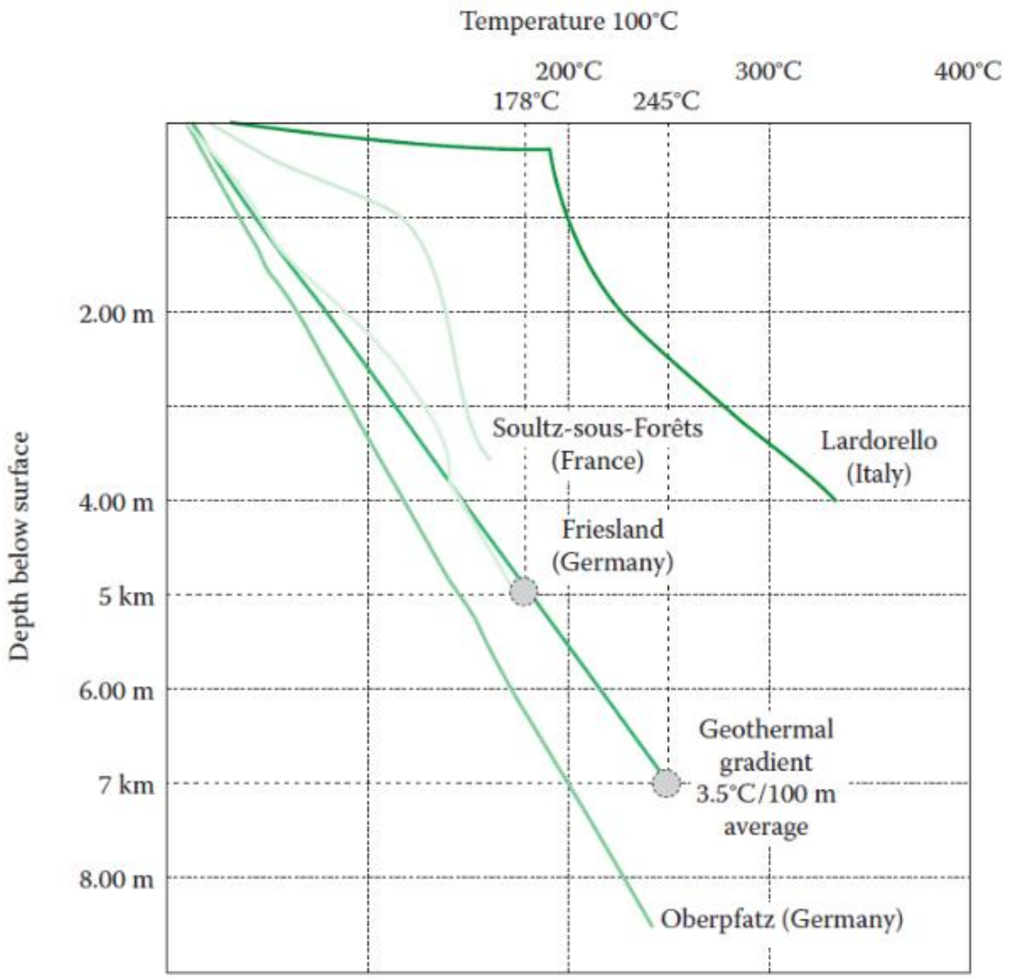
- Most geothermal reservoirs are deep underground with no visible clues showing above ground.
- Geothermal energy can sometimes find its way to the surface in the form of: volcanoes and fumaroles (holes where volcanic gases are released) hot springs and geysers.
- The most active geothermal resources are usually found along major plate boundaries where earthquakes and volcanoes are concentrated.
- Most of the geothermal activity in the world occurs in an area called the Ring of Fire.
- This area rims the Pacific Ocean.

- When magma comes close to the surface it heats groundwater found trapped in porous rock or water running along fractured rock surfaces and faults.
- Such hydrothermal resources have two common ingredients: water (hydro) and heat (thermal). Naturally occurring large areas of hydrothermal resources are called geothermal reservoirs.
- Geologists use different methods to look for geothermal reservoirs.
- Drilling a well and testing the temperature deep underground is the only way to be sure a geothermal reservoir really exists.
- Most of the geothermal reservoirs in the United States are located in the western states,
- Alaska, and Hawaii.
- California is the state that 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. The field has been producing electricity since 1960.



https://www.youtube.com/watch?v=rpgJWYp2OLA

- The inner core of the Earth reaches a maximum temperature of about 4000 ºC, with the outward heat flow maintained predominantly by natural radioactive decay of certain dispersed elements (e.g. uranium, thorium and certain isotopes of potassium).
- Heat passes out through the solid submarine and land surface mostly by conduction – geothermal heat – and occasionally by active convective currents of molten magma or heated water.
- The average geothermal heat flow at the Earth's surface is only 0.06 W/m^2, with average temperature gradient of 25 to 30 $^oC/km$.
- This continuous heat current is trivial compared with other renewable supplies in the above surface environment that in total average about 500 W/m^2



Earth's crust temperature in degrees Celsius versus depth in kilometers in selected places. (Courtesy of Geohil AG, U.K., http://www .mpoweruk.com /geothermal_energy .htm [modified by Electropaedia].)

The thermal gradient is the rate of change of temperature with depth.

The Earth has a radius of 6400 km, and at its center, the temperature is believed to be 7000 K, giving the convenient value of about 1 K/km or 1°C/km for the average gradient.

The gradient, however, does vary enormously both as a function of depth and as a function of the particular location on Earth.

Geothermal energy is not not renewable in a real sense.

However, it is an inexhaustible source of energy

It can be tapped from the underground water reservoirs,

if

$$Q_{removed} = Q_{replenished}$$

Characterization and relative abundance of the resources

1. Impact of the thermal gradient

To generate electricity, the most important characteristic is the thermal gradient because this quantity will determine the well depth that needs to be reached to access temperatures above some minimum needed for a power plant—typically 150°C, even though some types of power plants can operate at lower temperatures.

For this reason, geothermal resources are often put into three grades: high, medium, and low, based on the gradient.

High-grade resources have gradients in excess of 250°C/km, medium grade have gradients 150–250°C/km, and low grade have gradients below 150°C/km. These grades are quite arbitrary and depend on the intended usage of the resource—in this case, electricity generation.

Thus, it is not surprising that some experts prefer other categories, such as "hyperthermal" (above 80°C/km), "semithermal" (40–80°C/km), and "normal" (below 40°C/km).

It is clear from Figure 6.5 that in the case of the United States, it is mainly in some of the Western states that geothermal energy can most easily be exploited for producing electricity.

Geothermal energy resources at temperatures greater than 150 ^{o}C are available at depth ranging from 1500 m – to 3000 m : Good for electricity production

At smaller depths of below 1000 m the temperature is between 90 ^{o}C and 150 ^{o}C : Good for thermal utilization

Geothermal sources can be classified as

1. High temperature – Electricity production and direct heating:
   - Greater than 160 ^{o}C
2. Medium temperature – Electricity production and direct heating
   - 90 – 160 ^{o}C
3. Low temperature – Heat pump for heating and AC
   - 30 -90 ^{o}C
4. Very low temperature- Heat pump for heating and AC
   - Less than 30 ^{o}C

- The economic feasibility of extraction may make the exploitation of the low-gradient location (with the need for deeper wells) out of the question— but much more on this topic later.
- High-thermal gradient resources are more worthwhile to exploit in terms of extracting energy at reasonable cost crucially depends on whether the limitation on drilling technology is a matter of
  (1) maximum depth or
  (2) maximum temperature and the precise manner in which drilling costs depend on depth.

2. other geological factors effecting the amount of resource

In addition to the thermal gradient at a given location, a geothermal prospector will also want to know many other geological characteristics, including these five properties of the underlying rock formations: hardness;

thermal conductivity;

specific heat;

density; and

porosity,

the latter being the fraction of the rock volume that is empty space, which is often filled with fluids, usually water with dissolved salts.

http://www.oas.org/reia/geo-caraibes/PDF%20Documents/Presentations/Technical%20%20Geothermal%20Intro%20(Huttrer%20and%20Miletto).pdf

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Hot dry rock formations

- Aquifers are the easiest geothermal resource to exploit for extracting energy, because they already contain fluid, but most of the stored thermal energy in the Earth's crust is in dry rock formations, which may lack porosity.
- The porosity of rocks can occur in one of two ways: either because of the spaces between grains of the rocks or because of large-scale fractures, which are far more favorable in terms of yielding greater permeability, making them less prone to clogging up over time when fluid flows through the rock.
- This technique allowed engineers to extract energy from hot dry rock (HDR) formations, using what has also more recently been termed *enhanced geothermal systems* (EGSs).
- Although the fracking technique has been controversial in connection with oil and gas exploration, its use with geothermal power is not nearly as problematic since the chemical additives used to free up oil and gas in rock pores are not needed.

- However, at certain specific locations increased temperature gradients occur, indicating significant geothermal resources.
- Regions of geothermal potential generally have permeable rock of area ~10 sq km and depth ~5 km through which water may circulate.
- Consequently, they can be harnessed at fluxes of 10 to 20 W/m^2 to produce ~100 MW (thermal) per km^2 in commercial supplies for at least 20 years of operation.
- Regions of 'hot, dry rock' have to be fractured artificially to become permeable, so that water may be circulated through the fractures to extract the heat.

- At some reasonable depths, the rocks and water absorb heat from this magma. These sites are characterized as geothermal resources.
- By digging wells and pumping the hot water to the surface, we make use of geothermal energy.

Geothermal resources can be classified based on their thermal and compositional characteristics.

1. *Hydrothermal*

These are known geothermal fields containing high-temperature water in the steam, mixture, or liquid phases.

2. *Geopressurized*

These resources contain hot liquid water at 150°C to 180°C at very high pressures (up to 600 bar).

The fluid in these deposit-filled reservoirs also contains methane and high levels of dissolved solids.

The fluid is highly corrosive and thus very difficult to harvest and handle.

3. *Magma*

They are also called *molten rock*, and typically contained under active volcanoes at temperatures above 650 °C.

4. *Enhanced*

They are also called hot, dry rock geothermal systems.

These are not natural geothermal resources.

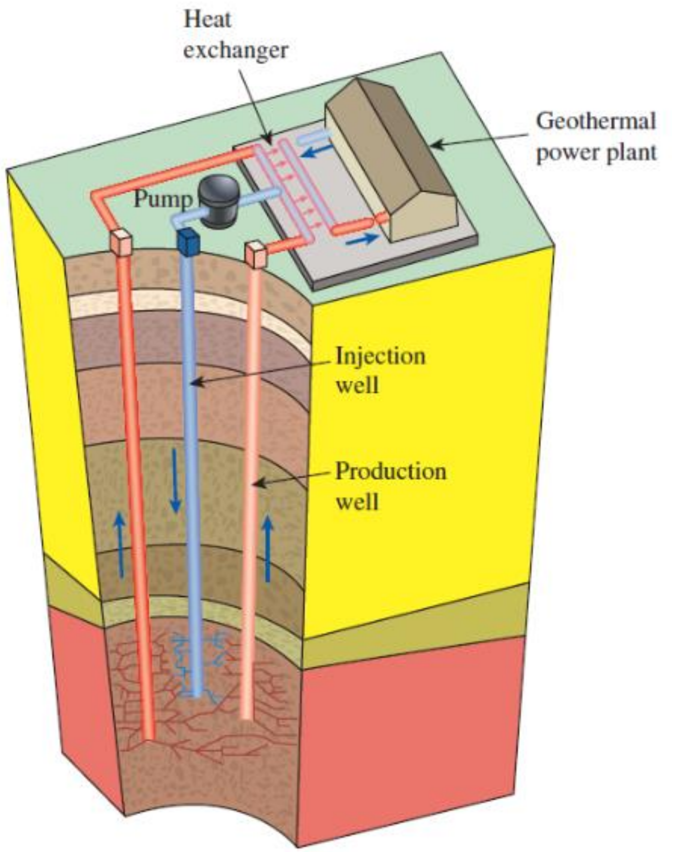
The idea is that water is injected into the hot rock formation at high pressure, and then the resulting hot steam is brought back to the surface.

The system involves the drilling of injection and production wells to a depth of 3 to 5 km.

The temperature of the hot rock in this depth can be around 250 °C.

Among these four geothermal resource categories, only hydrothermal resources are currently being exploited.

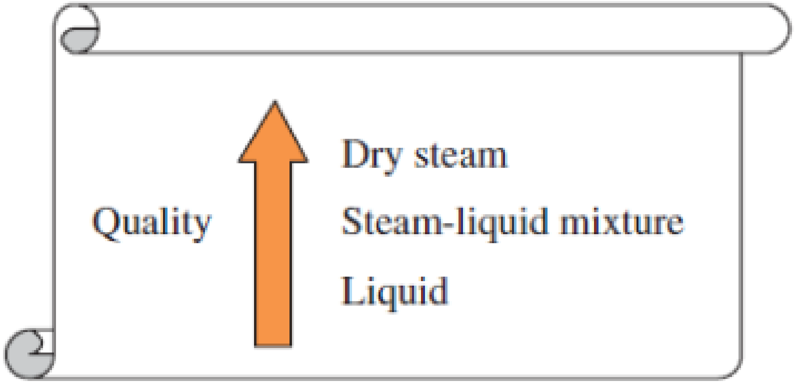
The other three are estimated to have enormous energy potentials but current technologies do not allow feasible energy production from these resources.



Operation of enhanced geothermal systems. (*Adapted from Geothermal Worldwide, 2019*)

- The quality and life of a hydrothermal resource can be prolonged by reinjecting the waste fluid, which is the most common method of disposal.
- Reinjection may also help to maintain reservoir pressure.
- Over-ground disposal of geothermal fluid has a potential hazard of water pollution of rivers and lakes as well as air pollution.
- Reinjection of geothermal water is a legal requirement in the United States.
- A geothermal resource contains geothermal water at a temperature higher than that of the environment.
- One common classification of geothermal resources is based on the resource temperature.

The quality of a geothermal resource depends on its phase (and temperature) in the reservoir. The higher the quality, the higher the work potential.



- A geothermal resource contains geothermal water at a temperature higher than that of the environment.
- One common classification of geothermal resources is based on the resource temperature.
  - High temperature resource: $T > 150°C$
  - Medium temperature resource: $90°C < T < 150°C$
  - Low temperature resource: $T < 90°C$

Uses of Geothermal Energy

Some applications of geothermal energy use the earth's temperatures near the surface, while others require drilling miles into the earth.

The three main uses of geothermal energy are:

1. **Direct Use and District Heating Systems** which use hot water from springs or reservoirs near the surface.

2. **Electricity generation** in a power plant requires water or steam at very high temperature (300 to 700 degrees Fahrenheit). Geothermal power plants are generally built where geothermal reservoirs are located within a mile or two of the surface.

3. **Geothermal heat pumps** use stable ground or water temperatures near the earth's surface to control building temperatures above ground.

There are three main *uses* of geothermal energy, order of *decreasing thermodynamic quality*, which happens also to be the order of their *increasing geographical availability*.

- *Electricity generation*
- *Hot water supply*
- *Heat pumps*

Geothermal heat has also proven to be useful for a wide range of non-residential uses, including district heating; hot water heating; horticulture; industrial processes; and even tourism, i.e., hot thermal baths.

Direct use

- It is possible to exploit this energy to produce water at high temperatures (η= 50 -70 %)
- Cold water is injected into a well 5000 m deep
- Injected water causes hot rocks to crack and release heat
- Heated water diffuses and recovered in other wells
- Hot water is pumped through a heat exchanger to heat air or liquid that is circulated to a heat building

- The direct use of hot water as an energy source has been happening since ancient times.
- The Romans, Chinese, and Native Americans used hot mineral springs for bathing, cooking and heating.
- Today, many hot springs are still used for bathing, and many people believe the hot, mineral-rich waters have natural healing powers.
- After bathing, the most common direct use of geothermal energy is for heating buildings through district heating systems.
- Hot water near the earth's surface can be piped directly into buildings and industries for heat.
- A district heating system provides heat for 95 percent of the buildings in Reykjavik, Iceland.
- Examples of other direct uses include: growing crops, and drying lumber, fruits, and vegetables.

Hot water supply.

In many more locations, geothermal heat is available at ~50 to 70°C; for instance, for 'medicinal' bathhouses in the Roman Empire, and today for greenhouse heating for vegetable crops and soft fruits, for crop drying, for aquaculture of fish and algae, for district heating servicing buildings and for industrial process heat (e.g. for paper pulp from wood processing, and for leaching chemicals).

More than 60 countries list such uses, many of which do not produce geothermal electricity.

Electricity generation

At a few locations geothermal heat is available at temperatures of more than 150 ^{o}C, as a natural flow of high- pressure water and/or steam, so having the potential for electrical power production from turbines.

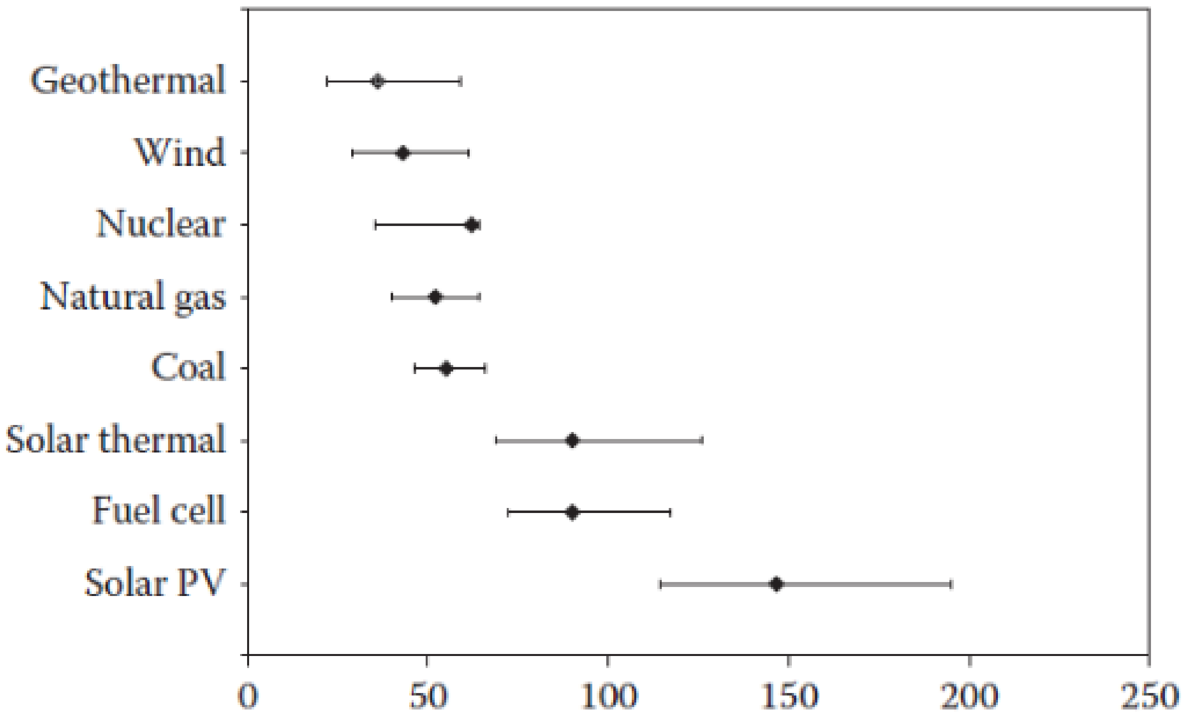
Several geothermal electric power complexes have operated for many years, especially in Italy, Iceland, New Zealand and the USA.

The number of similar installations has increased steadily since the 1970s.

As for hydropower, hydrothermal power technology is mature and long-lasting when tailored to specific sites.

The power may be used constantly for baseload at a cheap per unit cost.

New developments have increased rapidly in the relatively unexploited geothermally active regions of the Philippines, Indonesia and western USA.



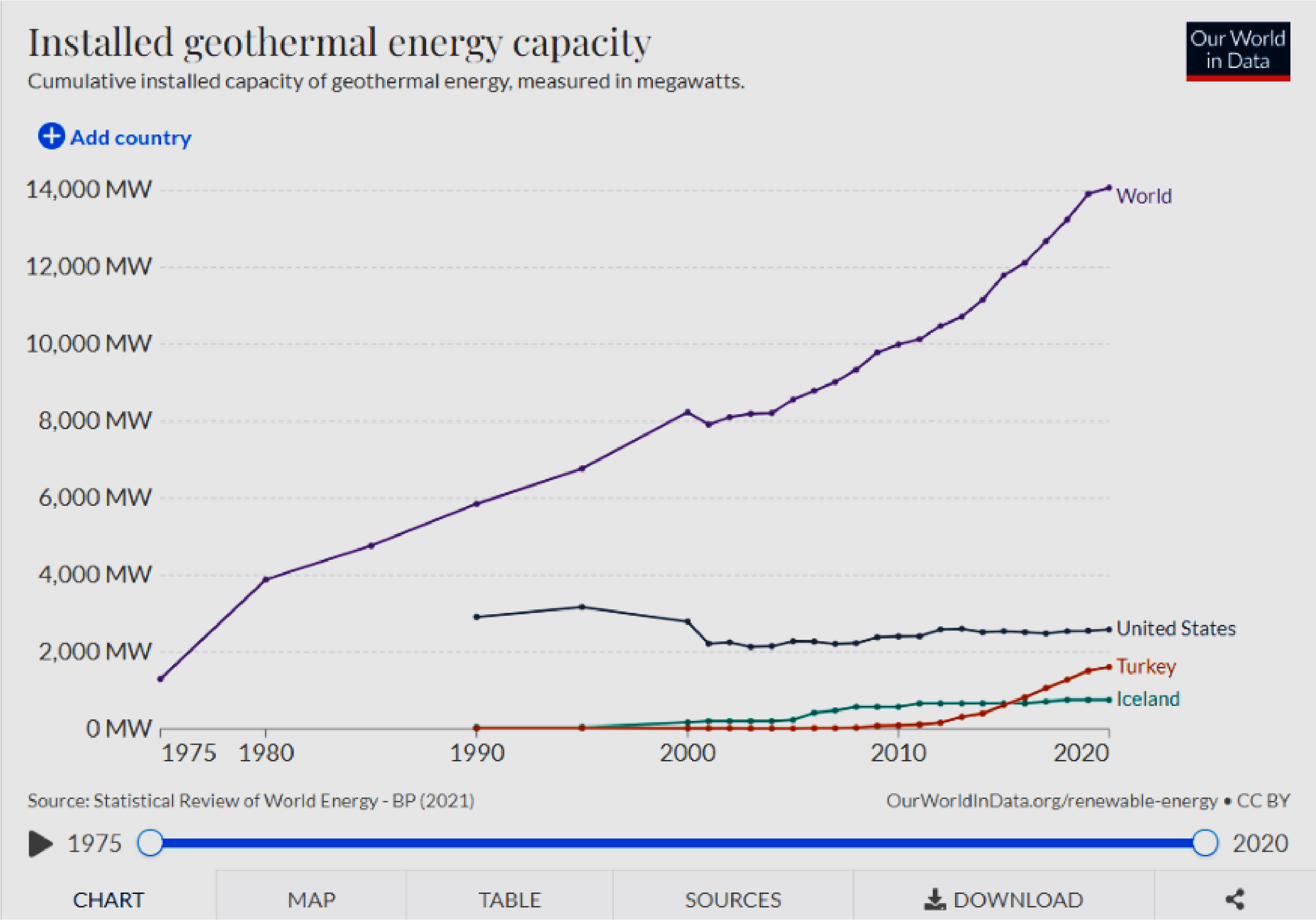
Comparison of electricity generation costs in dollars per megawatt-hour for eight fuel sources. The bars show high and low estimates for the ranges. The costs are for plants in the United States, and they include a $19/MWh tax incentive for renewable sources. Moreover, these are levelized costs, which assume that the same interest rates can be obtained for highly capital-intensive sources compared to others. These data are based on high and low estimates for a plant entering service in 2017, and they are based on US Energy Information estimates.

Geothermal Power Plants

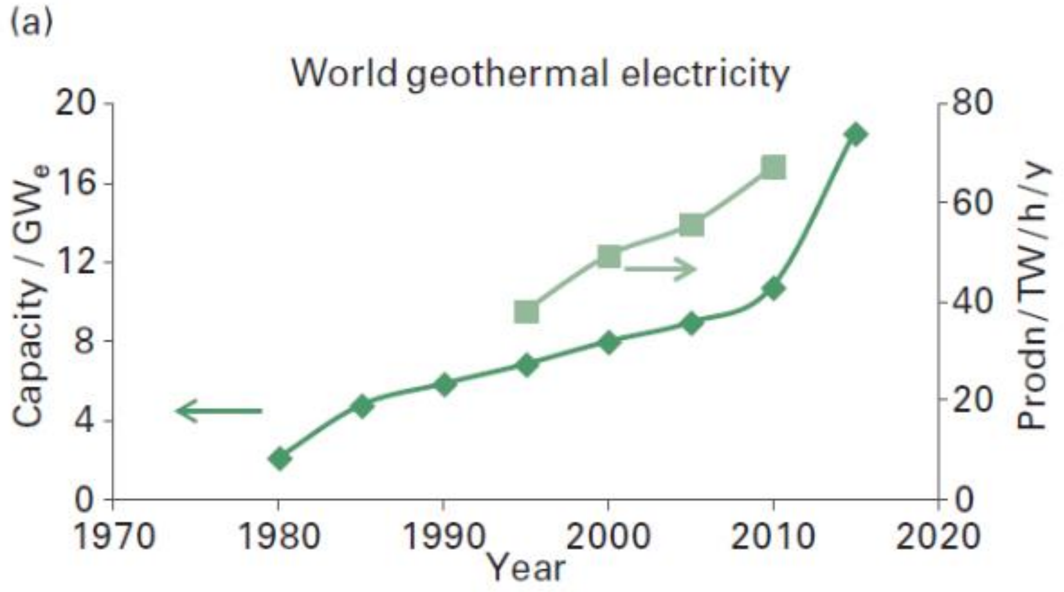
Geothermal power plants use hydrothermal resources which have two common ingredients: water (hydro) and heat (thermal).

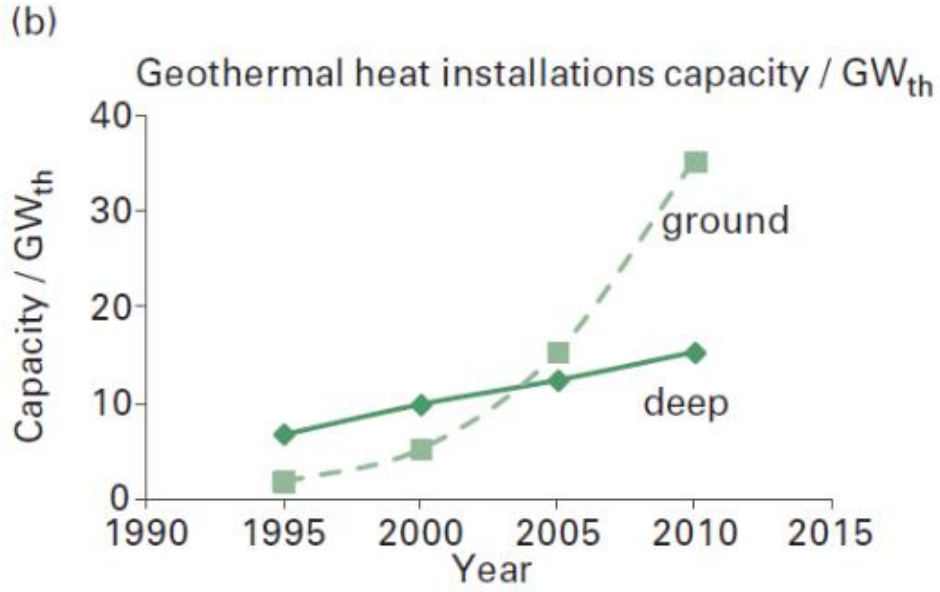
Geothermal plants require high temperature (300 to 700 degrees Fahrenheit) hydrothermal resources that may come from either dry steam wells or hot water wells.

We can use these resources by drilling wells into the earth and piping the steam or hot water to the surface. Geothermal wells are one to two miles deep.



(https://ourworldindata.org/grapher/installed-geothermal capacity?tab=chart&country=USA~ISL~TUR~OWID_WRL)





Growth in world geothermal installations.
a. Heat to electricity; electrical generation capacity (GW_e) (left axis) and annual electricity generation (TWh) (right axis);
capacity in 2015 is estimated from announced plans.
b. Heat use only: installed capacity (GW_{th}) drawing on ‘deep heat’ (solid curve) and on ‘ground heat’ (dashed curve).
Source: data from WGC(2010).

There are three basic types of geothermal power plants:

1. Dry steam plants –

use steam piped directly from a geothermal reservoir to turn the generator turbines.

The first geothermal power plant was built in 1904 in Tuscany, Italy at a place where natural steam was erupting from the earth.

2. Flash steam plants –

take high-pressure hot water from deep inside the earth and convert it to steam to drive the generator turbines. When the steam cools, it condenses to water and is injected back into the ground to be used over and over again.

Most geothermal power plants are flash plants.

3. Binary power plants –

transfer the heat from geothermal hot water to another liquid. The heat causes the second liquid to turn to steam which is used to drive a generator turbine.

Geothermal Power Production

Only a fraction of geothermal resources have relatively high temperatures making them suitable for electricity production.

Geothermal power plants have been in operation for decades in many parts of the world.

First geothermal power plant was built in Italy in 1904.

First geothermal plant was built in 1960 in the Geysers in northern California.

There are dozens of geothermal power plants in the United States located in California, Nevada, Utah, Idaho, Oregon, and Hawaii.

About 14,300 MW of geothermal electricity are produced in 24 countries as of 2018, and 28 percent of this is generated in the United States with 3550 MW.

- Different thermodynamic cycles can be used for producing power from geothermal resources.
- The readers are referred to DiPippo (2007) for a detailed coverage of geothermal power plants. A case study on an existing binary geothermal power plant is available in Kanoğlu and Çengel (1999b).
- The simplest geothermal cycle is the *direct steam* or dry steam cycle. Steam from the geothermal well is passed through a turbine and exhausted to the atmosphere or to a condenser.
- Flash steam plants are used to generate power from liquid-dominated resources that are hot enough to flash a significant proportion of the water to steam in surface equipment, either at one or two pressure stages.
- In a *single-flash* plant, the pressure of geothermal water is dropped to a predetermined value in a flash chamber.
- The resulting two-phase mixture is separated into liquid and vapor in the separator.
- The vapor is routed to turbine in which it is expanded to condenser pressure.
- Steam exiting the turbine is condensed with cooling water obtained in a cooling tower or a spray pond before being reinjected.
- The liquid geothermal water at state 6 and that in state 5 is reinjected back to the ground.

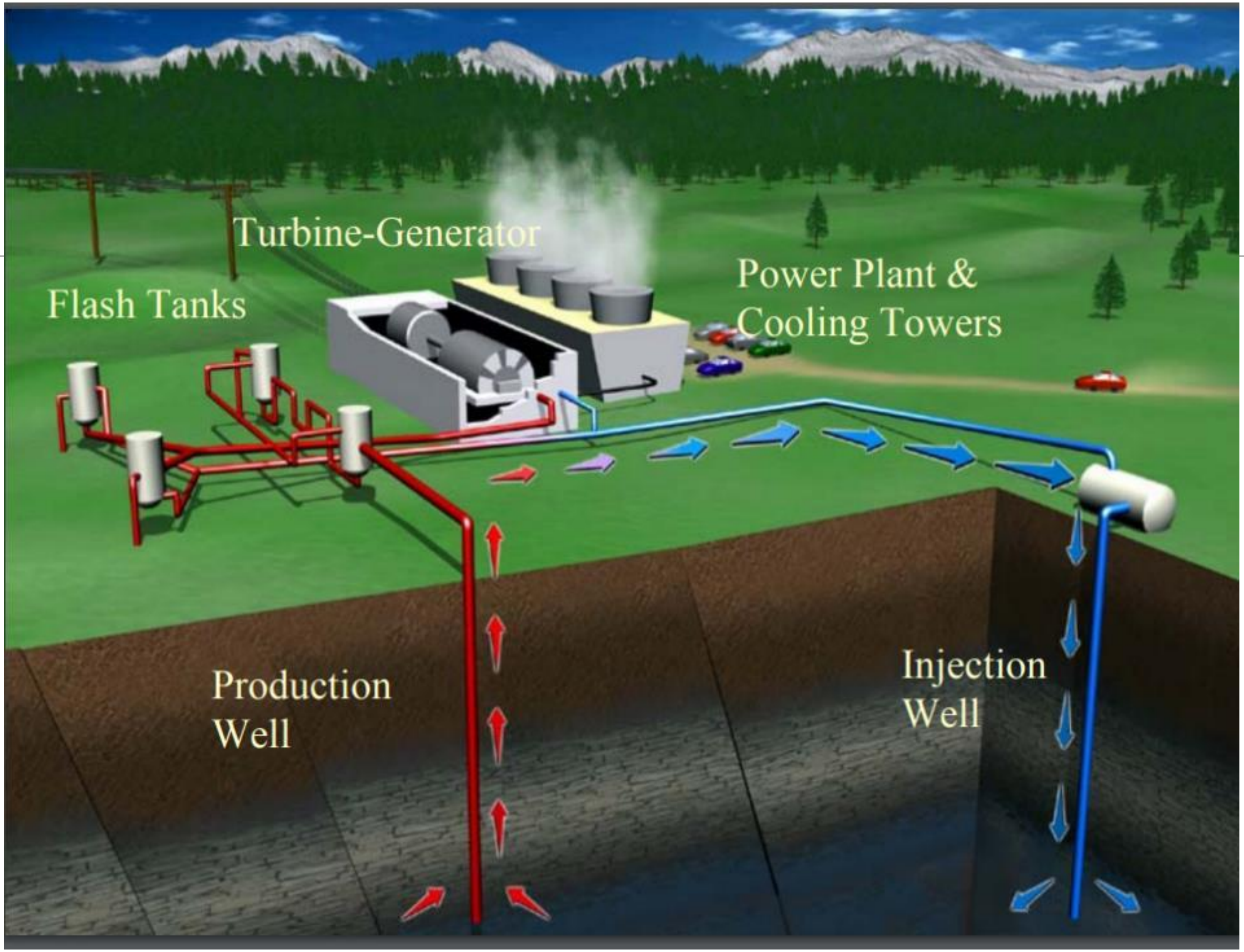
Thermodynamic analysis of a single-flash geothermal power plant is similar to analysis of Rankine cycle.

Neglecting kinetic and potential energy changes across the turbine, the power output (W_{out}) from the turbine is determined from

$$\dot{W}_{out} = \dot{m}_3(h_3 - h_4)$$

The thermal efficiency of the plant (η_{th}) may be defined as the ratio of the power output (W_{out}) to the energy input (E_{in}) to the plant:

$$\eta_{th} = \frac{\dot{W}_{out}}{\dot{E}_{in}}$$



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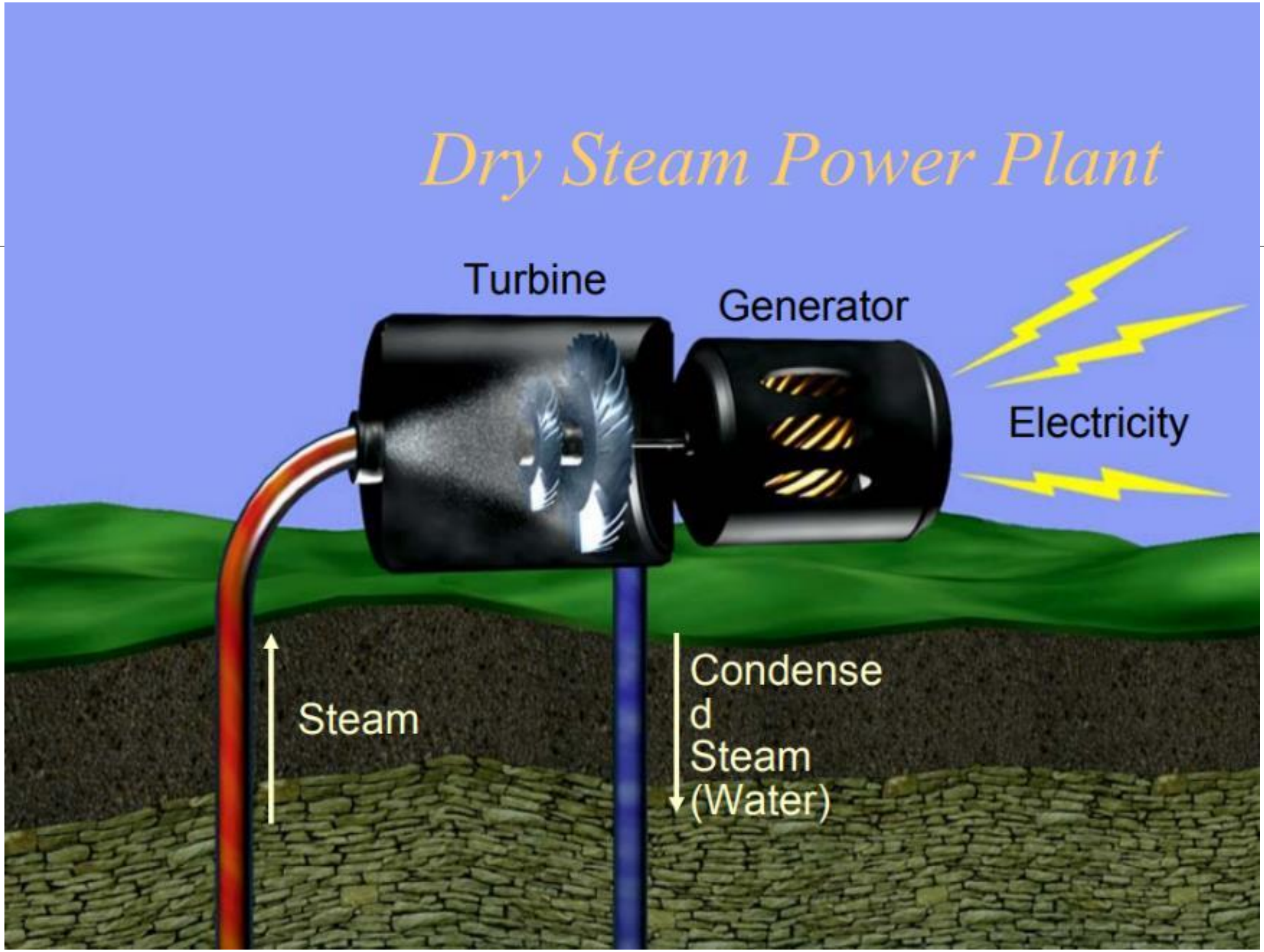

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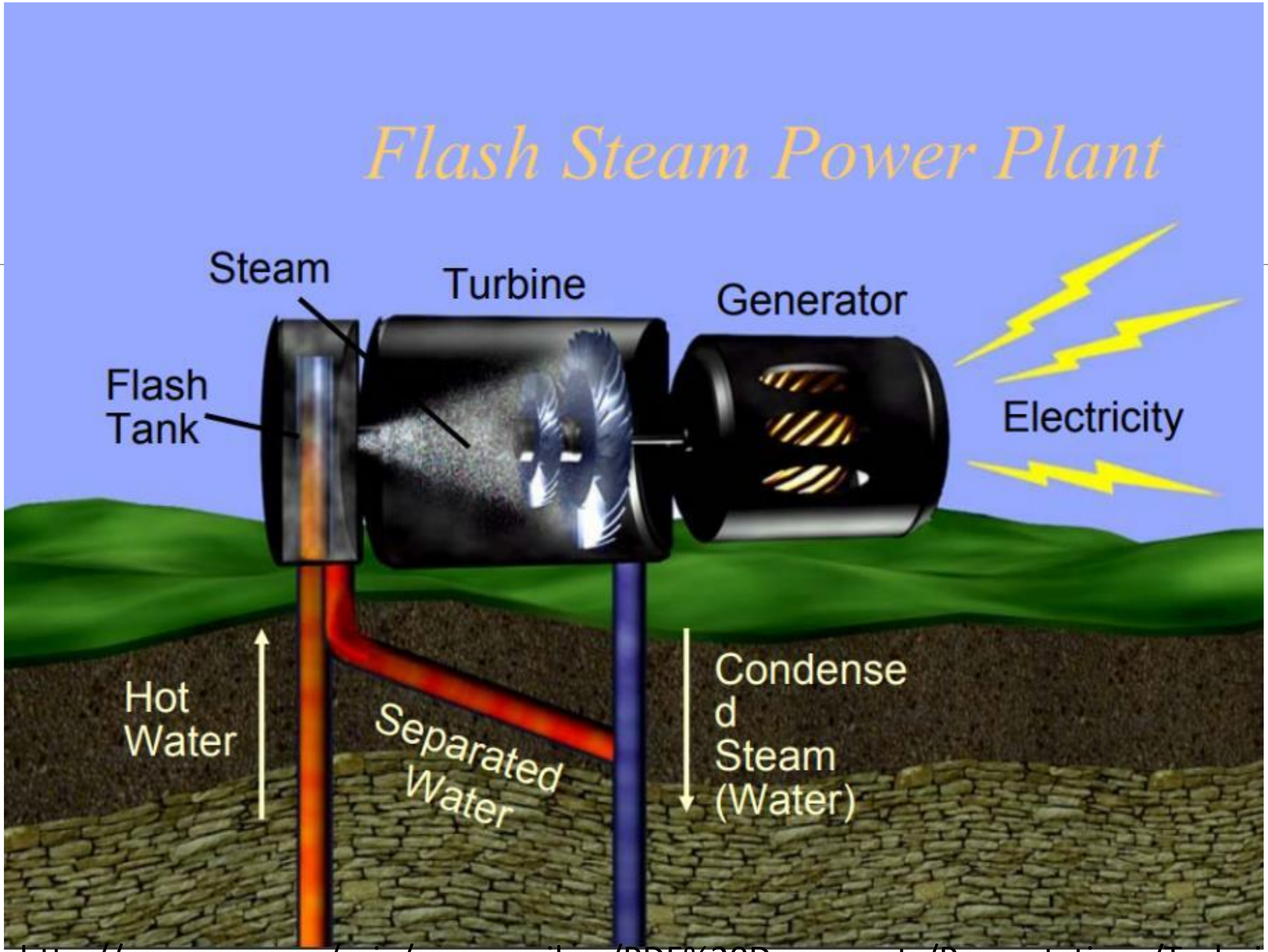

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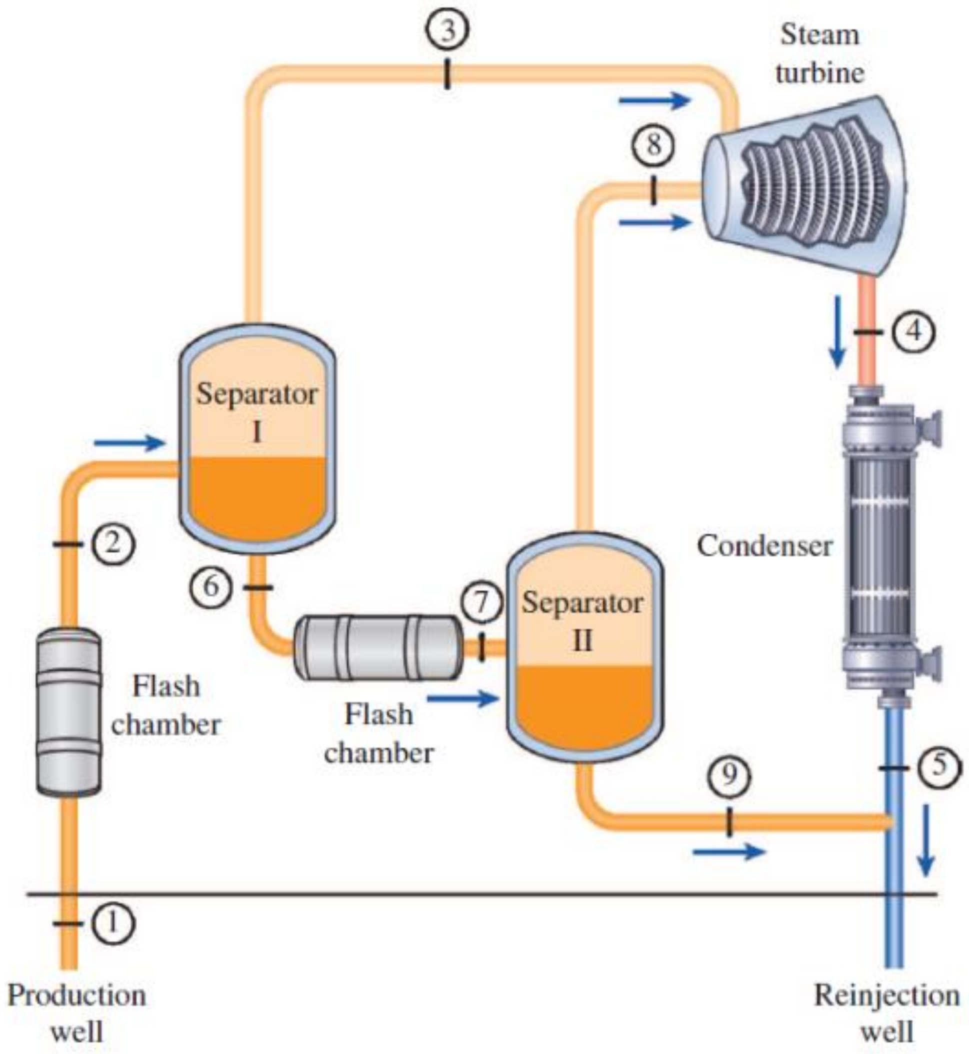
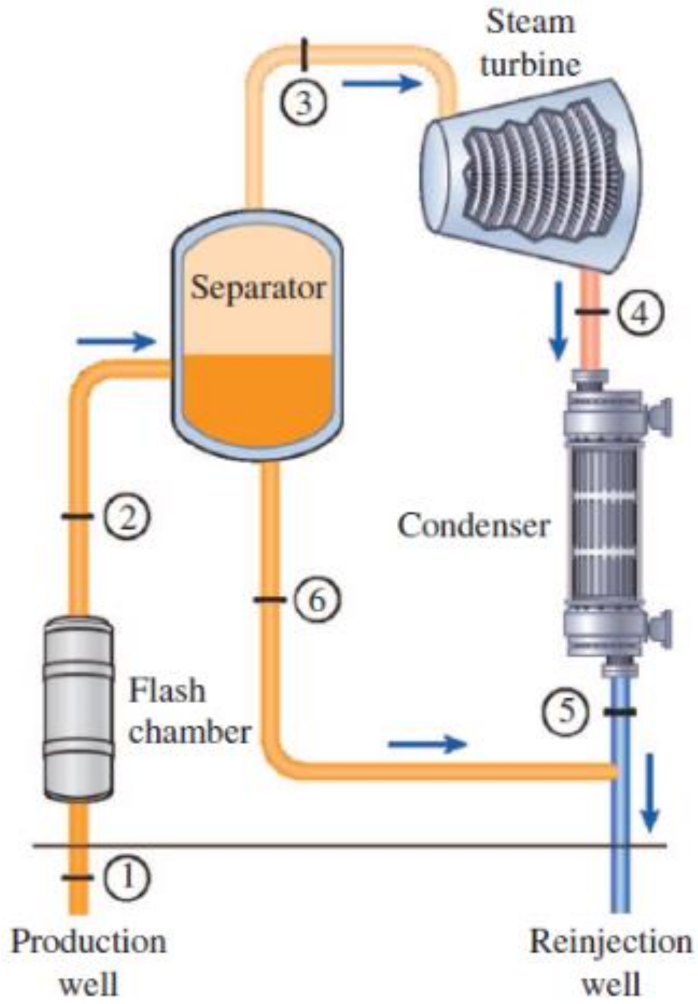
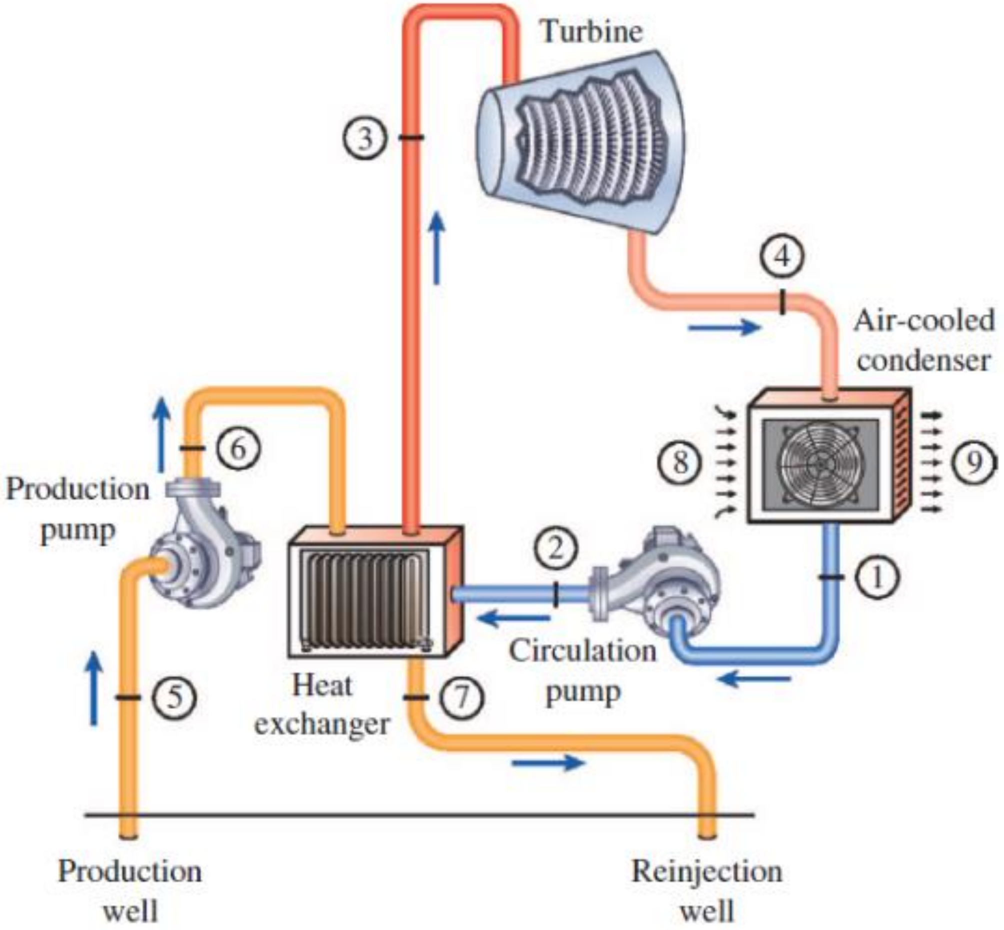


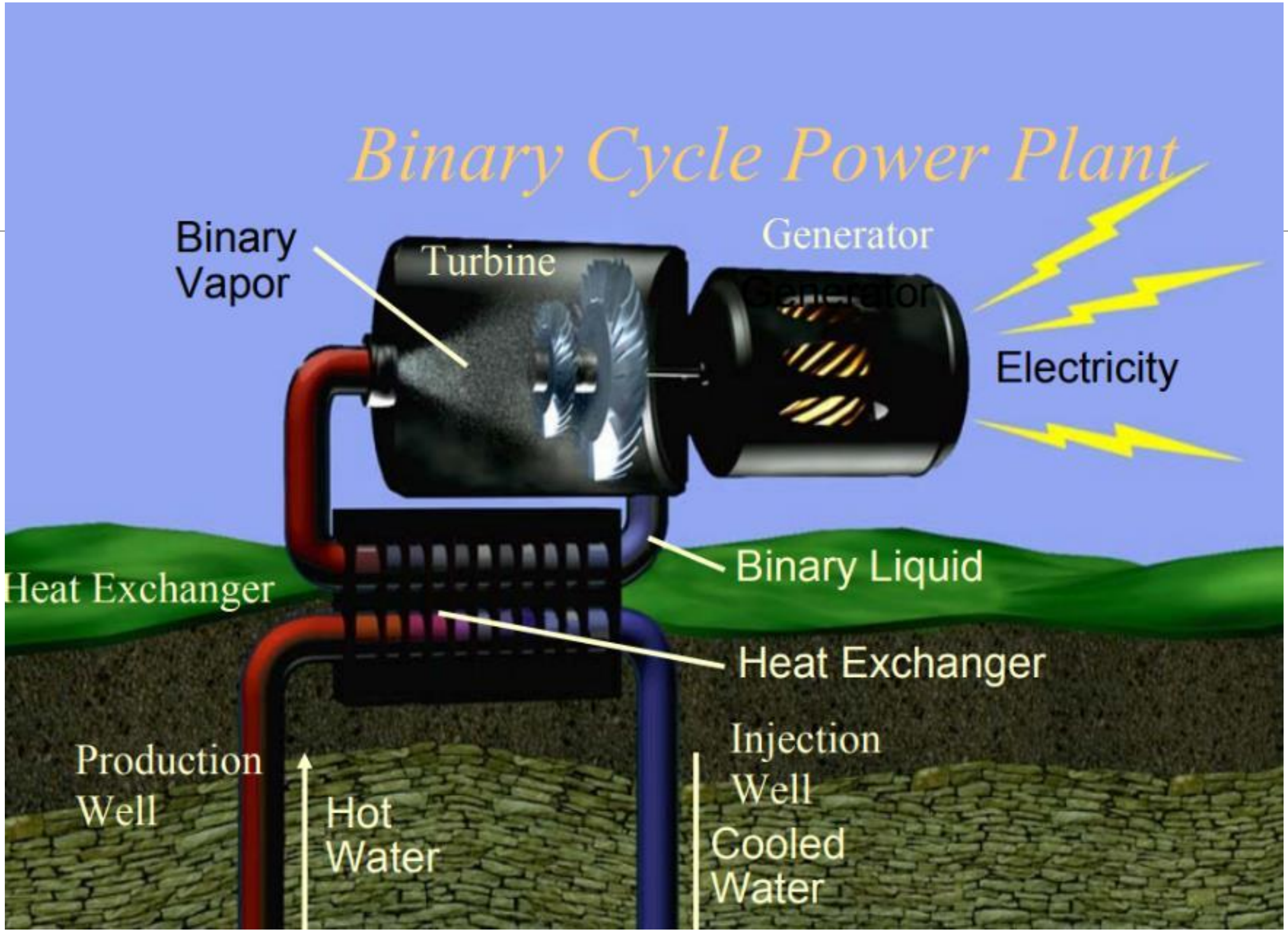
Double-flash geothermal power plant



Single-flash geothermal power plant



Binary cycle geothermal power plant



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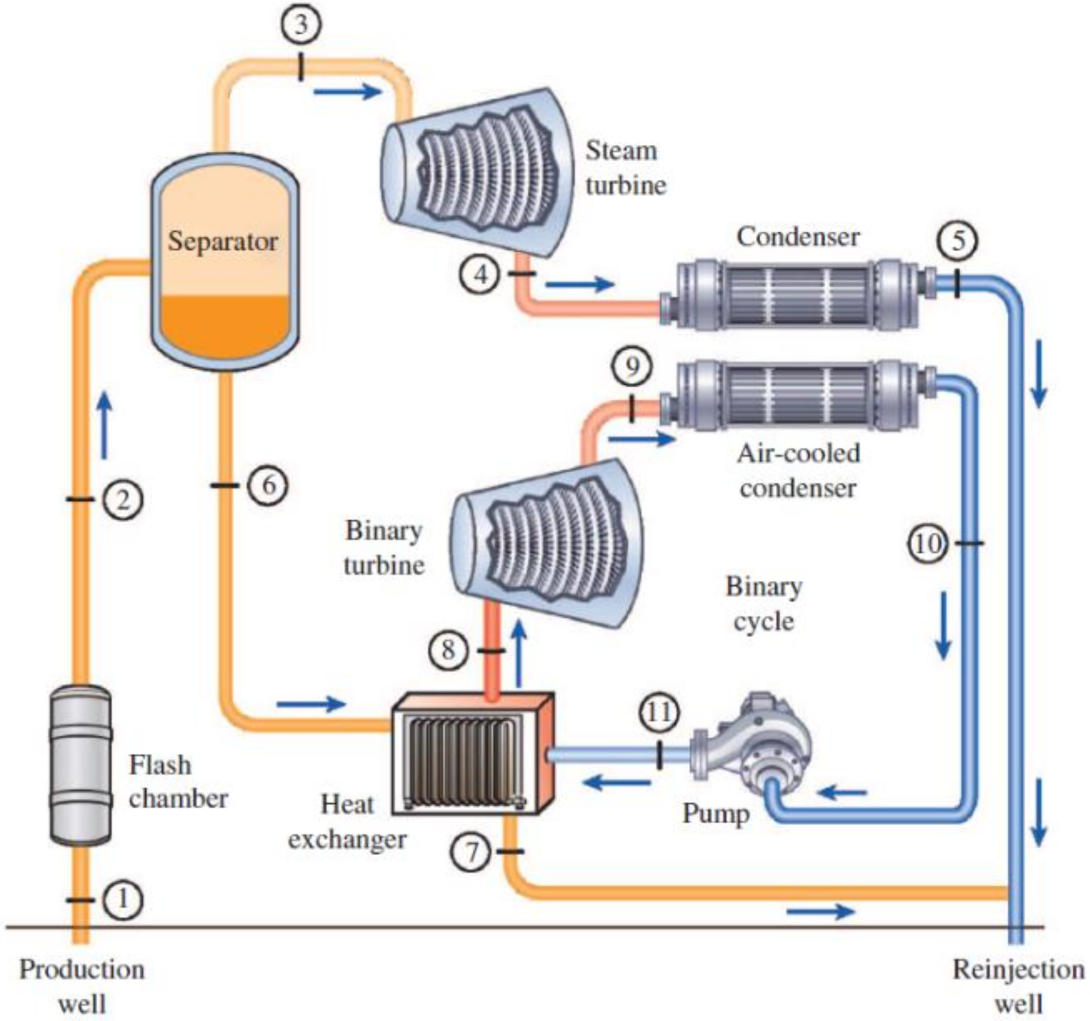


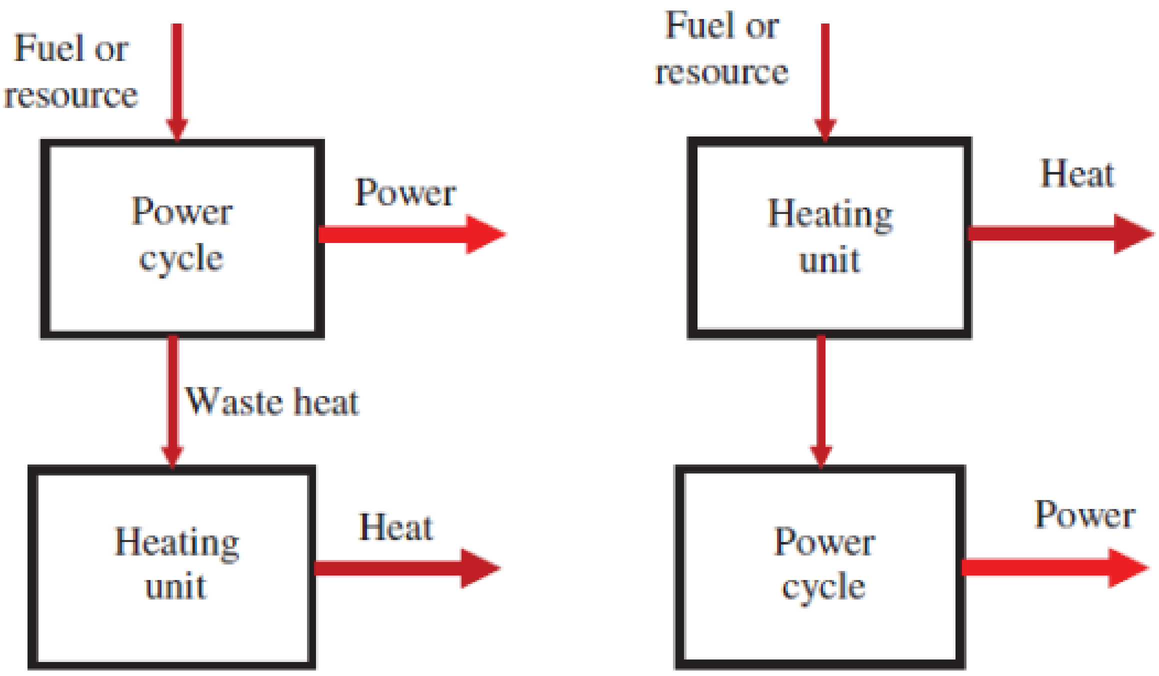
Combined flash/binary geothermal power plant

Geothermal Cogeneration

- *Cogeneration* is *the production of more than one useful form of energy (such as process heat and electric power) from the same energy source.*
- A combination of power production and cooling can also be used in a cogeneration scheme. It is called *trigeneration* if three useful forms of energy (such as electric power, process heat, and cooling) are produced from the same energy source.
- A steam-turbine (Rankine) cycle, a gas-turbine (Brayton) cycle, a combined cycle (combination of Rankine and Brayton cycles), an internal combustion engine, or any other power-producing plant (such as a geothermal power plant) can be used as the power cycle in a cogeneration plant.
- Cogeneration systems utilizing internal combustion engines and gas turbines in the open cycle are the most utilized technologies worldwide.

- The “cascading” of energy use from high- to low-temperature uses, often distinguishes cogeneration systems from conventional separate electrical and thermal energy systems (e.g., a power plant and an industrial boiler), and from simple heat recovery strategies.
- The principal technical advantage of cogeneration systems is their ability to improve the efficiency of fuel use in the production of electrical and thermal energy.
- Less fuel is required to produce a given amount of electrical and thermal energy in a single cogeneration unit than is needed to generate the same quantities of both types of energy with separate, conventional technologies.
- This is because heat from the turbine-generator set, which uses a substantial quantity of fuel to fire the turbine, becomes useful thermal energy (e.g., process steam) in a cogeneration system rather waste heat (Benelmir and Feidt, 1998; Wilkinson and Barnes, 1980).

- The technical advantages of cogeneration lead to significant energy savings and corresponding environmental advantages.
- That is the increase in efficiency and corresponding decrease in fuel use by a cogeneration system, compared to other conventional processes for thermal and electrical energy production, normally yield large reductions in energy use and greenhouse gas emissions.
- These reductions can be as large as 50 percent in some situations, while the same thermal and electrical services are provided.
- When cogeneration is used in a renewable energy scheme, the environmental benefits are greater with respect to fossil fuel–based cogeneration units.
- Renewable cogeneration systems make the most use of a resource and this translates into a greater replacement of fossil fuels.



(a) Topping cycle

(b) Bottoming cycle

Topping and bottoming cycles

Geothermal Heating

A number of residential and commercial districts are effectively heated in winter by low-cost geothermal heat in many parts of the world.

Some of the largest district heating installations are in China, Sweden, Iceland, Turkey, and the United States.

Almost 90 percent of buildings in Iceland (a relatively small country) are heated in winter by geothermal heat.

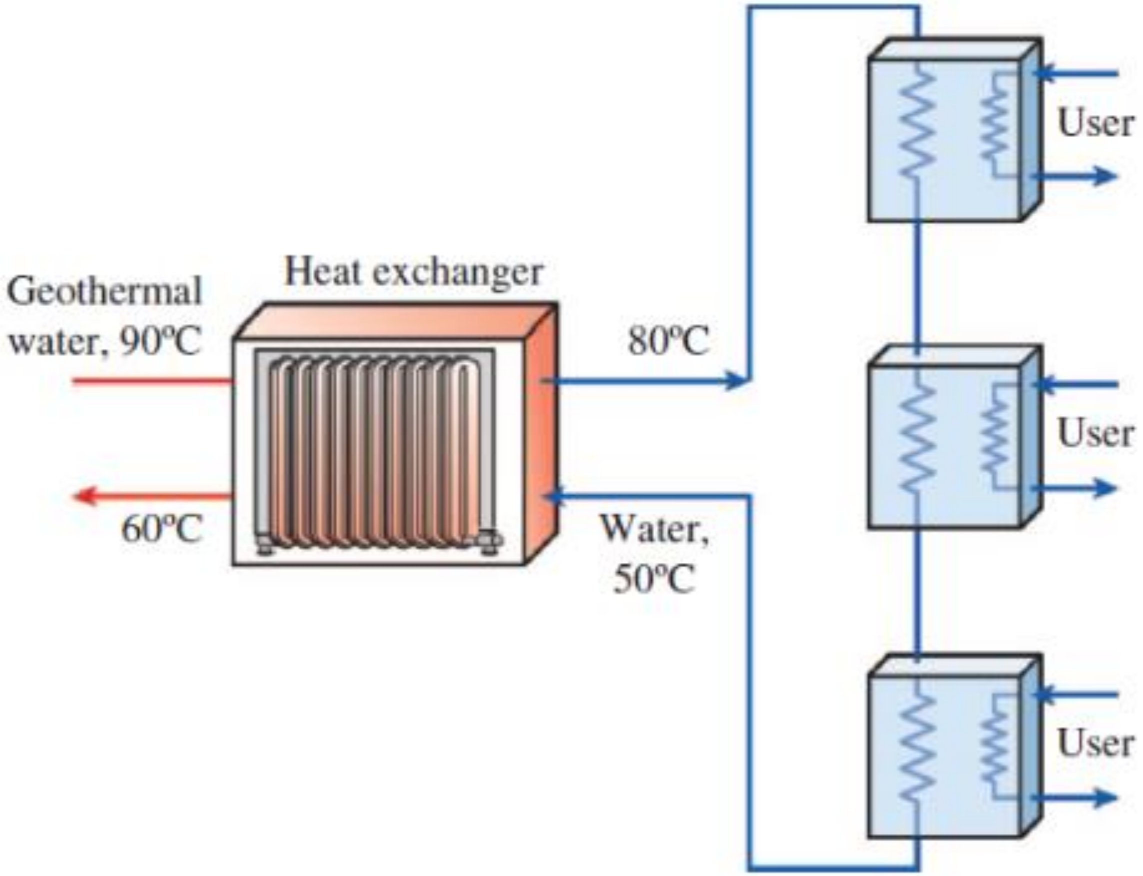
- Geothermal heat can also be used for producing hot water for residences, offices, and industrial processes.
- A possible process heat application of geothermal hot water can be accomplished by preheating water in steam boilers in various industries.
- The use of geothermal heat for space, water, and process heating and space cooling applications, is only viable when the resource is in a close proximity to the user district.
- Carrying geothermal water over long distances is not cost-effective.
- For space and water heating, the resource temperature should be greater than about 50°C.
- Geothermal energy is more effective when used directly than when converted to electricity, particularly for moderate and low-temperature geothermal resources since the direct use of geothermal heat for heating and cooling would replace the burning of fossil fuels from which electricity is generated much more efficiently (Kanoğlu and Çengel, 1999a).
- When a district is heated by geothermal water, the rate of geothermal heat supplied to the district is determined from

$$\dot{Q}_{\text{heat,useful}} = \dot{m} c_p (T_{\text{supply}} - T_{\text{return}})$$

Where, $\dot{m}$ = mass flow rate of geothermal water,

c_p = the specific heat of geothermal water, and

T_{supply} and T_{return} = Supply and return temperatures of geothermal water for the district



A common operating mode for geothermal district space heating systems. Temperature values are representative.

Assuming that this heat represents the average rate of heat supplied to the district, the amount of energy supplied for a specified period of time (i.e., operating hours) is determined from

$$\text{Energy consumption} = \frac{\dot{Q}_{\text{heat,useful}} \times \text{Operating hours}}{\eta_{\text{heater}}}$$

- Where η_{heater} is the efficiency of the heating equipment.
- For a geothermal heating application, it can be taken to be unity by neglecting fluid losses and heat losses in fluid lines and the heat exchange system.
- For a natural gas heater, it typically ranges between 80 and 90 percent. If the efficiency of a natural gas heater is 80 percent, this means that for 100 units of energy provided by natural gas, 80 units are transferred to the district as useful heat, and 20 percent are lost in the heater mostly by hot exhaust gases.

Once the amount of energy consumption is available, the corresponding cost of this energy can be determined from

$$\text{Energy cost} = \text{Energy consumption} \times \text{Unit price of energy}$$

Degree-Day Method for Annual Energy Consumption

- The simplest and most intuitive way of estimating the annual energy consumption of a building is the *degree-day* (or *degree-hour*) *method*, which is a *steady-state* approach.
- It is based on constant indoor conditions during the heating or cooling season and assumes the efficiency of the heating or cooling equipment is not affected by the variation of outdoor temperature.
- These conditions will be closely approximated if all the thermostats in a building are set at the same temperature at the beginning of a heating or cooling season and are never changed, and a seasonal average efficiency is used (rather than the full-load or design efficiency) for the heaters or coolers.

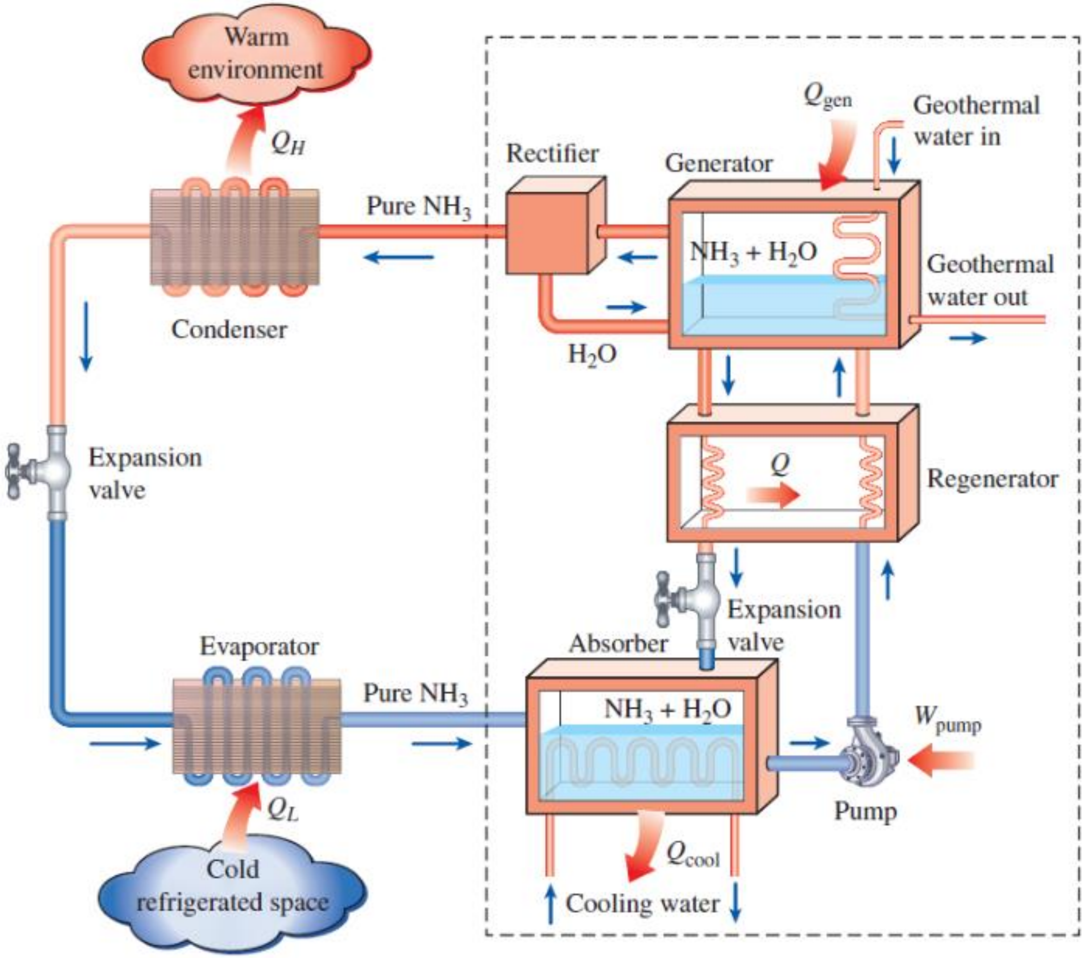
Geothermal Cooling

- Geothermal heat may be supplied to an absorption refrigeration system for space cooling applications.
- A district cooling system utilizing geothermal heat may be feasible depending on the annual cooling load of the district.
- The use of geothermal heat for cooling is not common since they typically involve high initial cost.
- A geothermal cooling system installed in Oregon Institute of Technology was estimated to pay for itself in about 15 years.
- Next, we provide an overview of absorption cooling systems.

Absorption Cooling System

- A form of cooling system that becomes economically attractive when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is absorption refrigeration.
- Some examples of inexpensive thermal energy sources include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is available at a relatively low price.
- A cogeneration plant may involve electricity generation and absorption cooling.
- As the name implies, absorption refrigeration systems involve the absorption of a refrigerant by a transport medium.
- The most widely used absorption refrigeration system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium. Other absorption refrigeration systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant.
- The latter two systems are limited to applications such as air-conditioning where the minimum temperature is above the freezing point of water.

- To understand the basic principles involved in absorption refrigeration, we examine the NH_3-H_2O system.
- The ammonia–water refrigeration machine was patented by the Frenchman Ferdinand Carre in 1859.
- Within a few years, the machines based on this principle were being built in the United States primarily to make ice and store food.



Ammonia absorption refrigeration cycle

- Ammonia vapor leaves the evaporator and enters the absorber, where it dissolves and reacts with water to form NH_3-H_2O.
- This is an exothermic reaction; thus heat is released during this process.
- The amount of NH_3 that can be dissolved in H_2O is inversely proportional to the temperature.
- Therefore, it is necessary to cool the absorber to maintain its temperature as low as possible, hence to maximize the amount of NH_3 dissolved in water.
- The liquid NH_3-H_2O solution, which is rich in NH3, is then pumped to the generator.
- Heat is transferred to the solution from a source (i.e., geothermal heat) to vaporize some of the solution.
- The vapor, which is rich in NH_3, passes through a rectifier, which separates the water and returns it to the generator.
- The high-pressure pure NH_3 vapor then continues its journey through the rest of the cycle.
- The hot NH_3-H_2O solution, which is weak in NH3, then passes through a regenerator, where it transfers some heat to the rich solution leaving the pump, and is throttled to the absorber pressure.

- Compared with vapor-compression systems, absorption refrigeration systems have one major advantage: A liquid is compressed instead of a vapor.
- The steady-flow work is proportional to the specific volume, and thus the work input for absorption refrigeration systems is very small (on the order of 1% of the heat supplied to the generator) and often neglected in the cycle analysis.
- The operation of these systems is based on heat transfer from an external source. Therefore, absorption refrigeration systems are often classified as *heat-driven systems*.
- The absorption refrigeration systems are much more expensive than the vapor-compression refrigeration systems.
- The **COP (Coefficient of performance)** of absorption refrigeration systems is defined as

$$\mathrm{COP}_{\text{absorption}} = \frac{Q_{\text{cooling}}}{Q_{\text{gen}} + W_{\text{pump,in}}} \cong \frac{Q_{\text{cooling}}}{Q_{\text{gen}}}$$

- They are more complex and occupy more space, they are much less efficient thus requiring much larger cooling towers to reject the waste heat, and they are more difficult to service since they are less common.
- Therefore, absorption refrigeration systems should be considered only when the unit cost of thermal energy is low or a free renewable energy source such as geothermal energy is available.
- An ideal use of an absorption system is when it uses the waste heat of a power plant such as geothermal in a cogeneration scheme.
- Absorption refrigeration systems are primarily used in large commercial and industrial installations.

- The COP of the chiller is affected less by the decline of the source temperature. The COP drops by 2.5 percent for each 6°C (10°F) drop in the source temperature.
- The nominal COP of single-stage absorption chillers at 116°C (240°F) is 0.65 to 0.70.
- Therefore, for each ton of refrigeration, a heat input of (12,000 Btu/h)/0.65 = 18,460 Btu/h is required.
- At 88°C (190°F), the COP drops by 12.5 percent and thus the heat input increases by 12.5 percent for the same cooling effect.
- Therefore, the economic aspects must be evaluated carefully before any absorption refrigeration system is considered, especially when the source temperature is below 93°C (200°F).

You will immediately notice from the figure that this system looks very much like the vapor-compression system, except that the compressor has been replaced by a complex absorption mechanism consisting of an absorber, a pump, a generator, a regenerator, a valve, and a rectifier.

Once the pressure of NH_3 is raised by the components in the box (this is the only thing they are set up to do), it is cooled and condensed in the condenser by rejecting heat to the surroundings, is throttled to the evaporator pressure, and absorbs heat from the refrigerated space as it flows through the evaporator.

So, there is nothing new there. Here is what happens in the box:

Geothermal Heat Pump Systems

Ground-source heat pumps represent the most common use of geothermal energy in terms of the number of units installed.

These heat pumps are called geothermal heat pumps as they utilize the heat of the earth. Ground-source heat pumps provide higher values of COP compared to air-source units.

The ground at a few meters depth is at a higher temperature than the ambient air in winter and it is at a lower temperature than the ambient in summer.

These systems use higher ground temperatures in winter for heat absorption (heating mode) and cooler ground temperatures in summer for heat rejection (cooling mode), and this is the reason for higher COPs.

Next, we present an overview of heat pumps, which is followed by the discussion of geothermal or ground-source heat pumps.

Geothermal Heat Pumps

- While temperatures above ground change a lot from day to day and season to season temperatures in the upper 10 feet of the Earth's surface hold nearly constant between 50 and 60 degrees Fahrenheit.
- For most areas, this means that soil temperatures are usually warmer than the air in winter and cooler than the air in summer.
- Geothermal heat pumps use the Earth's constant temperatures to heat and cool buildings.
- They transfer heat from the ground (or water) into buildings in winter and reverse the process in the summer.

- Heat at ambient temperature from *near-surface* ground (to depths of usually about 3 m), or from rivers and lakes, is input to electrical-powered heat pumps, which provide heat to buildings at increased temperature.
- The systems are often called ‘geothermal’, although the input heat arises from soil heated by sunshine and ambient air.
- Note that ground at depths of more than about 2 m has nearly constant temperature through the year.
- In reverse mode extracting heat from buildings, the same heat pumps may be used for cooling, i.e. they function as refrigerators.
- This technology is available worldwide and is by far the most rapidly growing ‘geothermal’ application.
- The relevant technology is outlined in §14.5.

- According to the U.S. Environmental Protection Agency (EPA), geothermal heat pumps are the most energy-efficient, environmentally clean, and cost-effective systems for temperature control.
- Although, most homes still use traditional furnaces and air conditioners, geothermal heat pumps are becoming more popular. In recent years, the U.S.
- Department of Energy along with the EPA have partnered with industry to promote the use of geothermal heat pumps.

- Air-conditioning systems based on absorption refrigeration, called *absorption chillers,* perform best when the heat source can supply heat at a high temperature with little temperature drop.
- The absorption chillers are typically rated at an input temperature of 116°C (240°F).
- The chillers perform at lower temperatures, but their cooling capacity decreases sharply with decreasing source temperature, about 12.5 percent for each 6°C (10°F) drop in the source temperature.
- For example, the capacity goes down to 50 percent when the supply water temperature drops to 93°C (200°F).
- In that case, one needs to double the size (and thus the cost) of the chiller to achieve the same cooling.

Heat Pump Systems

Heat pumps are generally more expensive to purchase and install than other heating systems, but they save money in the long run in some areas because they lower the heating bills.

Despite their relatively higher initial costs, the popularity of heat pumps is increasing.

The COP of a heat pump in the heating mode is defined as the heating effect divided by the work input

$$\mathrm{COP} = \frac{Q_{\mathrm{heating}}}{W_{\mathrm{in}}}$$

The COP of a heat pump in the cooling mode (called air conditioner) is defined as the cooling effect divided by the work input

$$\mathrm{COP} = \frac{Q_{\mathrm{cooling}}}{W_{\mathrm{in}}}$$

- The most common energy source for heat pumps is atmospheric air (air-to-air systems), although water and soil are also used.
- The major problem with air-source systems is *frosting,* which occurs in humid climates when the temperature falls below 2 to 5°C.
- The frost accumulation on the evaporator coils is highly undesirable since it seriously disrupts heat transfer.
- The coils can be defrosted, however, by reversing the heat pump cycle (running it as an air conditioner).
- This results in a reduction in the efficiency of the system. Water-source systems usually use well water from depths of up to 80 m in the temperature range of 5 to 18°C, and they do not have a frosting problem.
- They typically have higher COPs but are more complex and require easy access to a large body of water such as underground water.
- Ground-source systems are also rather involved since they require long tubing placed deep in the ground where the soil temperature is relatively constant.
- The COP of heat pumps usually ranges between 1.5 and 4, depending on the particular system used and the temperature of the source.
- Recently developed heat pumps that use variable-speed electric motor drives are at least twice as energy efficient as their predecessors.

Both the capacity and the efficiency of a heat pump fall significantly at low temperatures.

Therefore, most air-source heat pumps require a supplementary heating system such as electric resistance heaters or an oil or gas furnace.

Since water and soil temperatures do not fluctuate much, supplementary heating may not be required for water-source or ground-source systems.

However, the heat pump system must be large enough to meet the maximum heating load.

Heat pumps and air conditioners have the same mechanical components.

Therefore, it is not economical to have two separate systems to meet the heating and cooling requirements of a building.

One system can be used as a heat pump in winter and an air conditioner in summer, and it is just referred to as a heat pump.

This is accomplished by adding a reversing valve to the cycle, as shown in Fig. 7-9.

As a result of this modification, the condenser of the heat pump (located indoors) functions as the evaporator of the air conditioner in summer.

Also, the evaporator of the heat pump (located outdoors) serves as the condenser of the air conditioner. This feature increases the competitiveness of the heat pump.

Such dual-purpose units are commonly used in apartment units and motels.

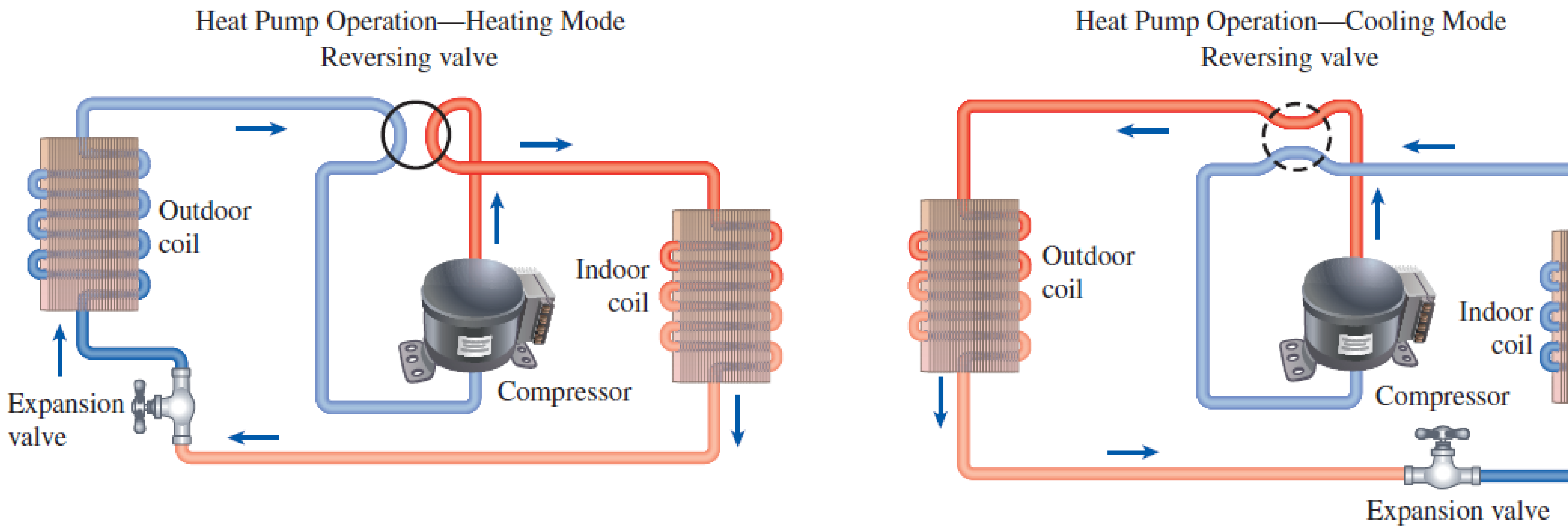


Fig. 7 A heat pump can be used to heat a house in winter and to cool it in summer

- Heat pumps are most competitive in areas that have a large cooling load during the cooling season and a relatively small heating load during the heating season, such as in the southern parts of the United States.
- In these areas, the heat pump can meet the entire cooling and heating needs of residential or commercial buildings.
- The heat pump is least competitive in areas where the heating load is very large and the cooling load is small, such as in the northern parts of the United States.

Ground-source heat pump systems

Ground-source heat pump systems are also known as *geothermal heat pumps* as they use the heat of earth in its operation.

They have higher COPs than ordinary air-source heat pumps because ground is at a higher temperature than ambient air in winter (heating mode) and at a lower temperature than ambient air in summer (cooling mode).

Table 7-2 shows how the ground temperature changes with depth in different seasons of the year.

The ground temperature increases with depth in winter (see January data) and decreases with depth in summer (see July data).

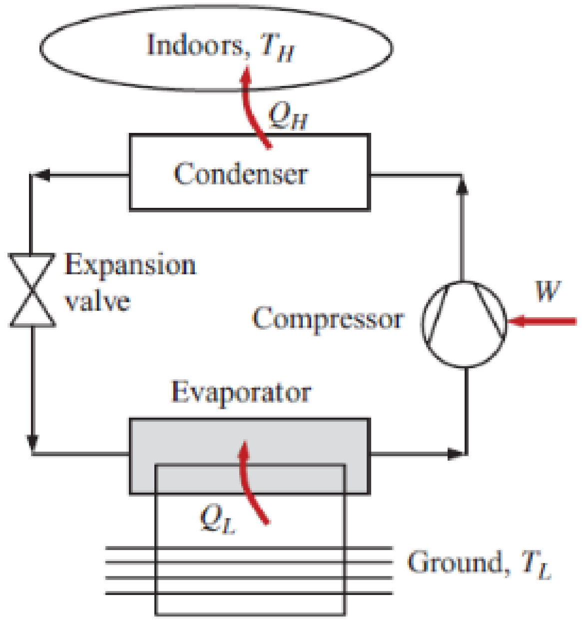
It is clear that the ground temperature is more stable than air temperature throughout the year.

It is essentially constant below a certain depth of about 10 m. It starts increasing again at a depth greater than about 60 m.

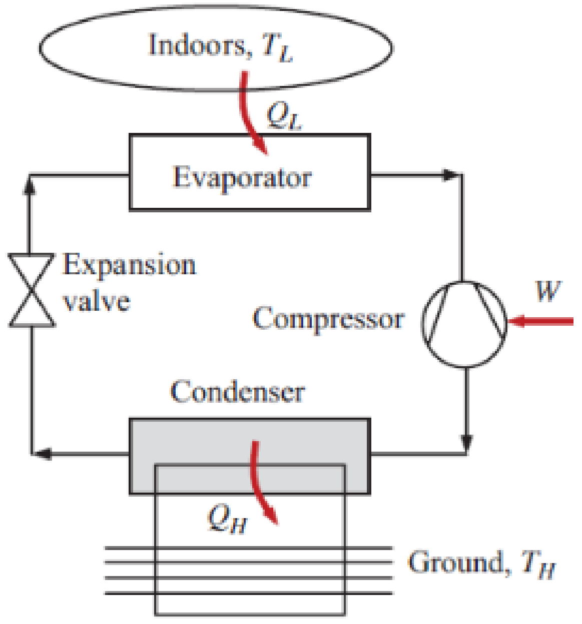
Variation of Ground Temperature with Depth in a Location for Different Months of the Year
(Schöffengrund- Schwalbach GSHP Test Plant, 1985−89)

	Ground Temperature, °C			
Depth, m	January	April	July	October
2	6	5	15	14
4	8	5	10	12
6	9	6	8	11
8	9	7	8	9
10	10	8	8	9
12	10	9	9	9
14	10	9	9	9
16	9	9	9	9

- In the heating mode operation of a ground-source heat pump, heat is absorbed from the ground at *TL* which is higher than the temperature of the ambient air.
- Heat is supplied to the indoors at *TH* by the heat pump.
- In the cooling mode, heat is absorbed from the indoors at *TL* and rejected to the ground at *TH* which is at a lower temperature compared to the temperature of the ambient air.



(a) Winter operation



(b) Summer operation

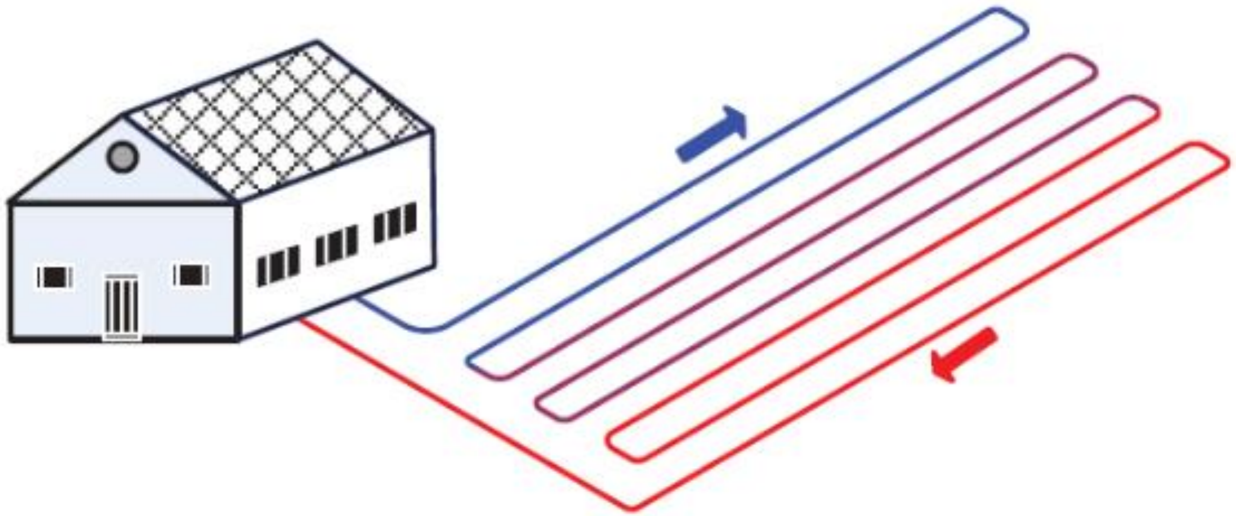
The maximum COP of the ground-source heat pump is 67 percent greater than that of the air-source heat pump.

Even though actual COP values are significantly lower than the calculated COPs above, the comparison is still applicable in actual cases.

Despite their much higher initial cost as compared to air-source units, ground-source heat pump units are preferred due to their higher COPs.

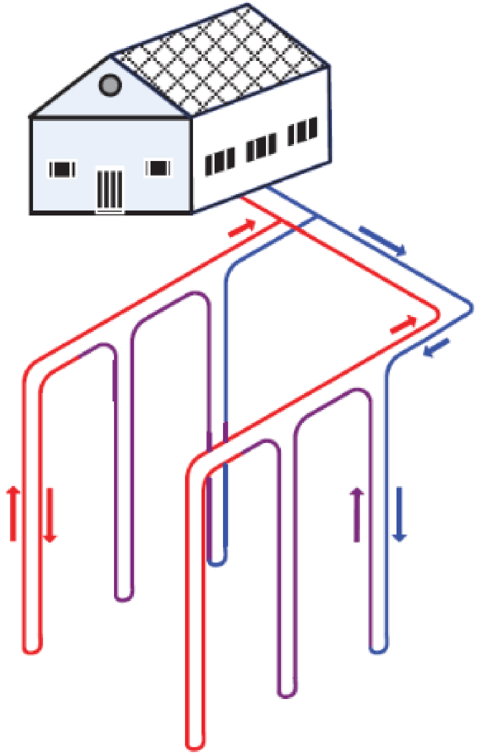
Actual COP of ground-source heat pumps ranges between about 3 and 5 while actual COP of air-source heat pumps ranges between about 1.5 and 3.

Ground-source heat pumps can be classified according to the configuration of piping and heat source.



Schematic of horizontal loop ground-source heat pump

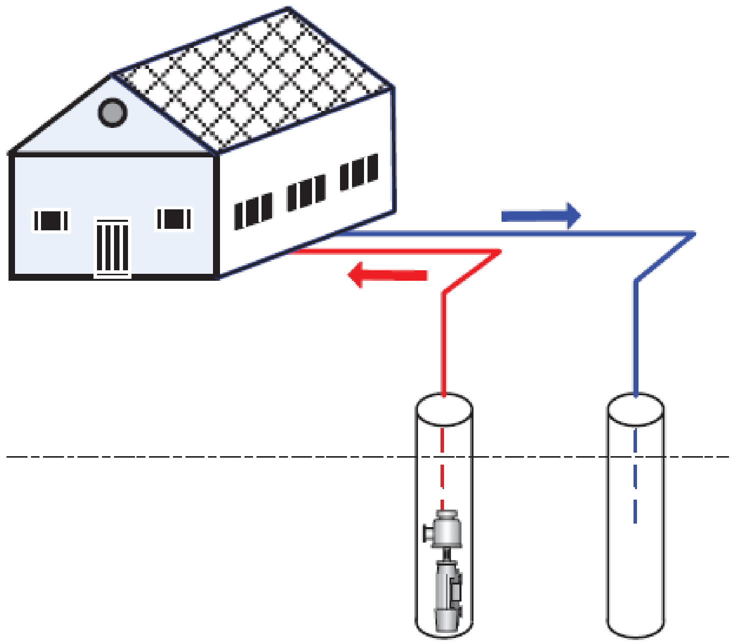
It involves horizontal underground piping in 1.2 to 2.0 m depths. It is suitable when there is sufficient area for pipe burial such as the relatively large backyard of a house.



Schematic of vertical loop ground-source heat pump

It is also called borehole loop heat pump. Vertical piping in 10 to 250 m depths is used. It can be installed everywhere as a small field allowing vertical drilling is sufficient.

Ground water wells heat pump



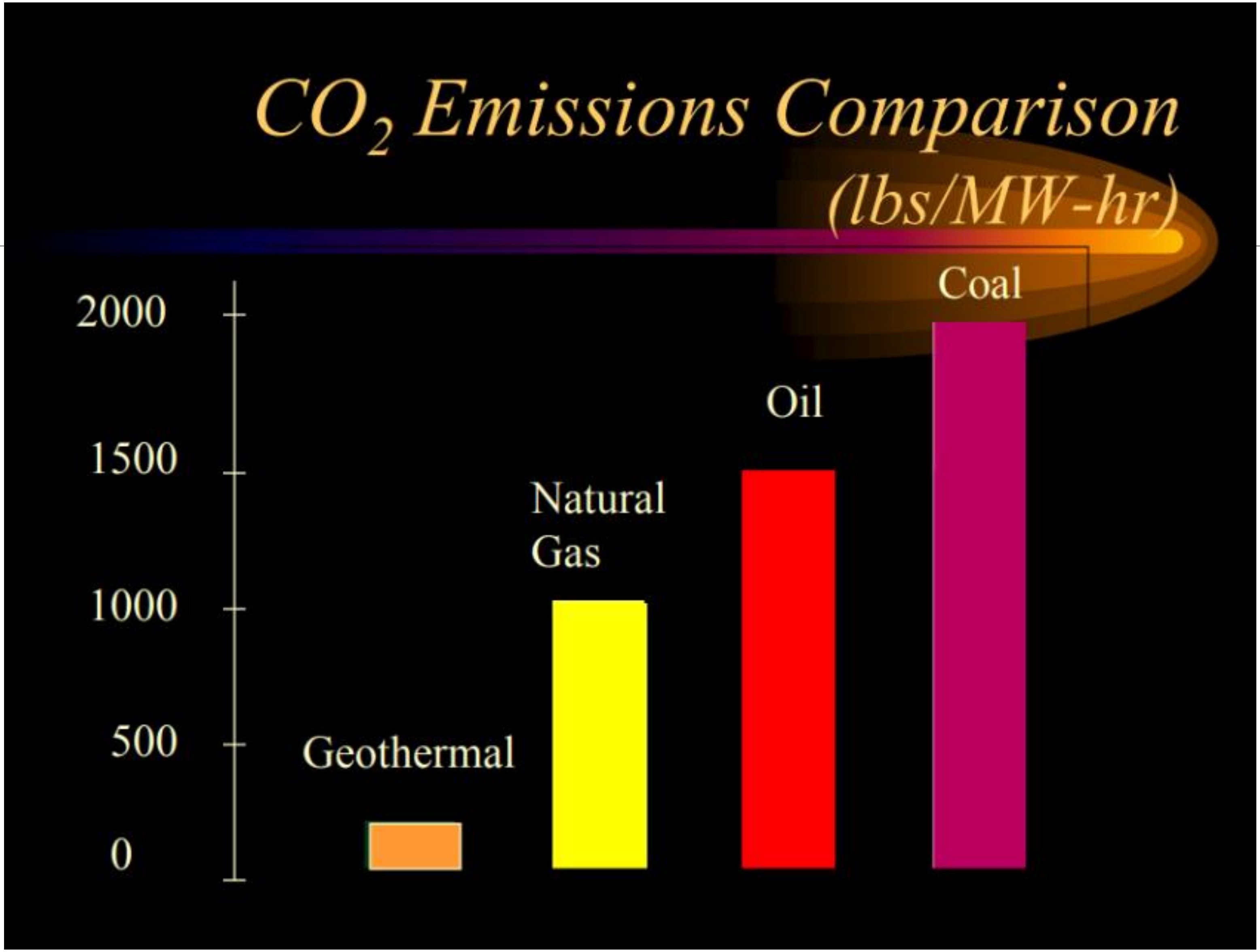
Schematic of groundwater wells ground-source heat pump

Underground water is circulated through the evaporator of the heat pump unit.
Heat is transferred from the water to the refrigerant flowing in the evaporator.
The cooler water leaving the evaporator is dumped back to the ground at a different location.
The water well is located in 5 to 50 m depths.
These systems can provide high capacities with relatively low cost.
The temperature of water is relatively high as compared to horizontal loop and borehole heat pumps.
An aquifer is needed for sufficient water yield.
The wells need to be maintained and water quality should be monitored.

Benefits of geothermal power

Provides clean and safe energy using little land

- Is renewable and sustainable
- Generates continuous, reliable “baseload” power
- Conserves fossil fuels and contributes to diversity in energy sources
- Avoids importing and benefits local economies
- Offers modular, incremental development and village power to remote sites


CO2 Emissions Comparison
(lbs/MW-hr)
2000
1500
1000
500
0
Geothermal
Natural Gas
Oil
Coal

Geothermal Energy and the Environment

- The environmental impact of geothermal energy depends on how it is being used.
- Direct use and heating applications have almost no negative impact on the environment.
- Geothermal power plants do not burn fuel to generate electricity, so their emission levels are very low.
  - They release less than 1 percent of the carbon dioxide emissions of a fossil fuel plant.
  - Geothermal plants use scrubber systems to clean the air of hydrogen sulfide that is naturally found in the steam and hot water.
  - Geothermal plants emit 97 percent less acid rain - causing sulfur compounds than are emitted by fossil fuel plants.
  - After the steam and water from a geothermal reservoir have been used, they are injected back into the earth

References

Mehmet Kanoğlu, Yunus A. Çengel, John M. Cimbala. 2020. Fundamentals and Applications of Renewable Energy. McGraw-Hill Education.