



National Research Council of Italy

Institute of Geosciences and Earth Resources

# Geothermal energy generalities

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The Abdus Salam  
International Centre  
for Theoretical Physics

**International School on Geothermal Development  
Trieste, 7-12 December 2015**

# Geothermal Energy

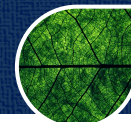


Status and perspectives 



What is the source of geothermal energy? What part is used?

# What is **Geothermal Energy**



# WHAT is Geothermal energy

## Geothermal Energy

From Greek *gêo* (earth) e  
*thermòs* (heat)



Heat inside the Earth

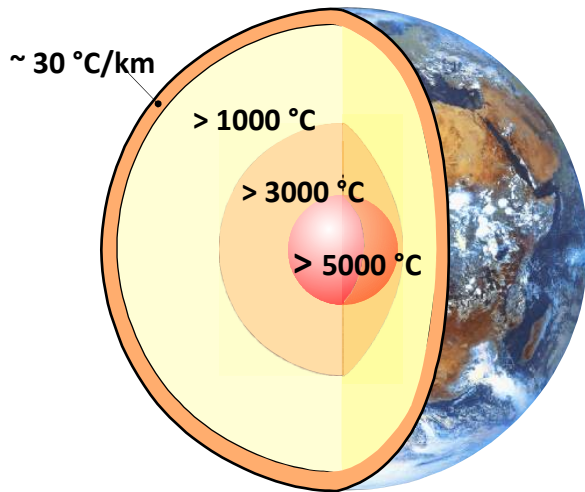


The basis of geothermal energy is the immense heat content of the earth's interior: the Earth is slowly cooling down. Since billions of years the heat in the Earth Crust is constantly supplied by the decay of natural radioactive isotopes or the cooling of hot, shallow magmatic bodies.

The resource is vast and ubiquitous and has a corresponding **large potential for utilization.**

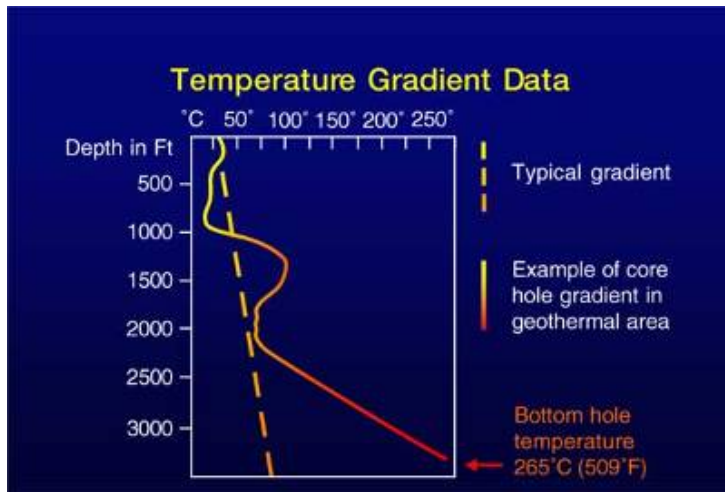


# WHAT is Geothermal energy



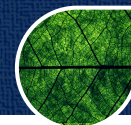
The resource is vast and ubiquitous and has a corresponding **large potential for utilization**.

However, only a fraction can be used. By “geothermal energy” we will mean here the part that can be recovered and exploited by man.



# WHAT is Geothermal energy

The temperature increase with depth, as well as volcanoes, geysers, hot springs etc., are in a sense the visible or tangible expression of the heat in the interior of the Earth, but this heat also engenders other phenomena that are less discernable by man, but of such magnitude that the Earth has been compared to an immense "thermal engine".



# WHAT is Geothermal energy

The Earth's **heat flow** at the surface is the amount of heat that is released into space from the interior through a unit area in a unit of time. It is measured in watt per square meter ( $\text{Wm}^{-2}$ )

The heat flow is the product of the geothermal gradient (increase of temperature with depth) and the thermal conductivity of rocks. On average, heat flow is 40-90  $\text{mW/m}^2$

The total global output is over  $4 \times 10^{13} \text{W}$ , four times more than the present world energy consumption which is  $10^{13} \text{W}$ .

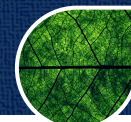
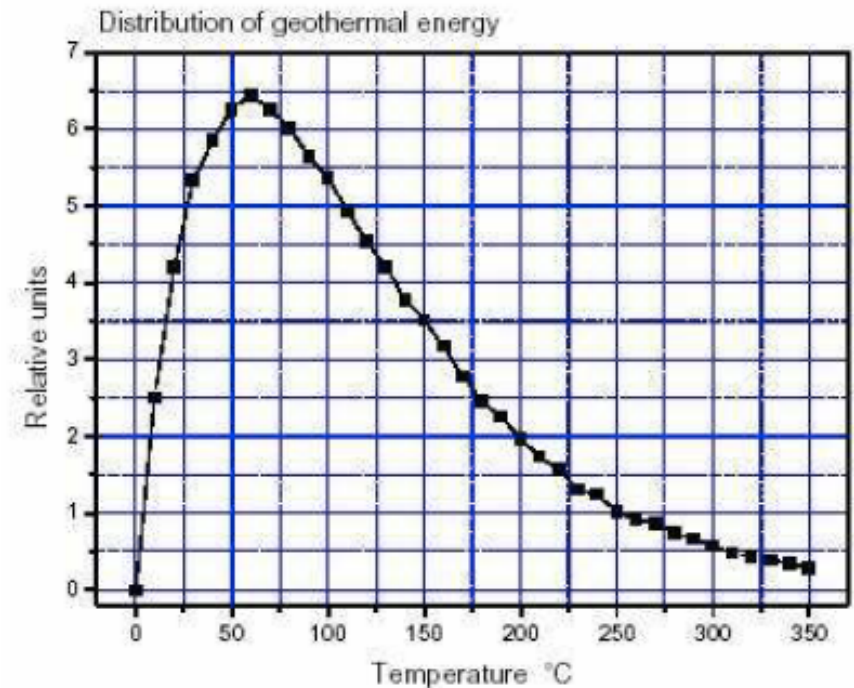
The thermal energy of the Earth is therefore immense, but only a fraction can be utilized by man.



# WHAT is Geothermal energy

Only a fraction can be utilized by man, because **this heat is available at a low average temperature.**

So far our utilization of this energy has been mostly limited to areas in which geological conditions allow a carrier (water in the liquid phase or steam) to "transfer" the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources.





# WHAT is Geothermal energy

Two forms of heat transfer occur within the Earth:

## Conduction

- transfer of random kinetic energy between molecules without transfer of material. Moving molecules strike neighbouring molecules, causing them to vibrate faster and thus transfer heat energy.
- Primary heat transfer mode in **solids**.

## Convection

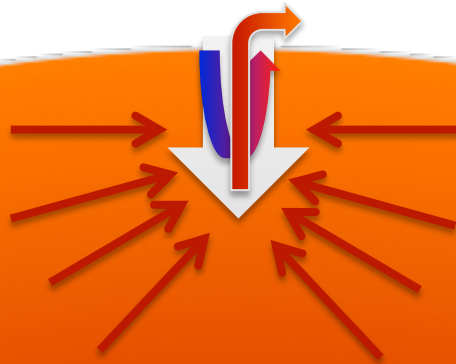
- Movement of hot fluid (liquid or gas) from one place to another. Because motion of material occurs, it is more efficient than conduction.
- Common heat transfer process in **liquids** or **gases**



Figure 1-1 part 1  
Understanding Earth, Fifth Edition  
© 2011 by W. H. Freeman and Company



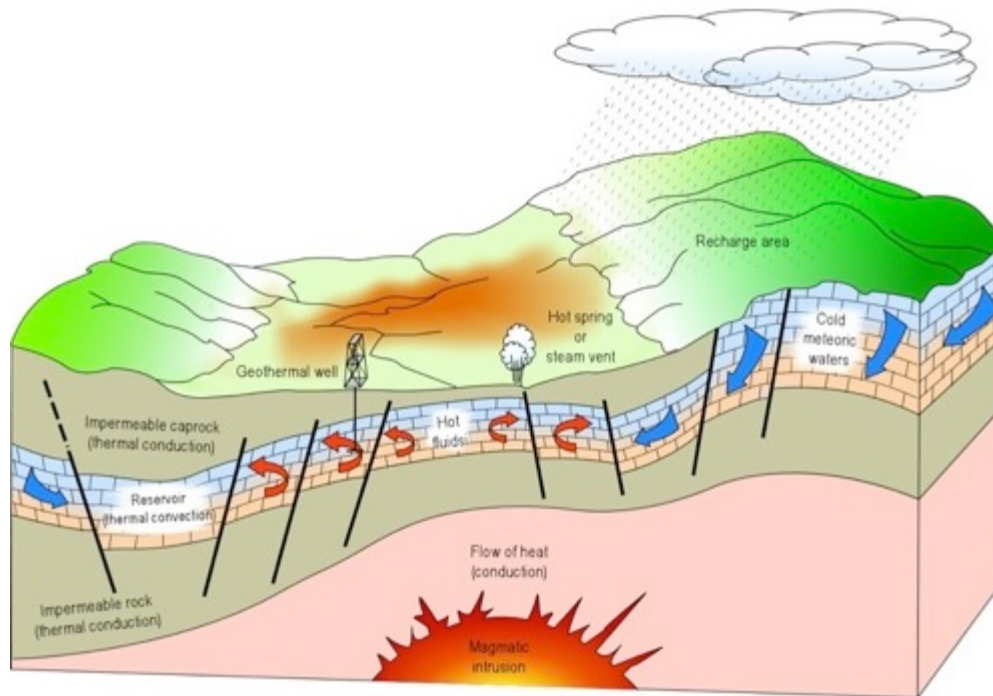
# WHAT is Geothermal energy



# WHAT is Geothermal energy

A heat source alone is not enough for creating a geothermal resource.

A **geothermal system** can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface".



# WHAT is Geothermal energy

Elements of a hydrothermal geothermal system:

a **heat source** at relatively shallow depth

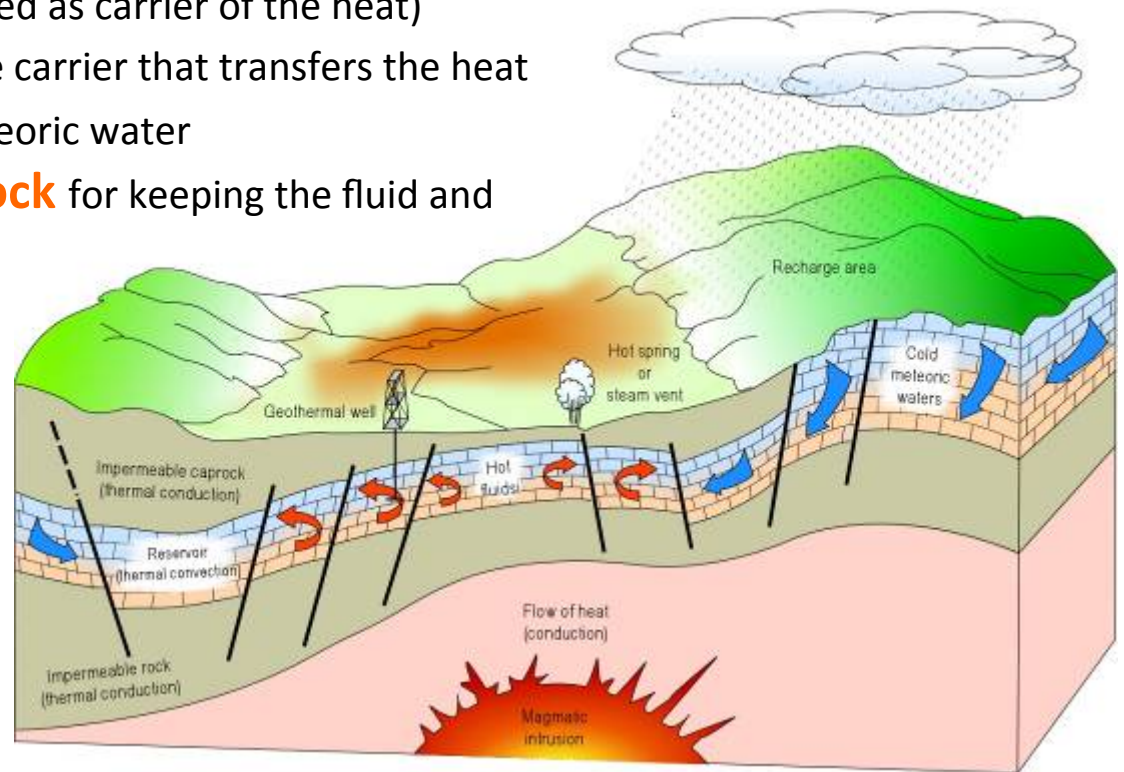
a **reservoir** (a porous and fractured rock system, where there are fluids (water or steam), which can be used as carrier of the heat)

enough **fluid** which is the carrier that transfers the heat

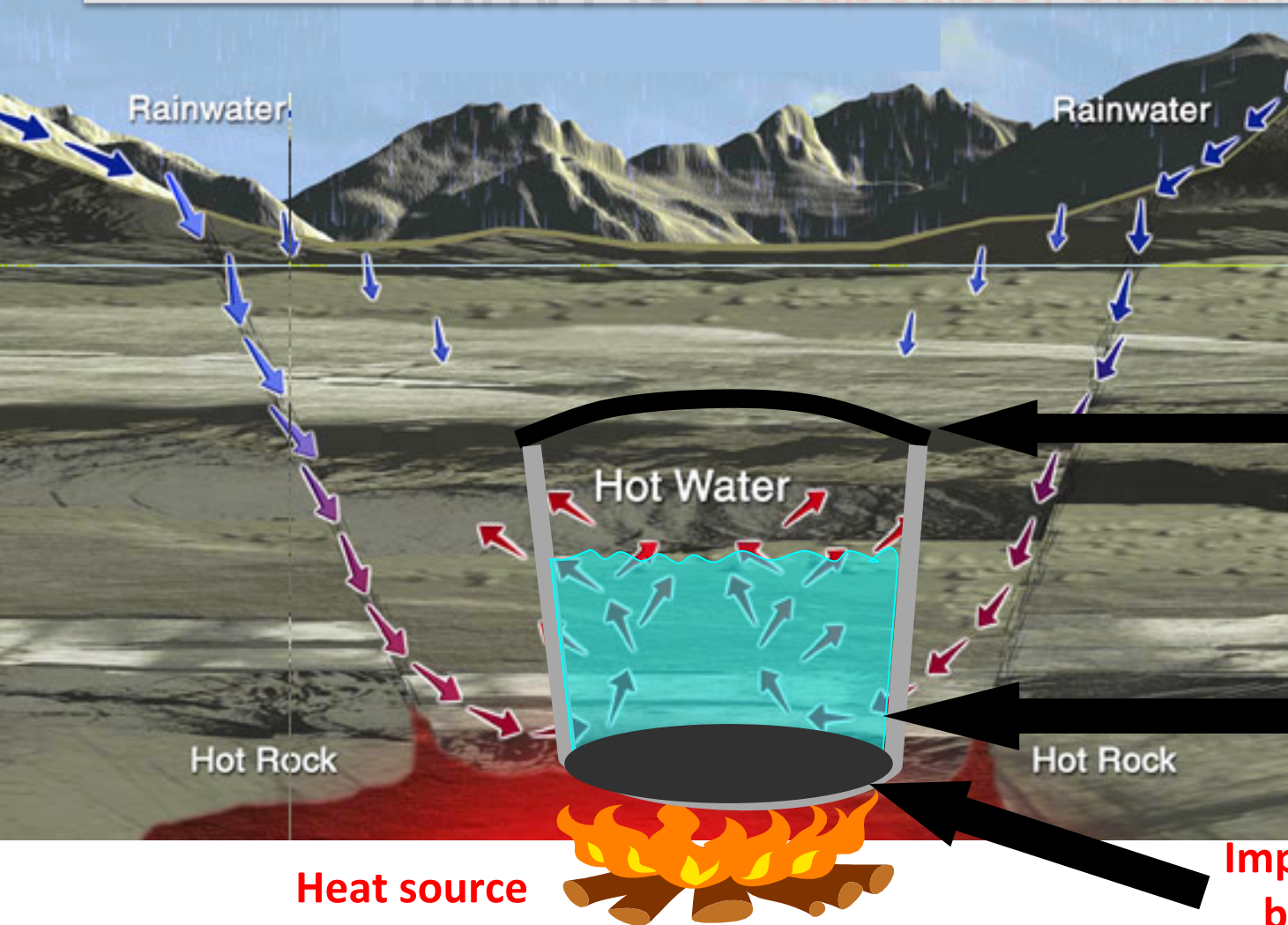
a **recharge area** for meteoric water

an **impermeable caprock** for keeping the fluid and the heat in a confined space

In a geothermal system the meteoric waters are trapped in the reservoir, are heated and a natural convective circulation is activated, driving the heat up to the surface.



# WHAT is Geothermal energy



**Impermeable coverage**

**Reservoir: fluid inside a porous and permeable rock**

**Impermeable basement**

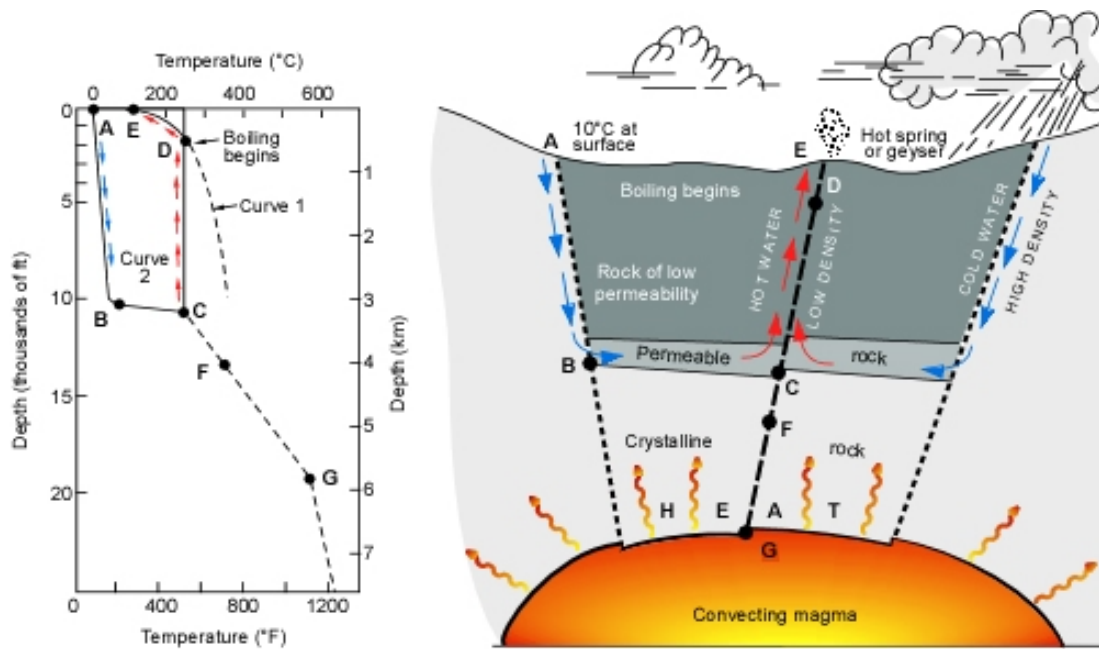
**Heat source**



# WHAT is Geothermal energy

The mechanism underlying geothermal systems is by and large governed by **fluid convection**.

Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field.

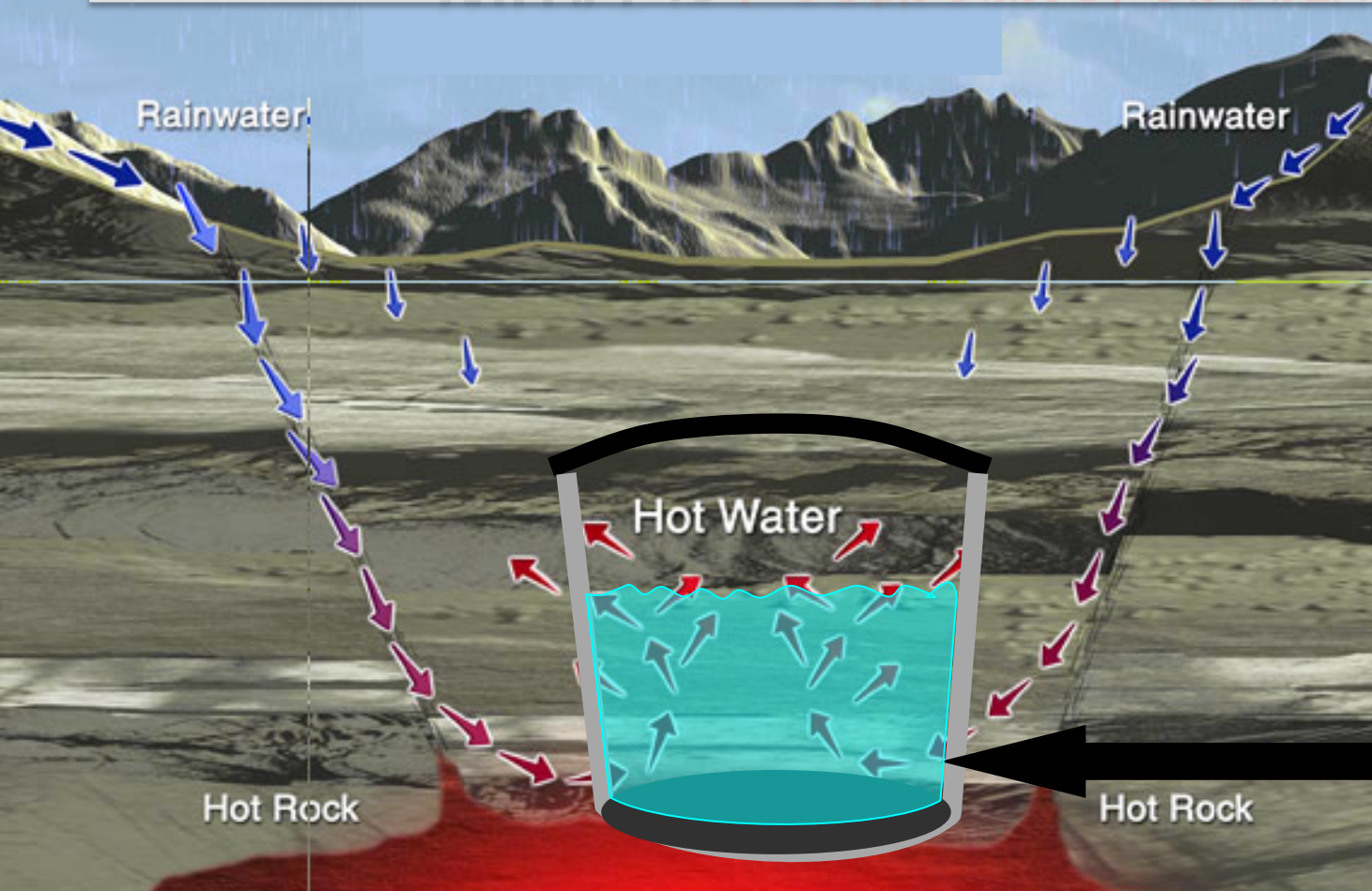


*Model of a geothermal system. Curve 1 is the reference curve for the boiling point of pure water. Curve 2 shows the temperature profile along a typical circulation route from recharge at point A to discharge at point E*

*(From White, 1973).*

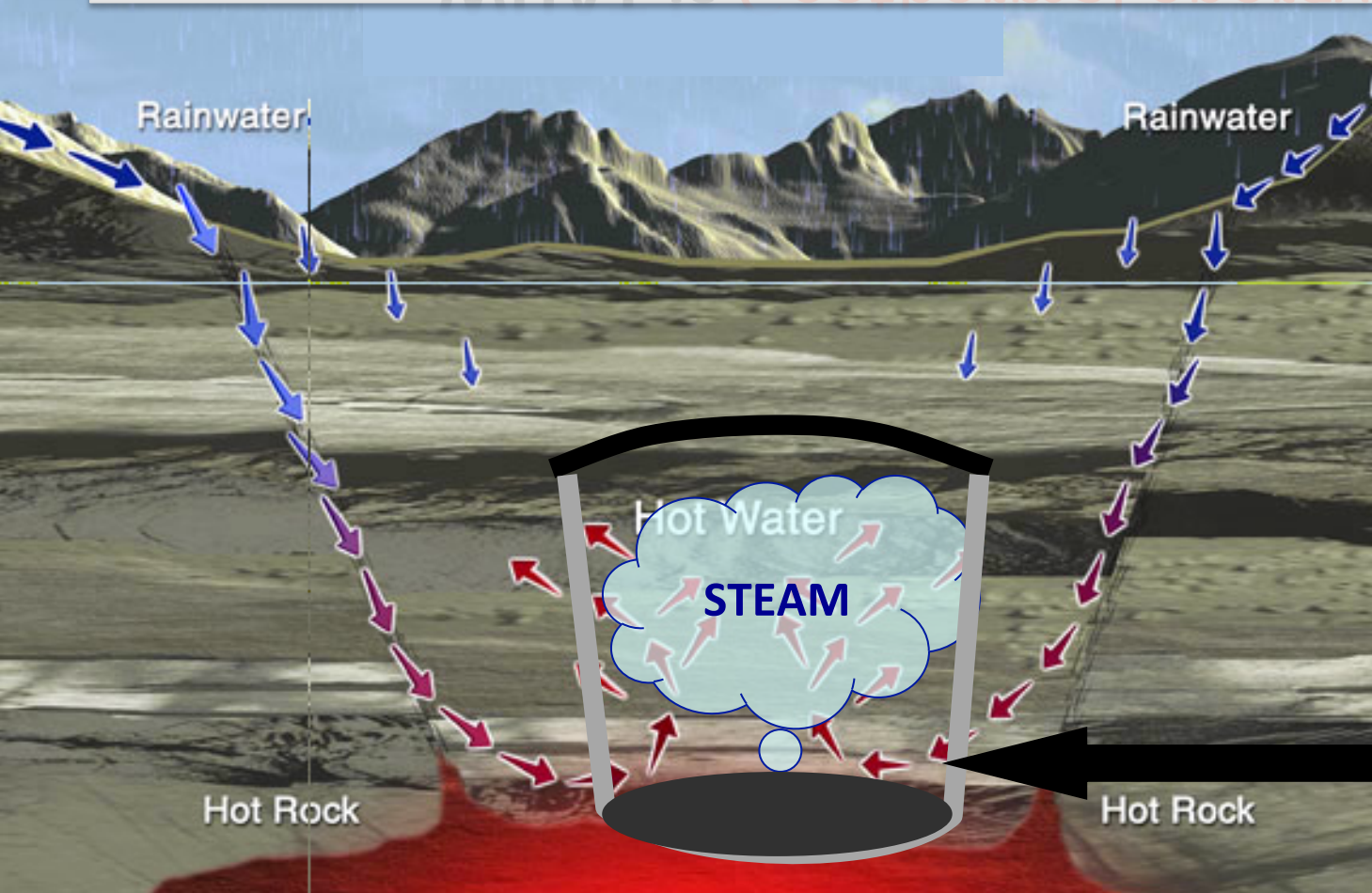


# WHAT is Geothermal energy



Hydrostatic pressure in the reservoir:  
**Water dominated systems.**

# WHAT is Geothermal energy



In some situations, the pressure is relatively low and the temperature is regulated by the steam phase:

**Steam dominated systems**



# WHAT is Geothermal energy

When hot water and steam reach the surface, they can form fumaroles, hot springs, mud pots and other interesting phenomena.



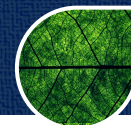
# WHAT is Geothermal energy



Geyser - Iceland



Boiling spring - USA



# WHAT is Geothermal energy

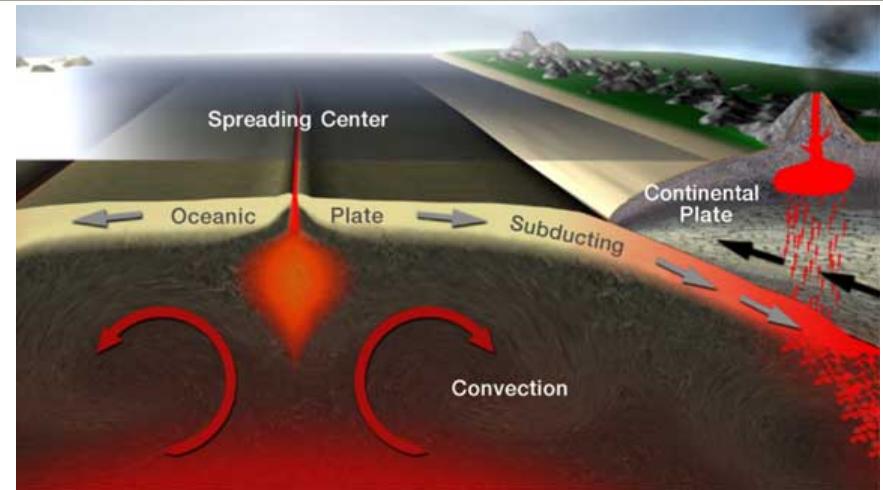
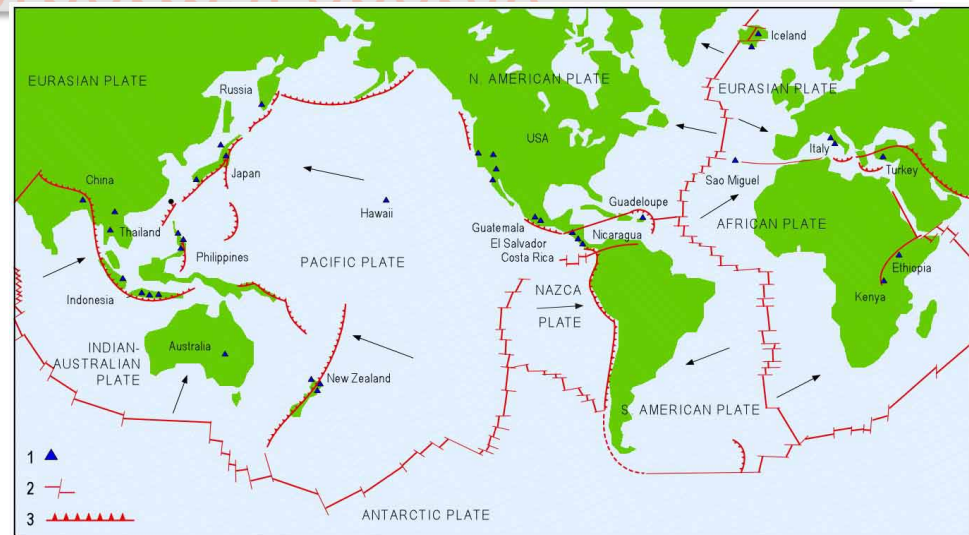


El Tatio- Chile

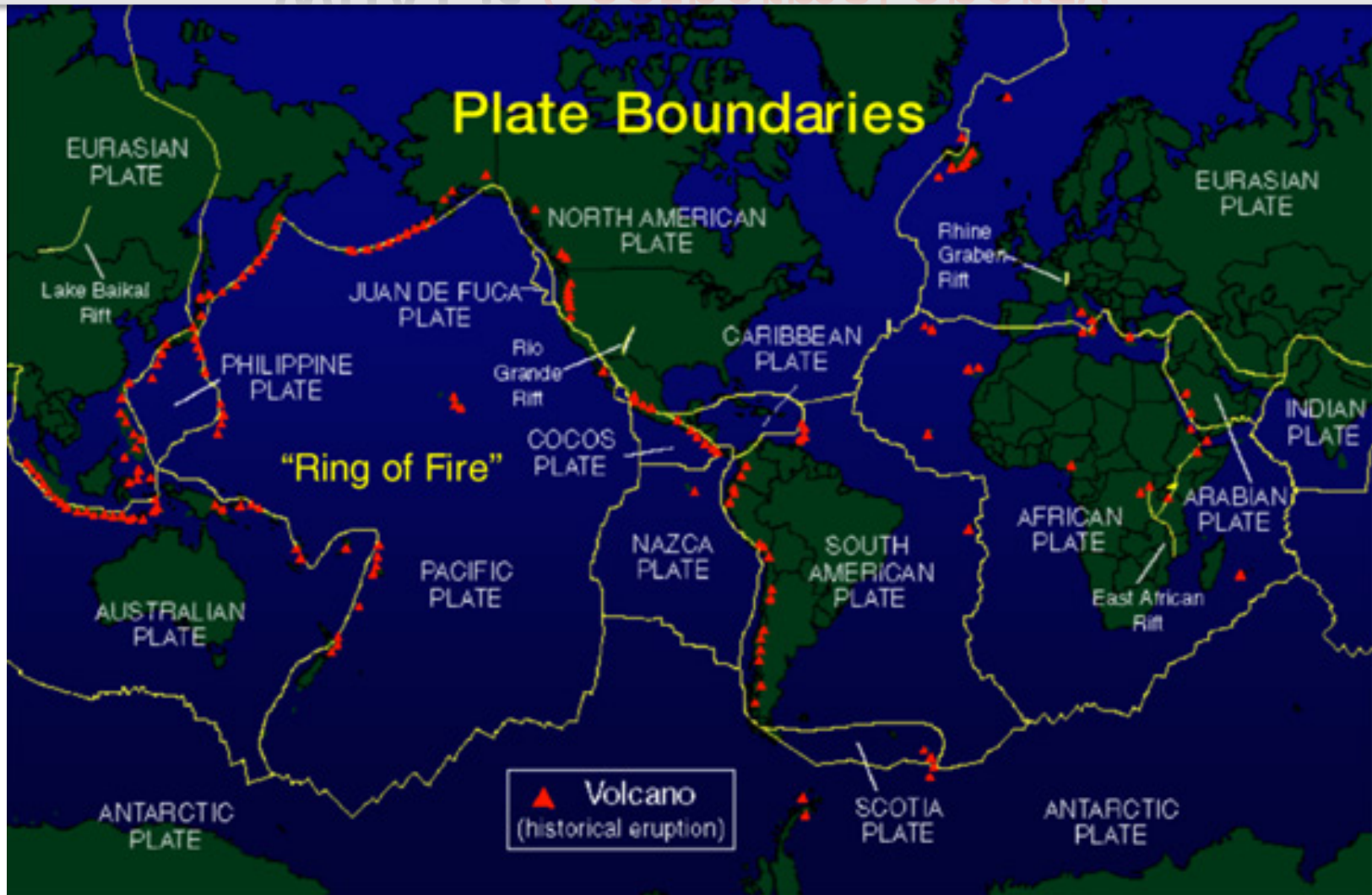
# WHAT is Geothermal energy

Geothermal resources are generally confined to areas of the Earth's crust where heat flow higher than in surrounding areas heats the water contained in permeable rocks (reservoirs) at depth.

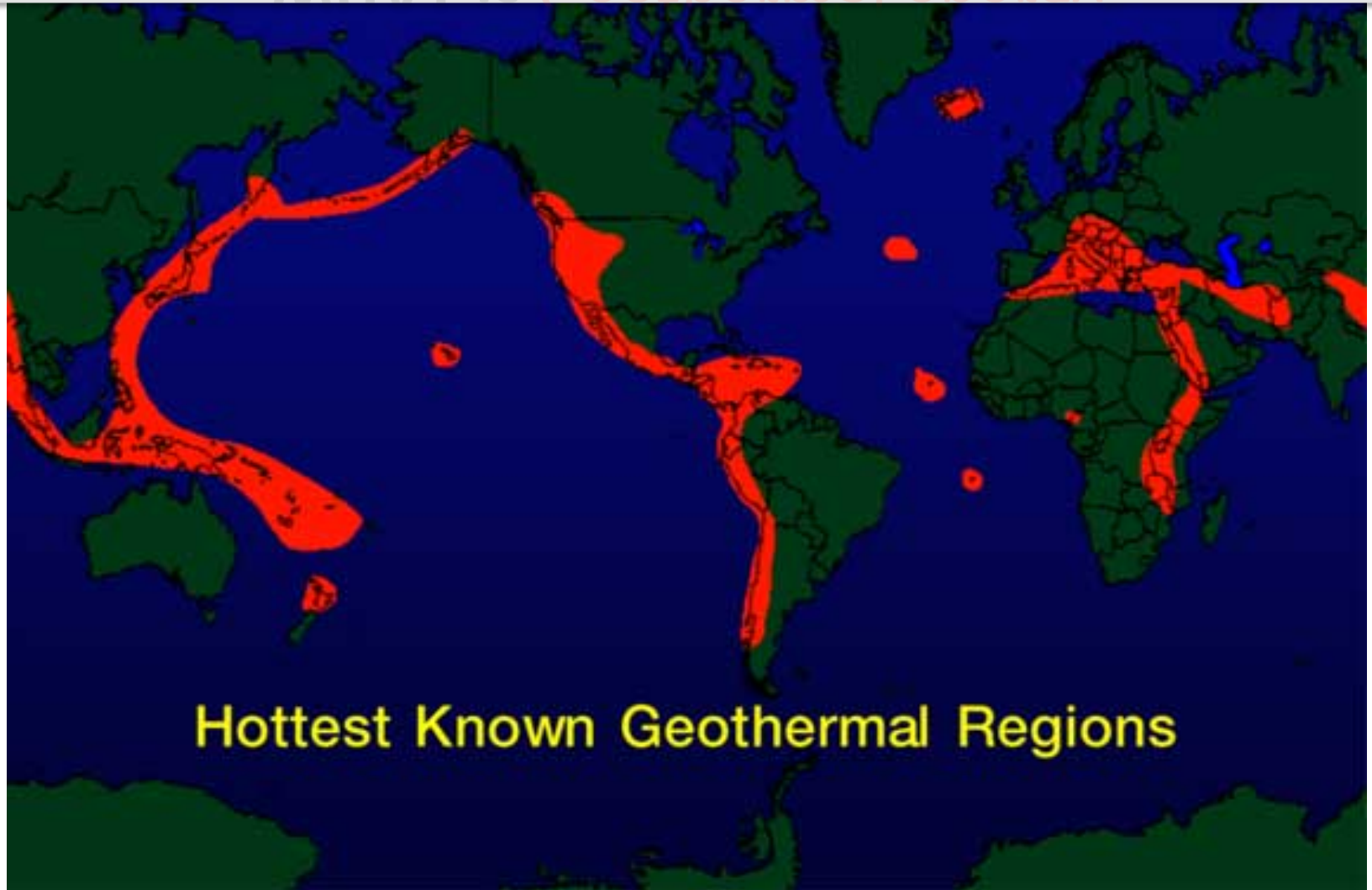
The resources with the highest energy potential are mainly concentrated on the boundaries between plates where geothermal activity frequently exists.



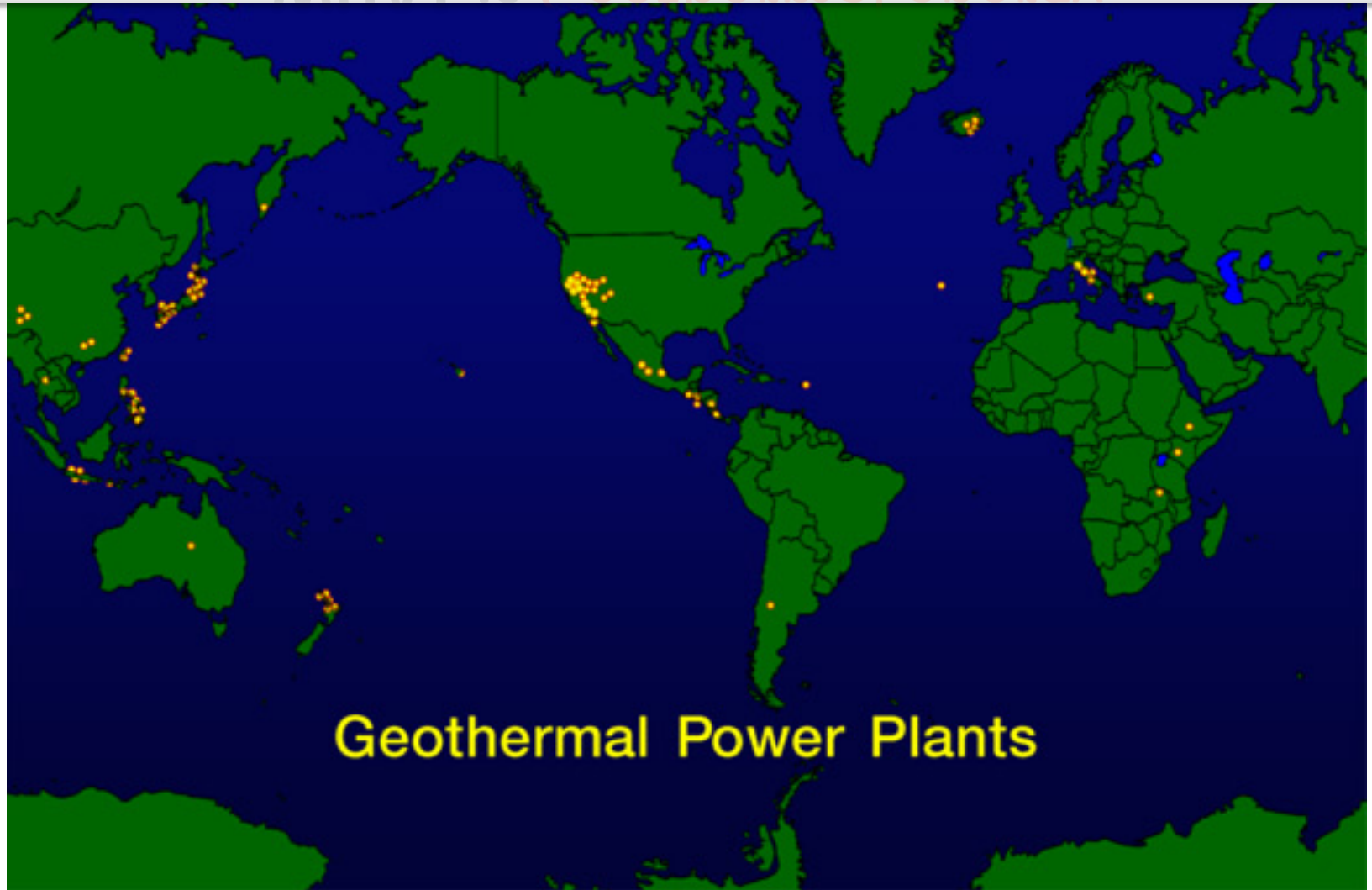
# WHAT is Geothermal energy



# WHAT is Geothermal energy



# WHAT is Geothermal energy



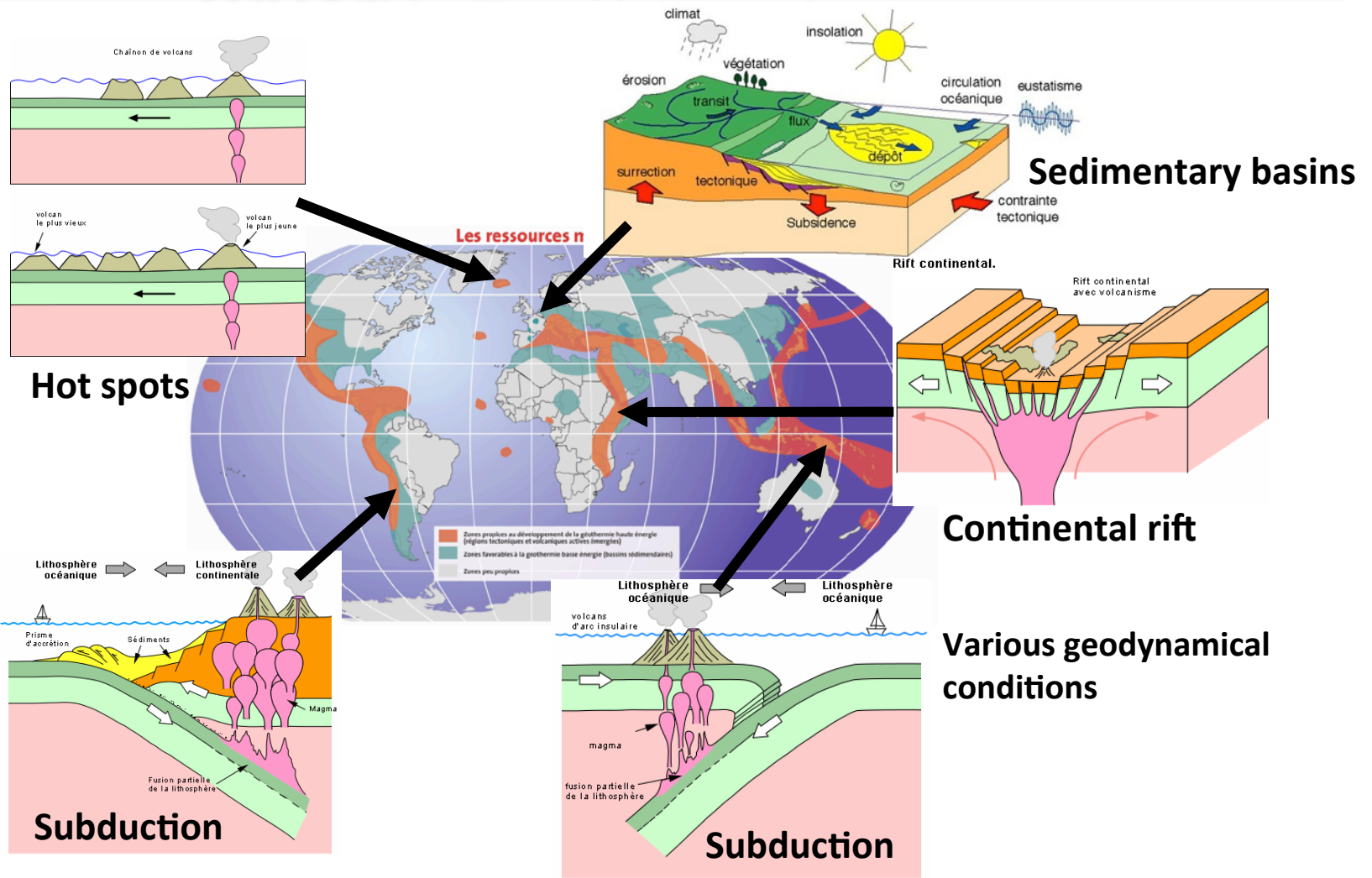
Geothermal Power Plants



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# WHAT is Geothermal energy





The geological setting where a geothermal reservoir can be found varies widely. The largest geothermal fields currently under exploitation occur in rocks that range from limestone to shale, volcanic and metamorphic rocks.

Specific lithology does *not* define geothermal reservoirs

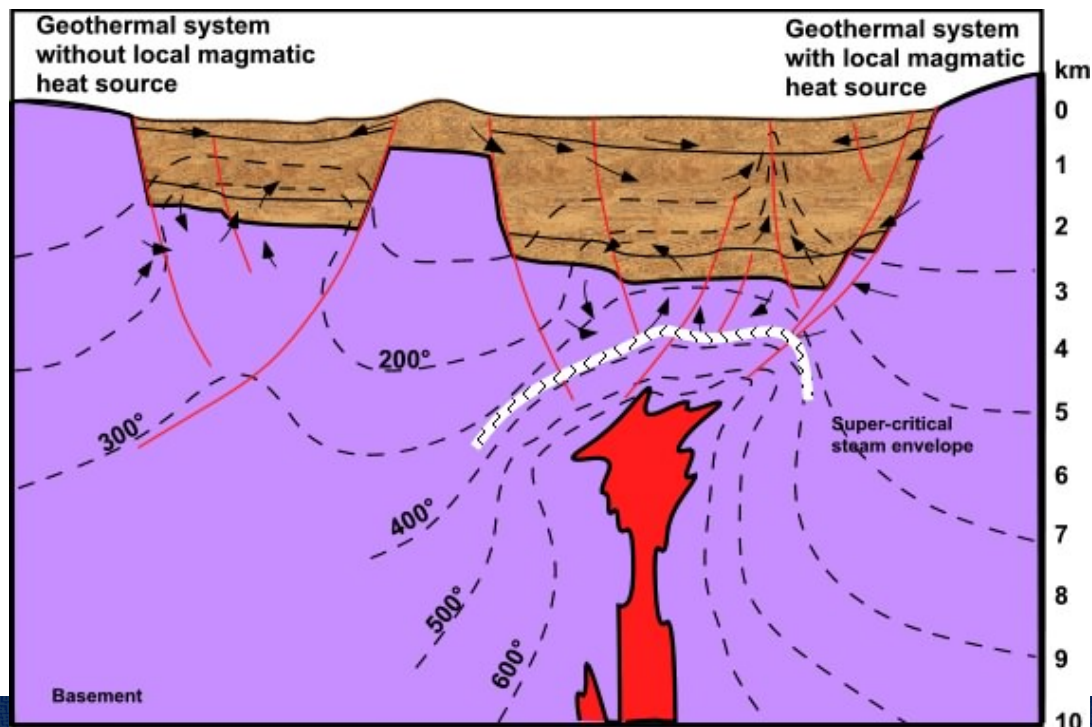
Volcanic rocks are the most common single rock type in which reservoirs occur.



High heat flow conditions ➡ rift zones, subduction zones and mantle plumes.  
Thick blankets of thermally insulating sediment covering a basement rock that has a relatively normal heat flow ➡ lower grade

Other sources of thermal anomaly:

- Large granitic rocks rich in radioisotopes
- Very rapid uplift of meteoric water heated by normal gradient



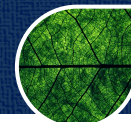
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Heat? Power? Depending on what?

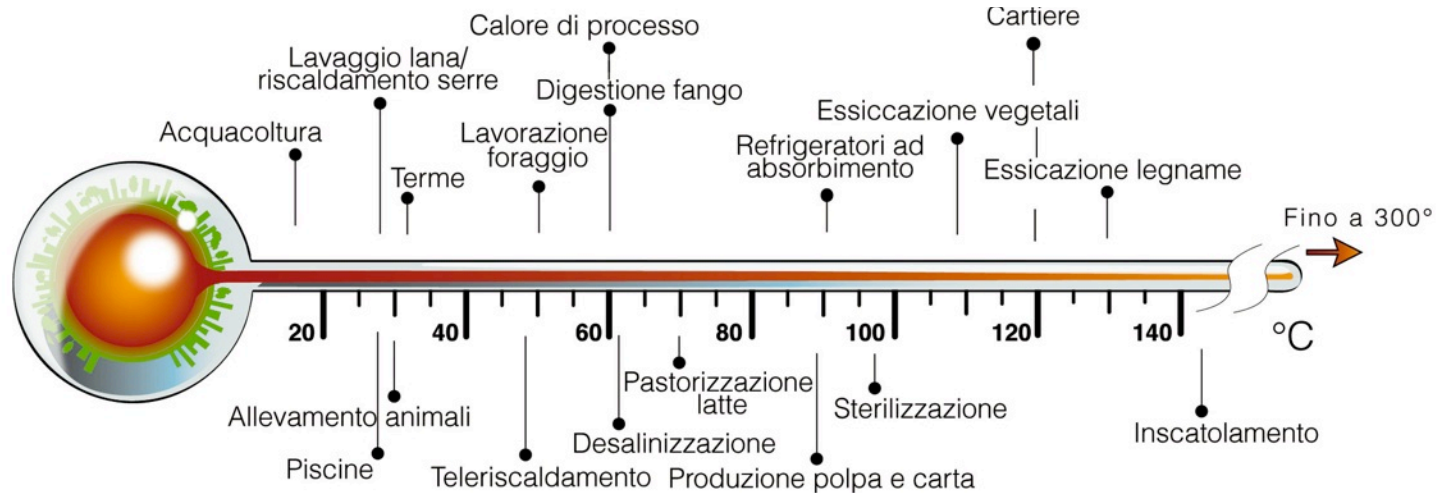
# How **Geothermal Energy** is used



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# How Geothermal Energy is used



## Heat pump systems for Space heating and cooling

CLIMATIZZAZIONE  
Pompe di Calore Geotermiche

## Power production

Ciclo binario

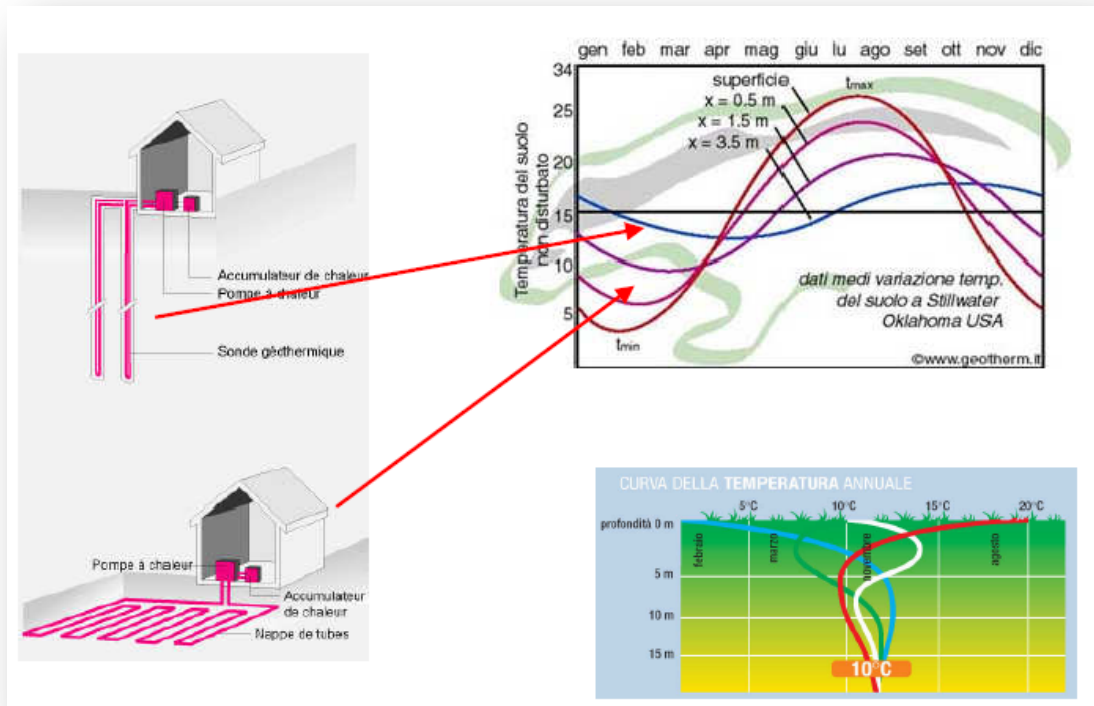
Vapore

Warm and hot fluids can be extracted from the underground in a wide range of temperature and discharge rate, and used **directly for their heat content or to produce electric power**. Even the modest temperatures found at shallower depths can be used to extract or store heat by means of ground source heat pumps, that are nowadays a widespread application for geothermal energy.

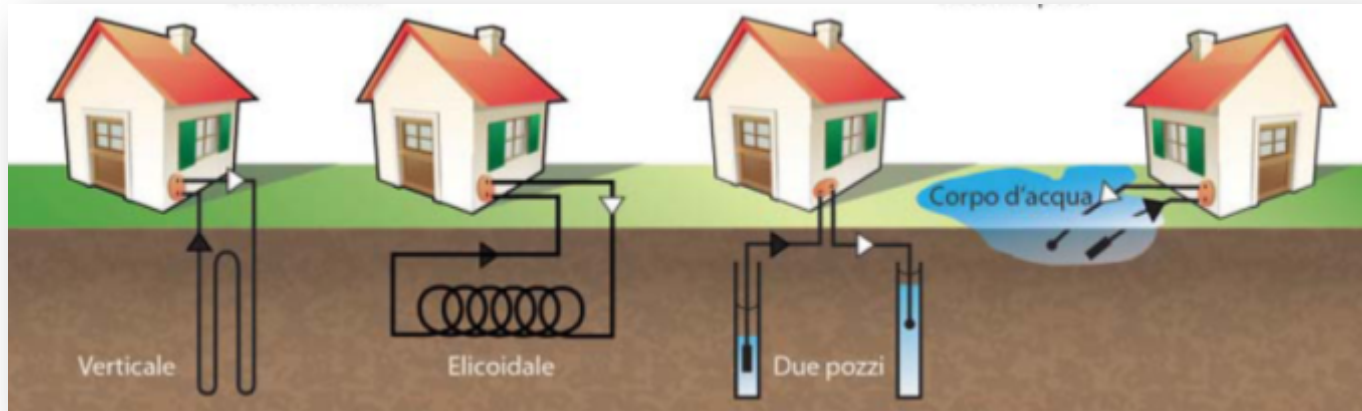


# How Geothermal Energy is used

**Geothermal heat pump (GHP) or Ground Source Heat Pump (GSHP)** is a form for direct use of geothermal energy based on the relatively constant ground or groundwater temperature in the range of 4°C to 30°C available anywhere in the world, to provide space heating, cooling and domestic hot water for homes, schools, factories, public buildings and commercial buildings.



# How Geothermal Energy is used



## Closed loop systems

A ground-coupled systems where a plastic pipe is placed in the ground, either horizontally at 1-2 m depth or vertically in a borehole down to 50-250 m depth. A water-antifreeze solution is circulated through the pipe collecting heat from the ground in the winter and optionally rejecting heat to the ground in the summer.

## Open loop systems

It uses groundwater or lake water as a heat source in a heat exchanger and then discharges it into another well, a stream or lake or even on the ground.



# How Geothermal Energy is used

## Closed loop systems

### Advantages:

- feasible almost everywhere in principle
- efficient exploitation of thermal energy
- more wells (high cost and impact) than for CL
- easy authorization
- zero emissions
- small underground thermal anomaly

### Disadvantages:

- High cost
- requires more space
- delicate installation to avoid interference with aquifers
- require heat pump

## Open loop systems

### Advantages:

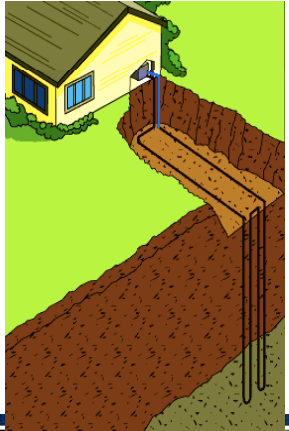
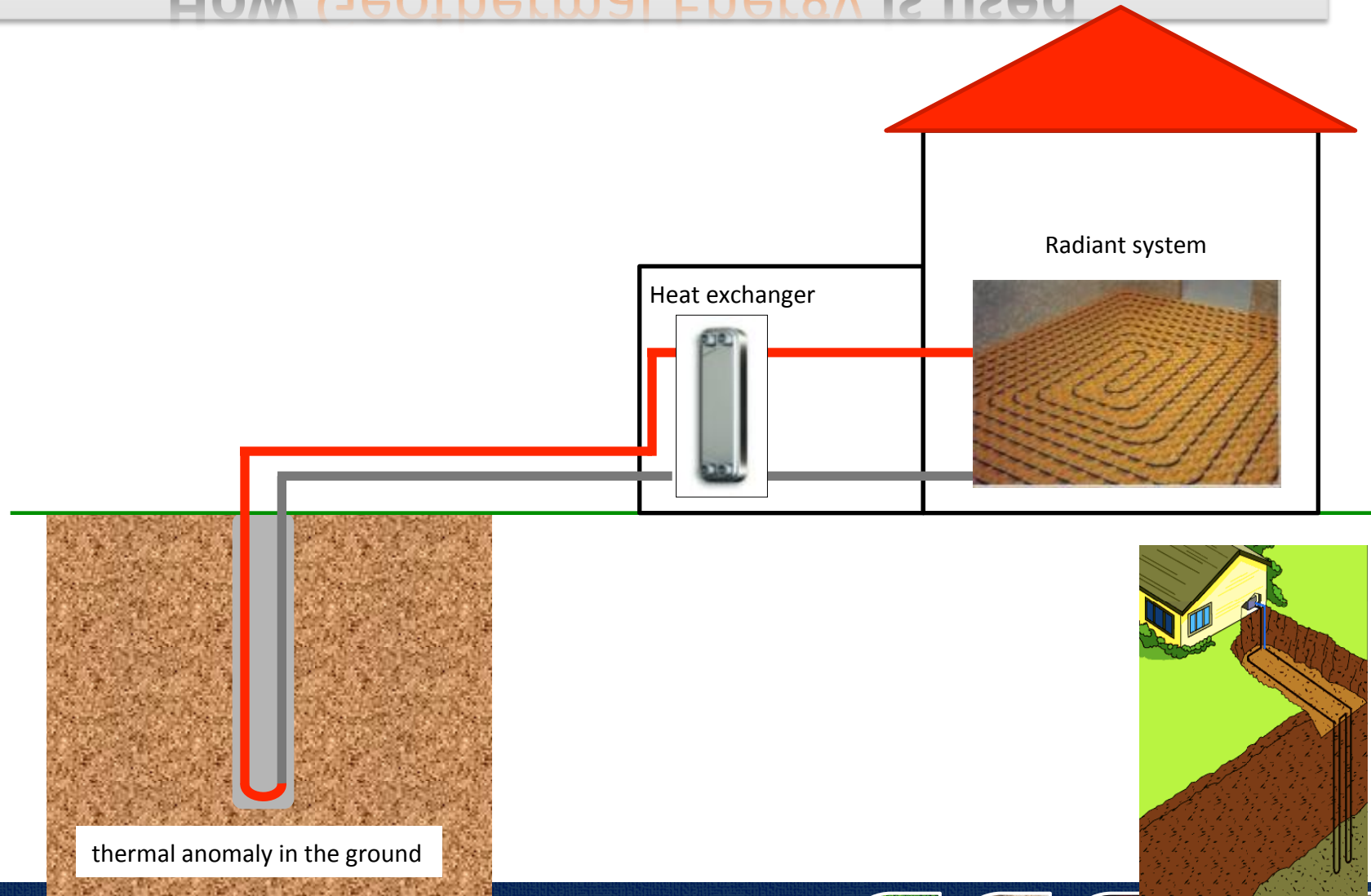
- higher thermal capacity than for CL for each well, therefore less wells
- less wells (low cost and impact)
- lower cost than for Closed Loop (CL)
- efficient exploitation of thermal energy
- relatively easy installation
- zero emissions
- may be used without heat pumps

### Disadvantages:

- Complexity of regulation and authorization
- Not always feasible
- accurate planning to avoid shortcircuiting

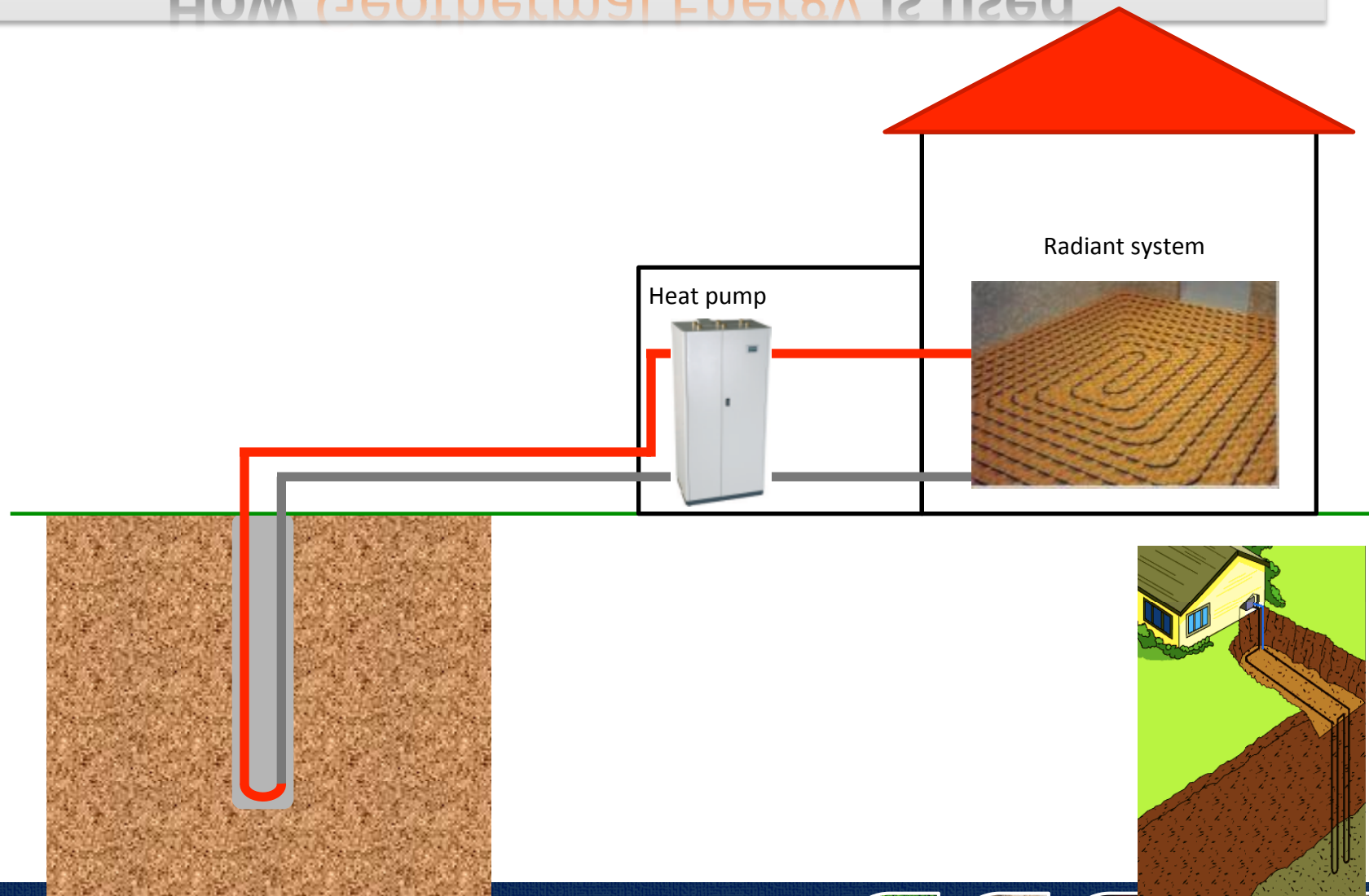


# How Geothermal Energy is used

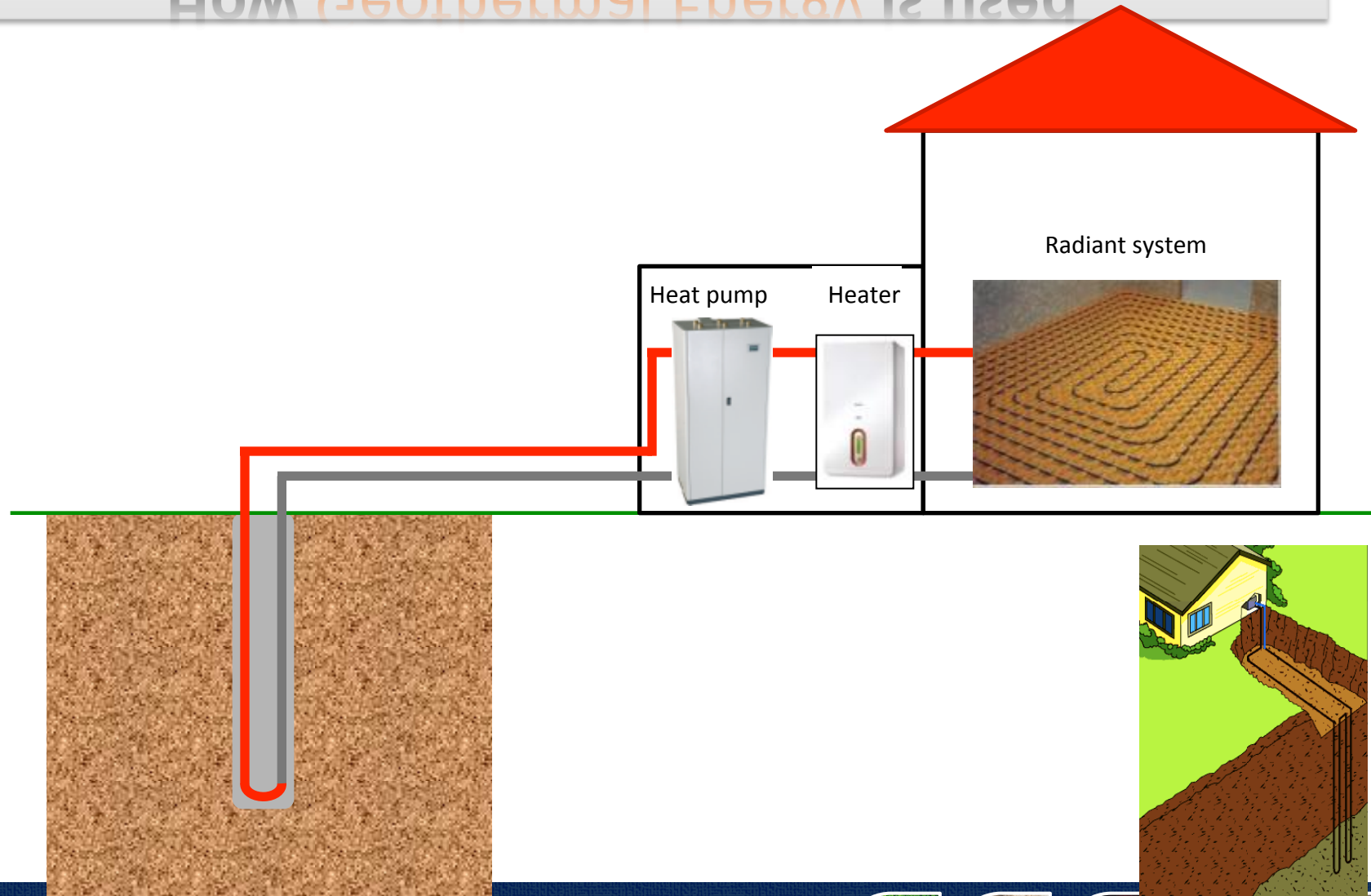




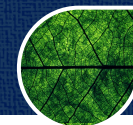
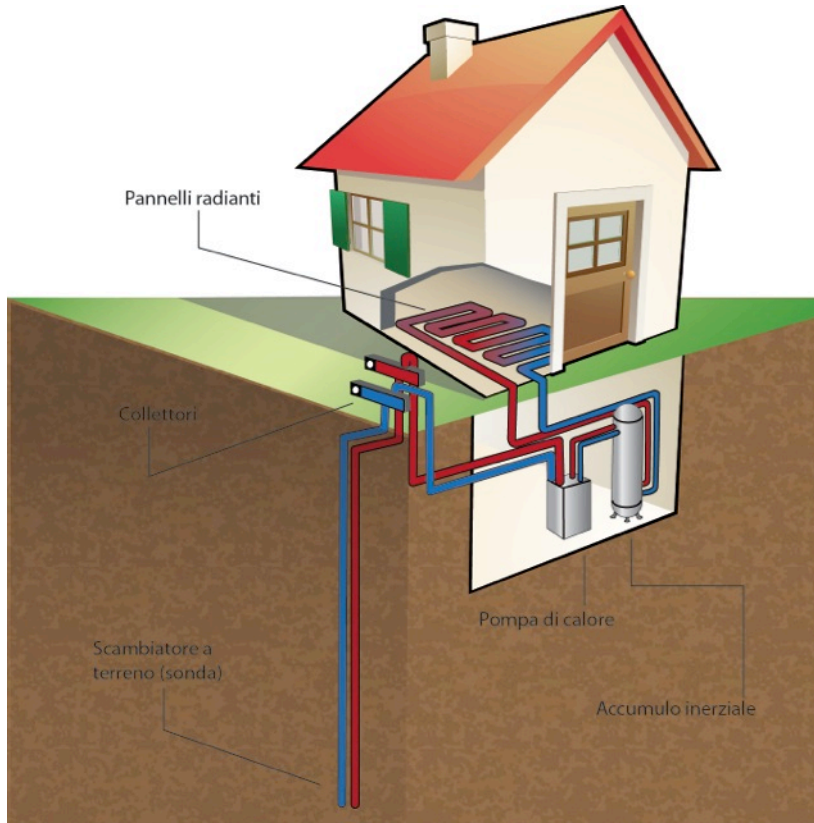
# How Geothermal Energy is used



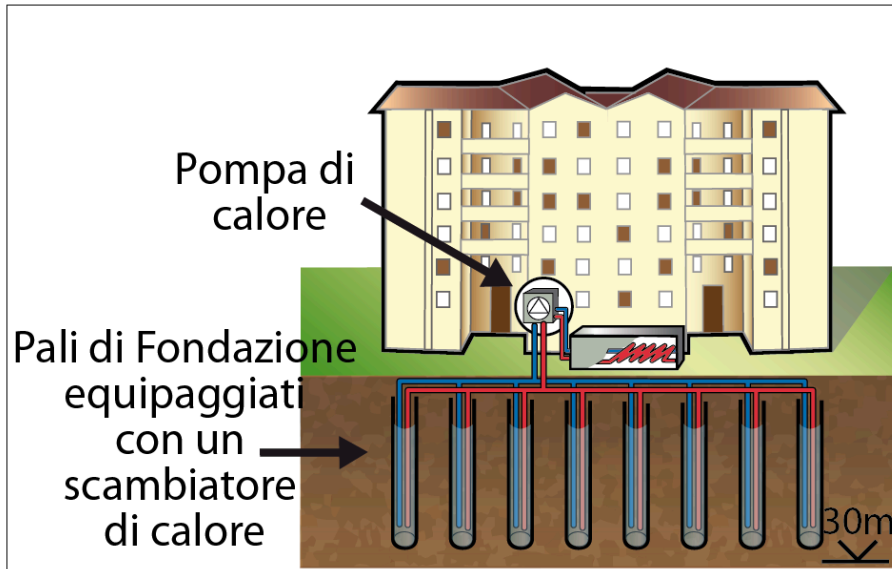
# How Geothermal Energy is used



# How Geothermal Energy is used



# How Geothermal Energy is used



# How Geothermal Energy is used

In the European Union, heat generated by hydrothermal, air- and ground-source heat pumps is considered renewable under the Renewable Energy Directive (Directive 2009/28/EC).

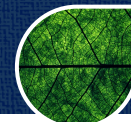
According to the EU Directive 2009/28/EC, heat pumps can be considered a renewable technology as long as they result in a primary energy efficiency of at least 115%, which corresponds to a seasonal performance factor of 2.875 at an average efficiency of the electricity production of 40% (EC/RHC Platform, 2012).

The energy considered renewable is the heat delivered, minus the electricity consumption of the pump.



# How Geothermal Energy is used

Heating and cooling system of Palazzo Lombardia, Milan, by geothermal heat pump

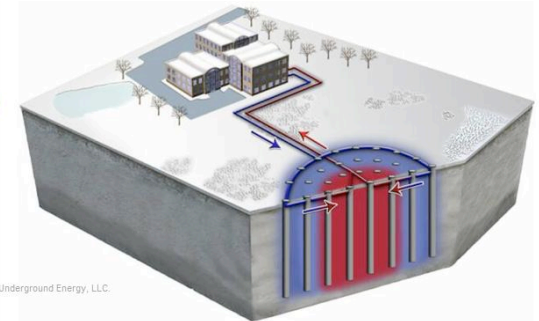
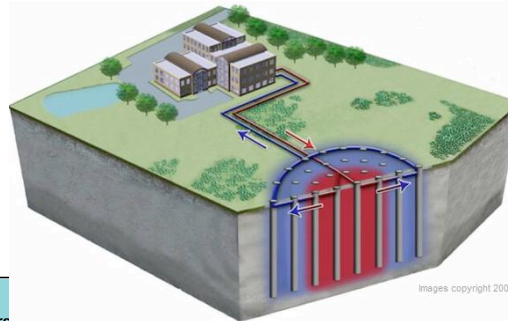
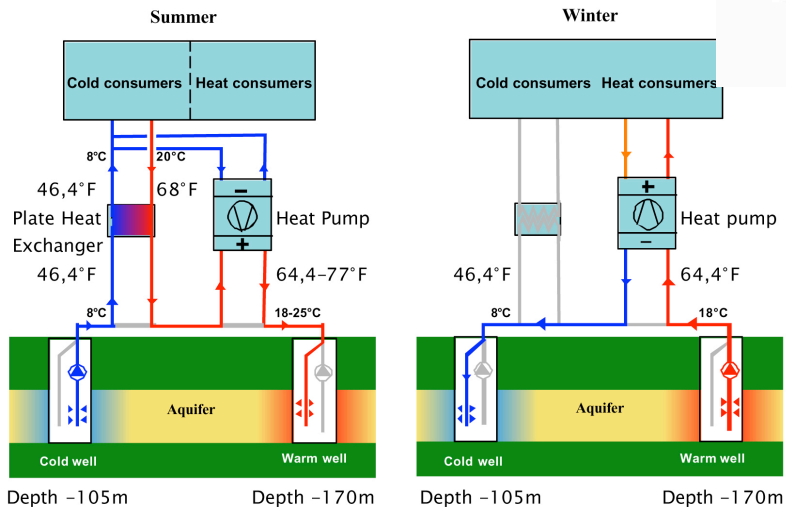


# How Geothermal Energy is used

UTES (*Underground Thermal Energy Storage*) is an increasing research field for storing heat/cold and use it when necessary

## ATES

### Aquifer Thermal Energy Storage



Images copyright 2009, Underground Energy, LLC.

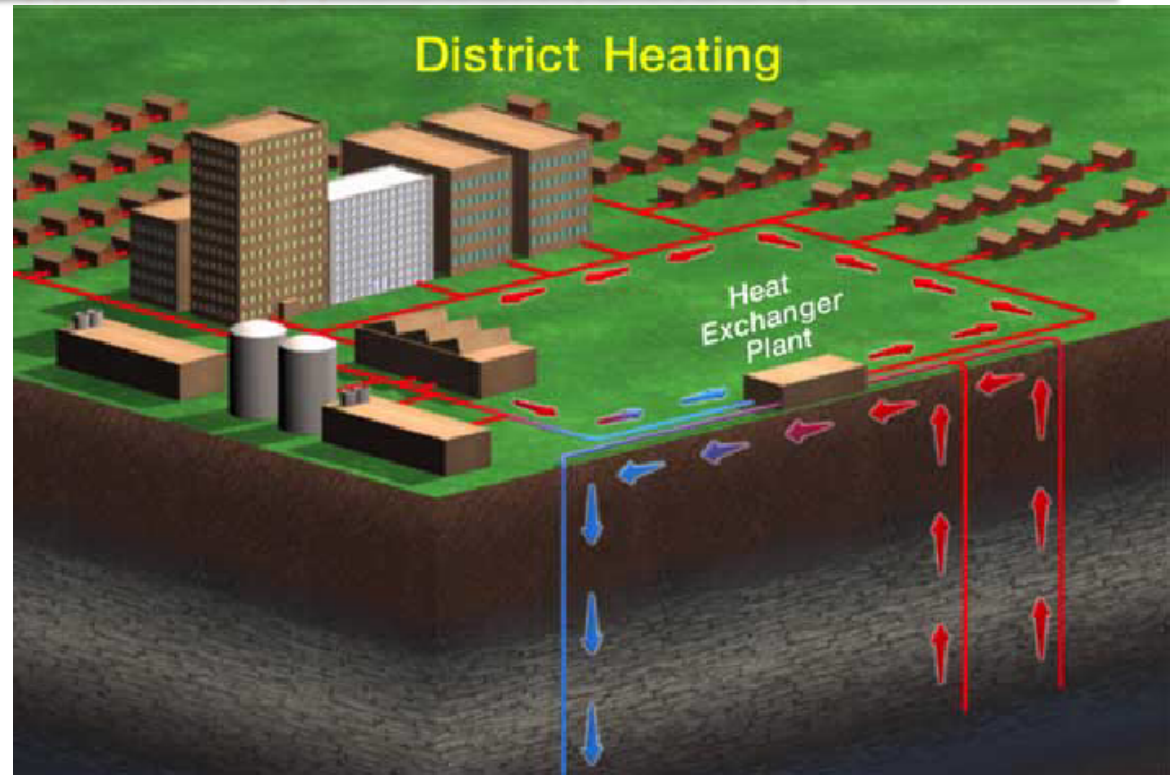
## BTES

### Borehole Thermal Energy System

# How Geothermal Energy is used

**Space heating**, of which more than 80% are district heating, is among the most important direct uses of geothermal energy

Open loop (single pipe) distribution systems are used where the water quality is good and recharge into the geothermal system adequate (fluids are wasted). In the more commonly used closed loop (double pipe) systems the spent water is disposed into reinjection wells.



Hot water from one or more geothermal wells is piped through a heat exchanger plant to heat city water in separate pipes. Hot city water is piped to heat exchangers in buildings to warm the air.

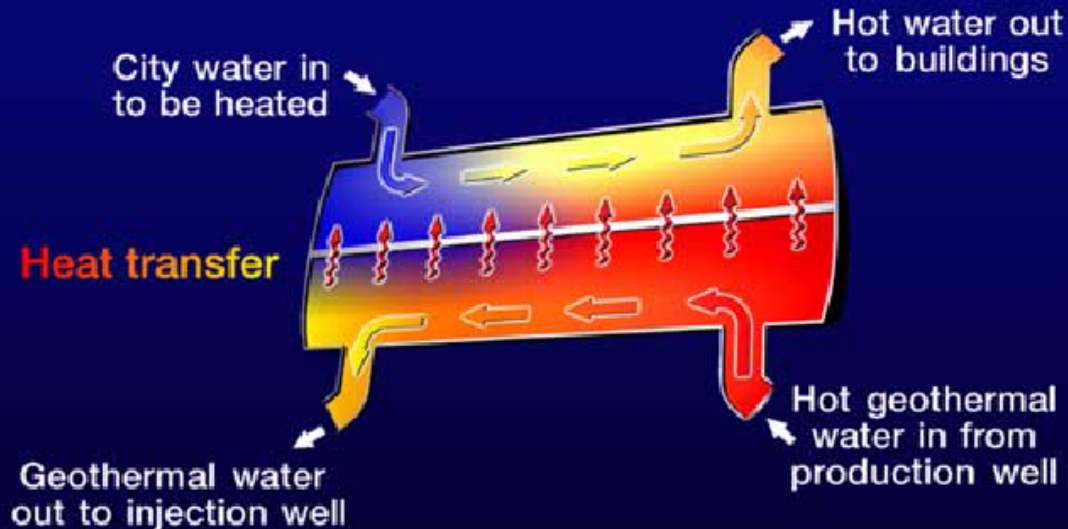
Slide 90 of 122, © 2000 Geothermal Education Office





# How Geothermal Energy is used

## District Heating Heat Exchanger

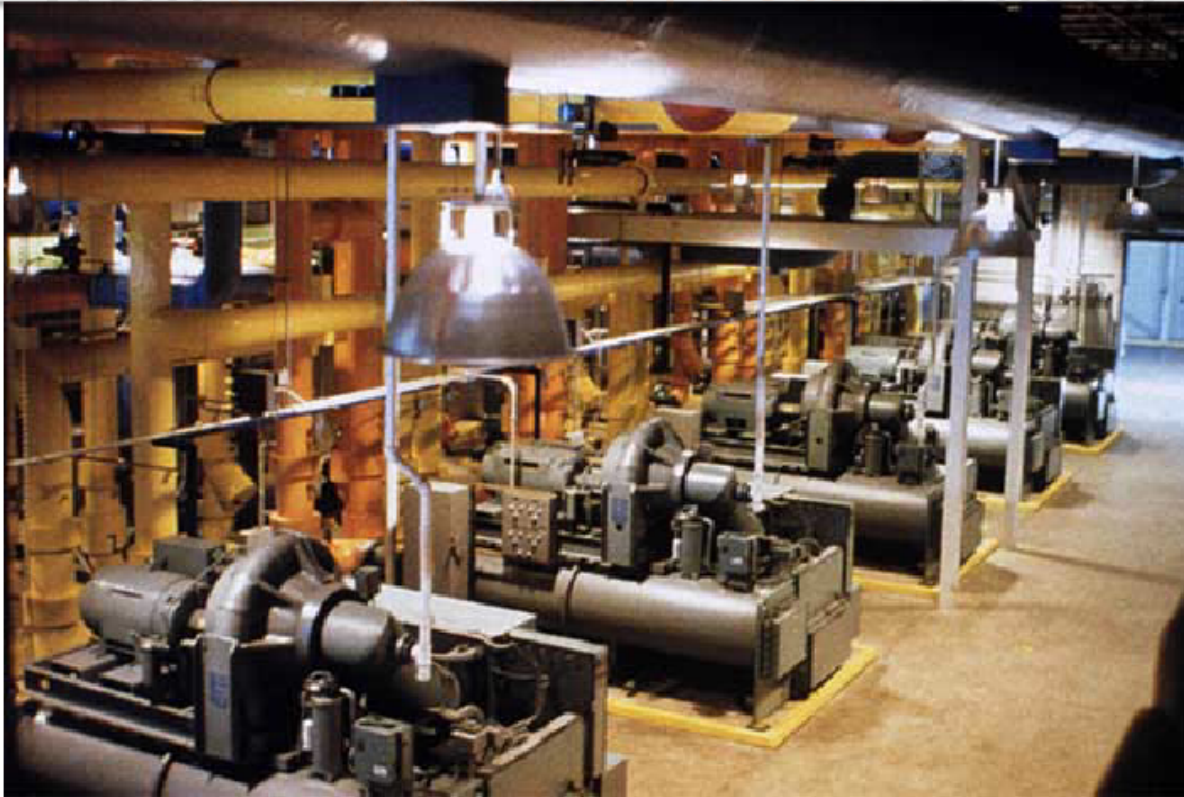


The geothermal water never mixes with the city water. Once its heat is transferred to the city water, the geothermal water is injected back into the reservoir to be reheated and recycled.

Slide 91 of 122, ©2000 Geothermal Education Office

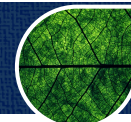


# How Geothermal Energy is used

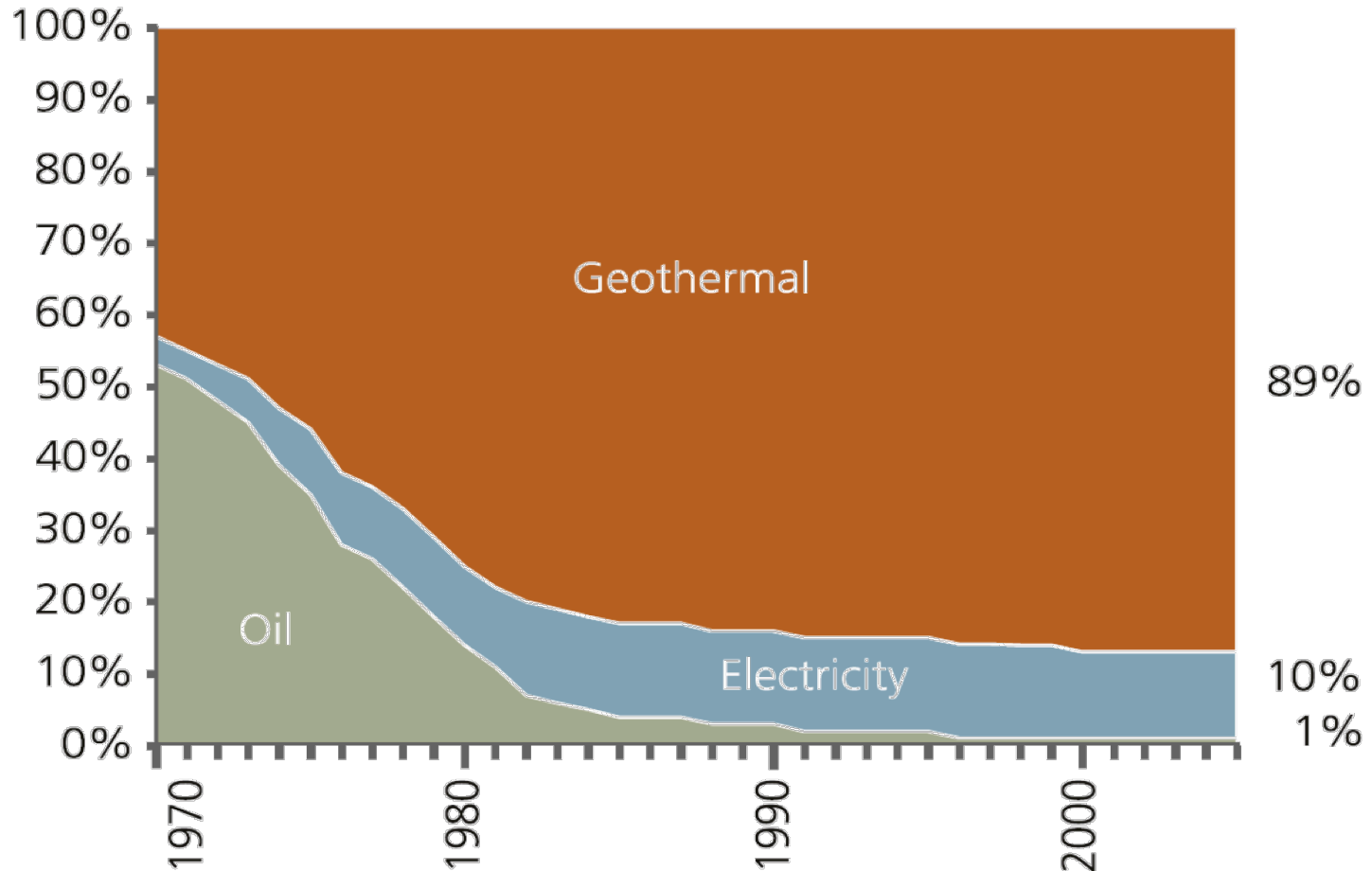


These pumps are used to pump the heated water to buildings in a district heating system, after it has passed through the heat exchanger.

Slide 93 of 122, © 2000 Geothermal Education Office



# How Geothermal Energy is used



Energy source for district heating in Iceland

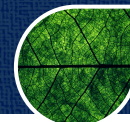




Reykjavik Using F



Reykjavik Using Geothermal



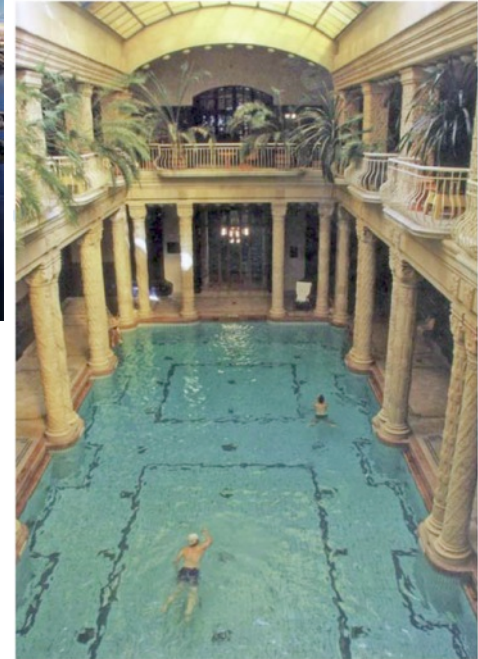
# How Geothermal Energy is used



Fish and other animal farming



Greenhouse heating



Bathing and balneology

The most common direct uses of geothermal heat

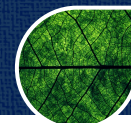


# How Geothermal Energy is used

The **agricultural applications** of geothermal fluids consist of the plant growing temperature control in open-fields and greenhouses. Thermal water can be used in *open-field agriculture* to heat the soil and, sometime, to irrigate it where ponds and rivers are not available. Soil heating is provided by burying thin pipelines where warm fluids are circulated.

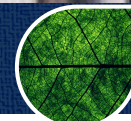
Disadvantages:

- high cost, resulting economic only in few cases
- lack of irrigation system could decrease the heat conductivity of the soil, because of the drop in humidity around the pipes, and consequent thermal insulation
- possible aggressive chemical composition



# How Geothermal Energy is used

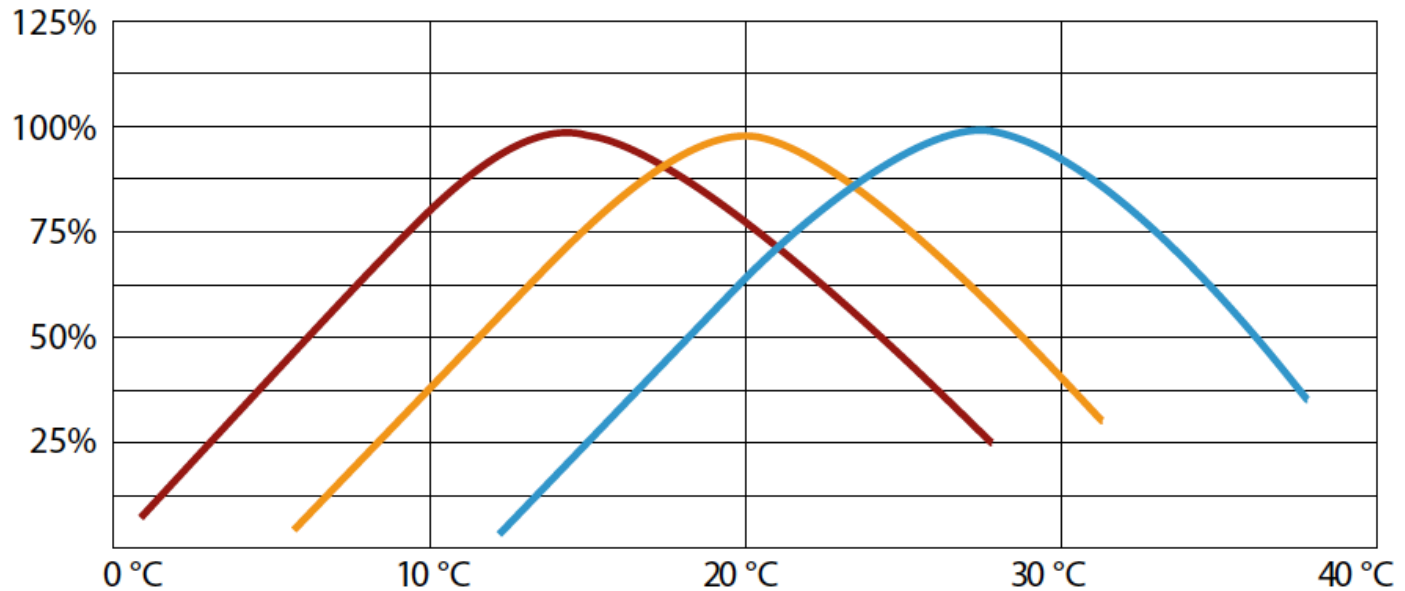
The most common application of geothermal energy in agriculture is, however, in **greenhouse heating**, which has been developed on a large scale in many countries. The greenhouse heating extends the cultivation of vegetables and flowers out-of-season or in an unnatural climate, and can now draw on a widely experimented technology.



# How Geothermal Energy is used

■ Lettuce ■ Tomato ■ Cucumber

Productive trend with temperature of common vegetables



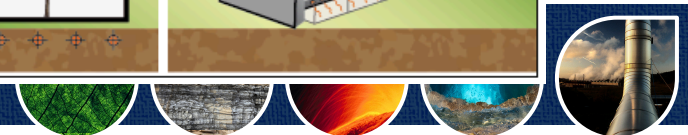
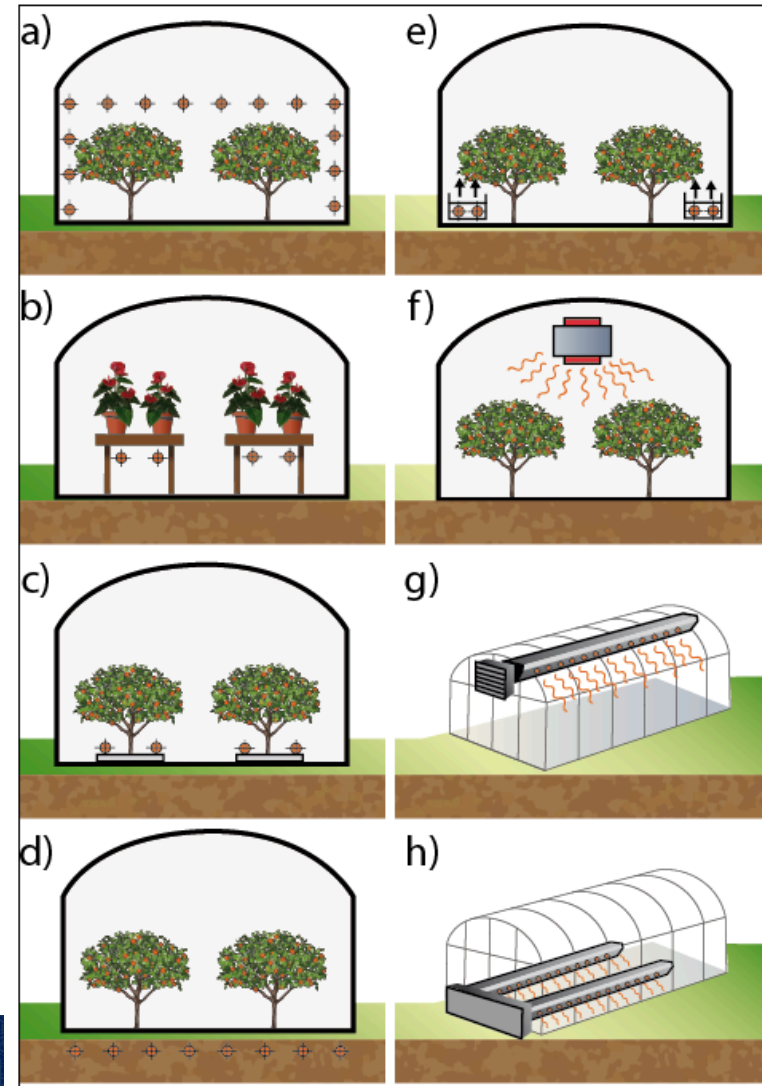
Various solutions are available for achieving optimum growth conditions, based on the optimum growth temperature of each plant, and on the quantity of light, on the CO<sub>2</sub> concentration in the greenhouse environment, on the humidity of the soil and air, and on air movement.





# How Geothermal Energy is used

Greenhouse heating can be accomplished by forced circulation of air in heat exchangers, hot-water circulating pipes or ducts located in or on the floor, finned units located along the walls and under benches, or a combination of these methods



# How Geothermal Energy is used

Operating costs of greenhouse heating, which in some cases account for 35% of the product costs (vegetables, flowers, house-plants and tree seedlings), can considerably be reduced by geothermal heat. This is the case in particular when geothermal fluids naturally flow at the surface and abstraction pumps are not required

Geothermal brines often require treatment, since their chemical composition may produce deposits in the pipes, pumps and heat exchanger plates.



# How Geothermal Energy is used

This technology has taken maximum advantage from heat pump technology, and shallow groundwater or ground energy is more and more used. In Netherlands, for examples, there has been a major boost of local tomato production thanks to geothermal technology.

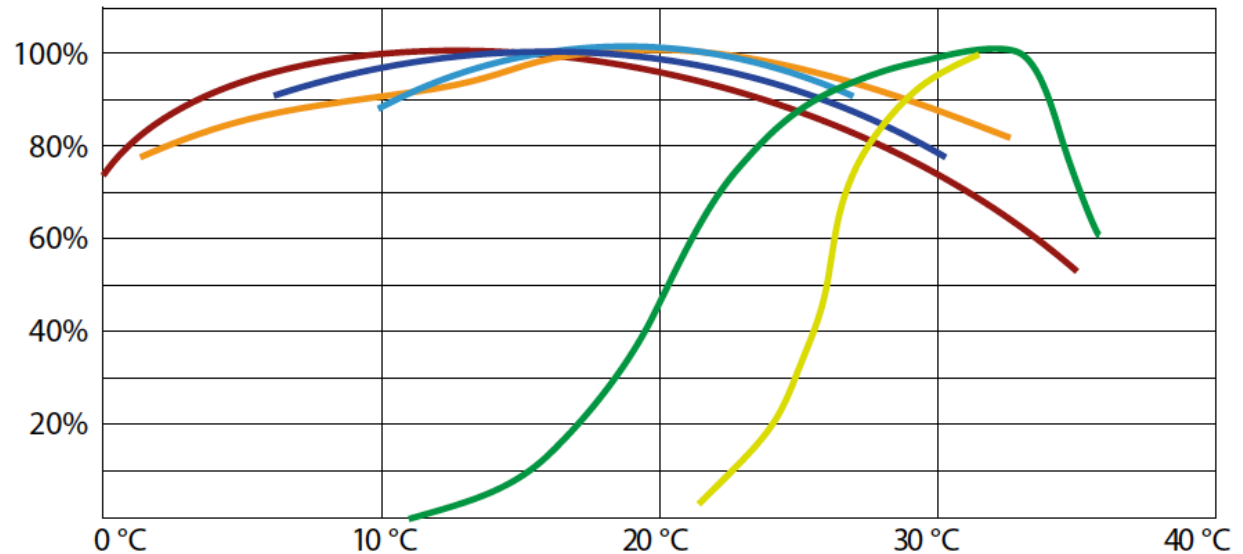


# How Geothermal Energy is used

Farm animals and aquatic species, like vegetables and plants, benefit in quality and quantity from optimum conditioning of their environmental temperature

- chicken, egg production
- poultry, weight increase
- cow, milk production
- pork, weight increase
- shrimps, weight increase
- cat-fish, weight increase.

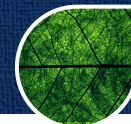
Productive trend with temperature of different animal species



# How Geothermal Energy is used

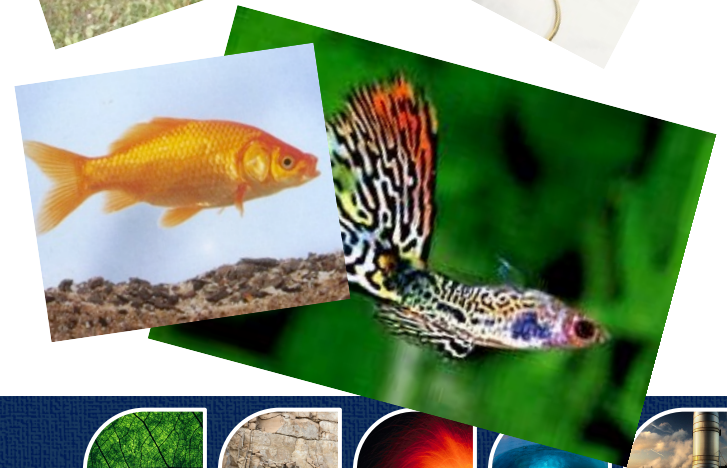
**Aquaculture**, the controlled breeding of aquatic forms of life, is the most common application of geothermal animal husbandry.

By maintaining an optimum temperature artificially we can breed more exotic species, improve production and even, in some cases, double the reproductive cycle. The species that are typically raised are carp, catfish, bass, tilapia, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone.



# How Geothermal Energy is used

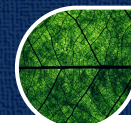
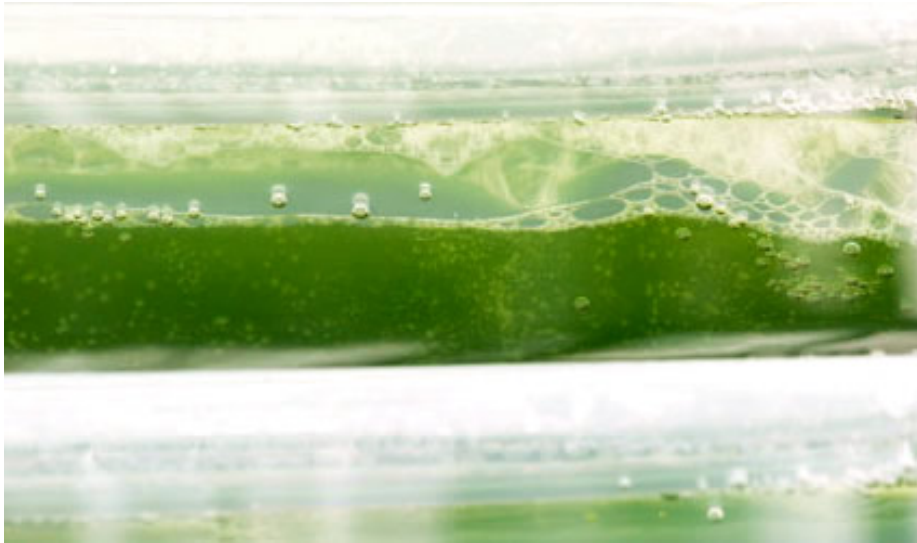
The temperatures required for aquatic species are generally in the 20 - 30 °C range. The size of the installation will depend on the temperature of the geothermal source, the temperature required in the fish ponds and the heat losses from the latter.



# How Geothermal Energy is used

Spirulina is being farmed in a number of tropical and sub-tropical countries, in lakes or artificial basins, where conditions are ideal for its fast and widespread growth (a hot, alkaline environment rich in CO<sub>2</sub>).

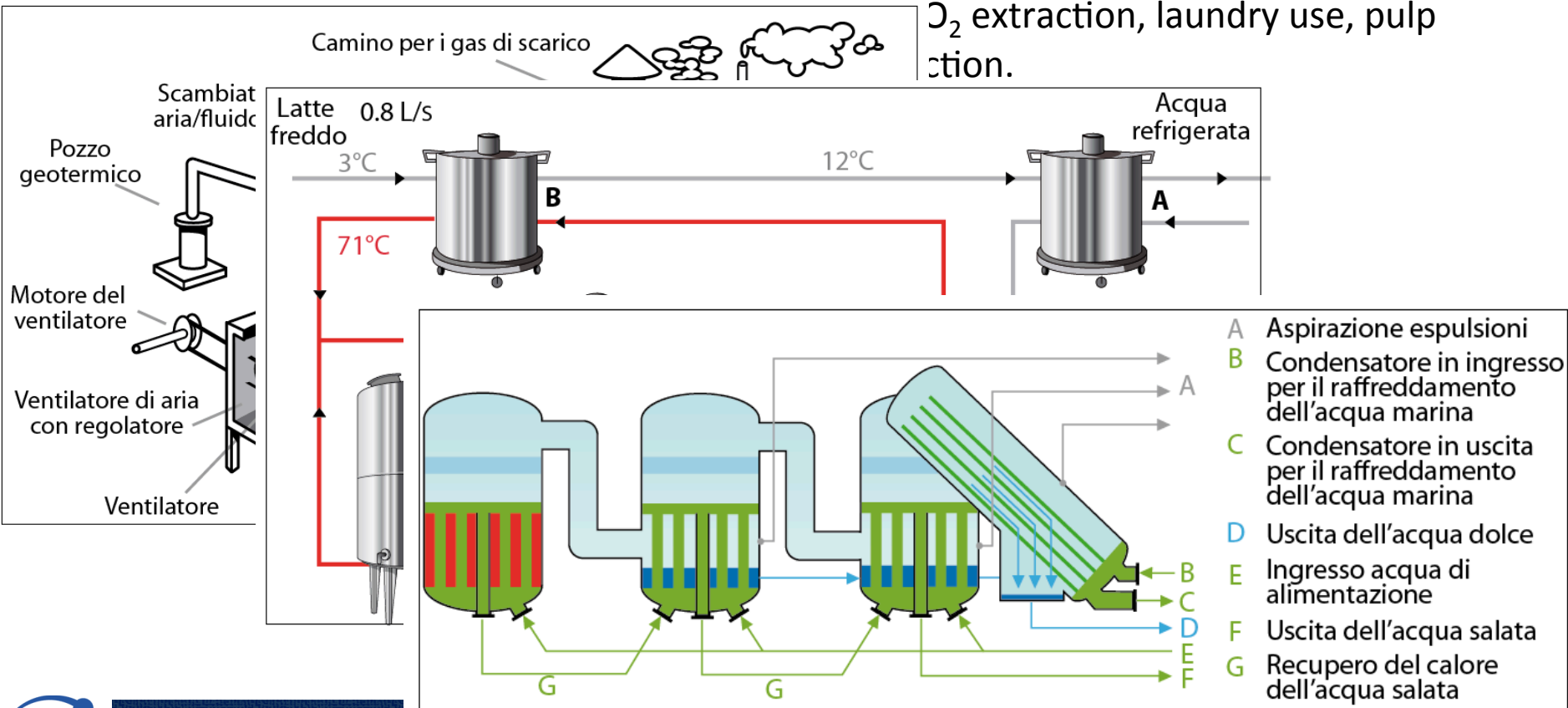
Other kinds of algae are grown to extract oil and produce bio-fuels



# How Geothermal Energy is used

**Industrial applications**, including process heating, evaporation, drying, distillation, sterilization, washing, de-icing, and salt extraction, bottling of water and carbonated drinks, paper and vehicle parts production, oil recovery, food processing and milk

$O_2$  extraction, laundry use, pulp  
ction.





# How Geothermal Energy is used

Food processes using heated fluids or heating&cooling may benefit from geothermal energy

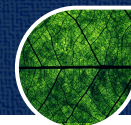


# How Geothermal Energy is used

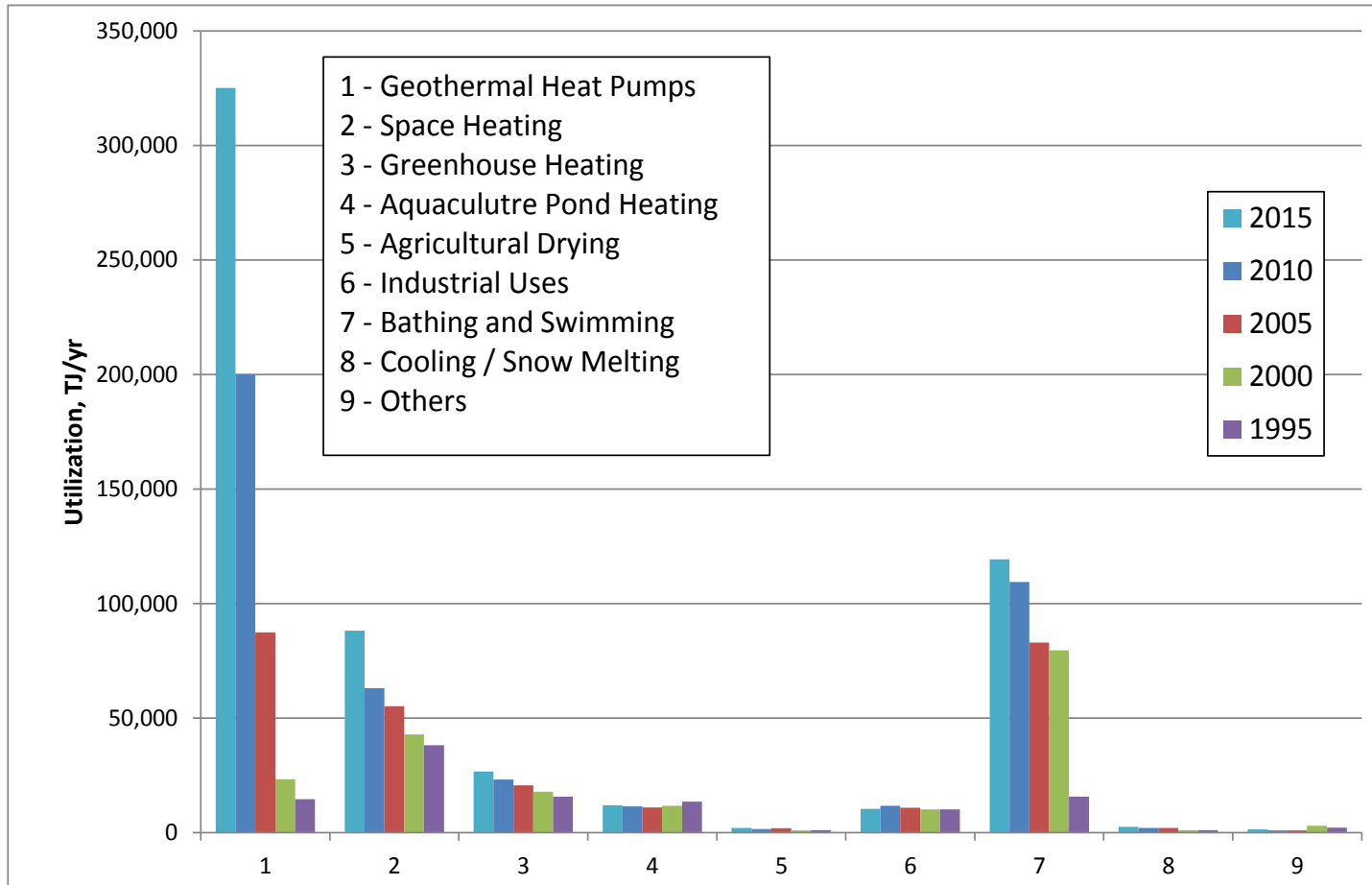


Pipes of geothermal water can be installed under sidewalks and roads to keep them from icing over in winter, like this sidewalk.

Slide 88 of 122, © 2000 Geothermal Education Office



# How Geothermal Energy is used



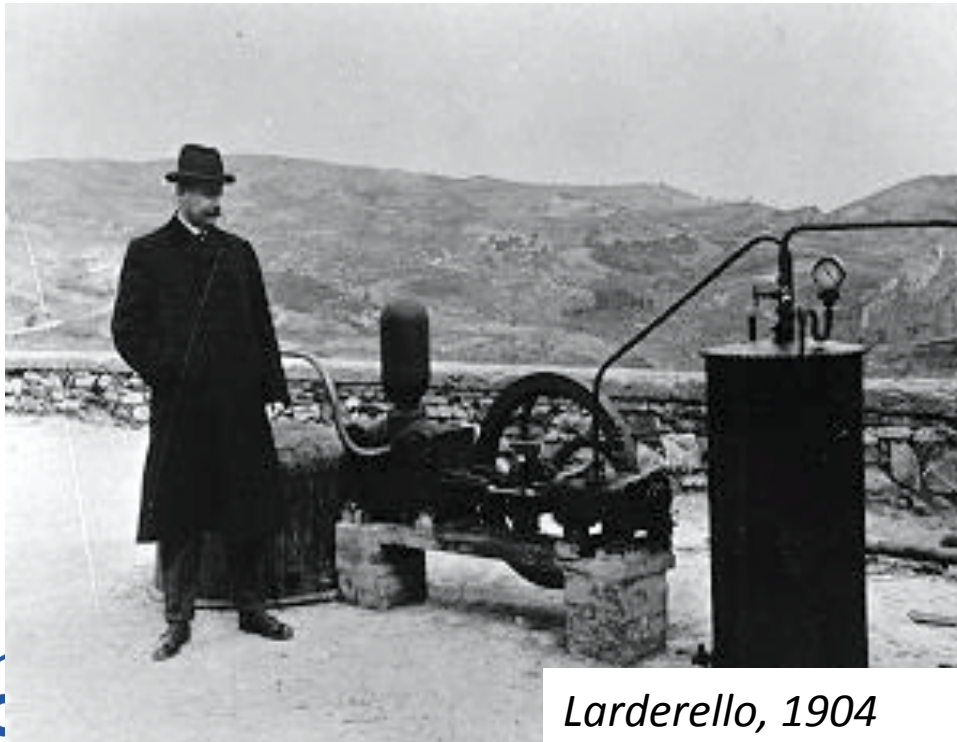
da Lund e Boyd, WGC 2015



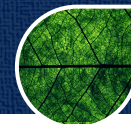
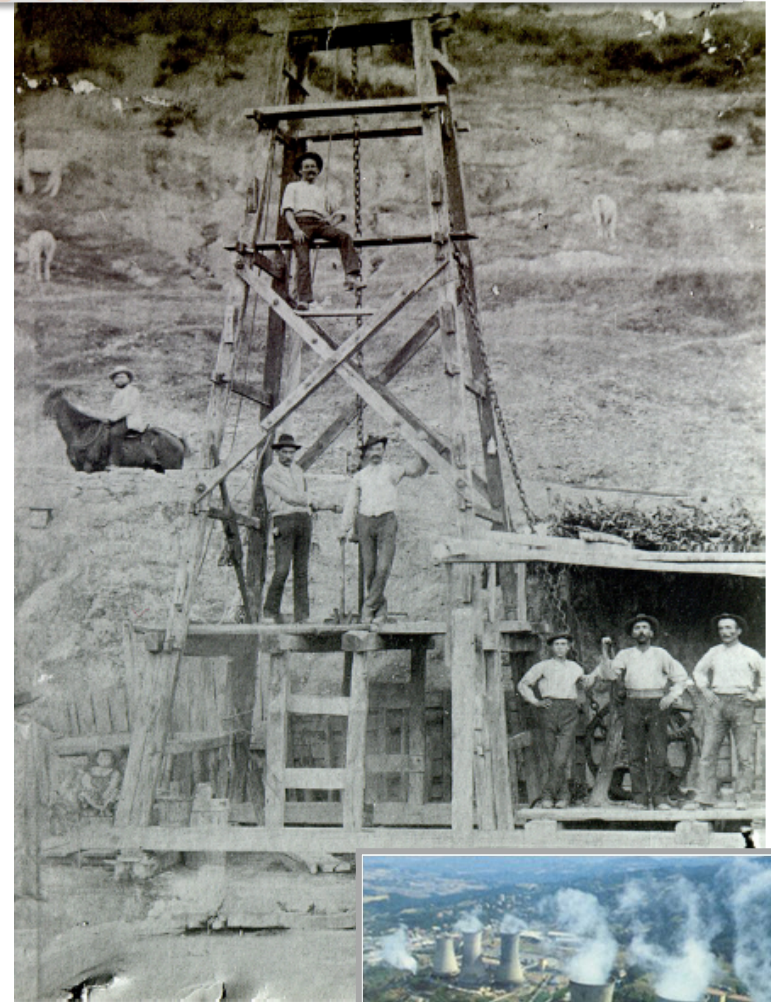
# How Geothermal Energy is used

Italy has been the first country in the world to produce **electricity by geothermal energy** on 1904.

Power production started on 1908 and increased in Italy and the world since then.



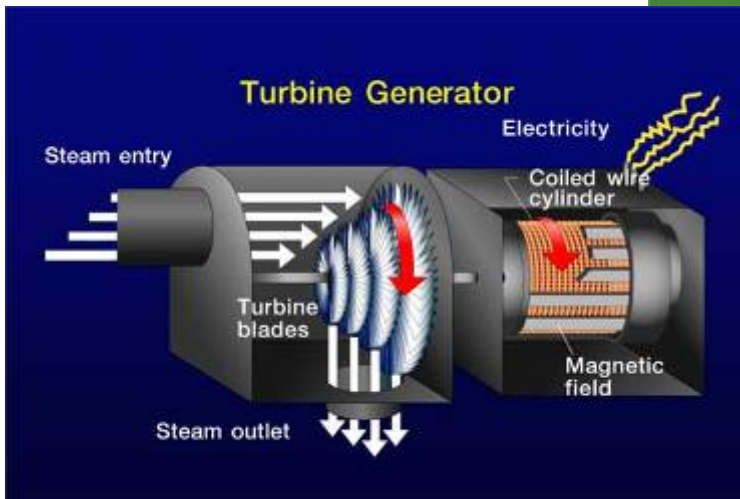
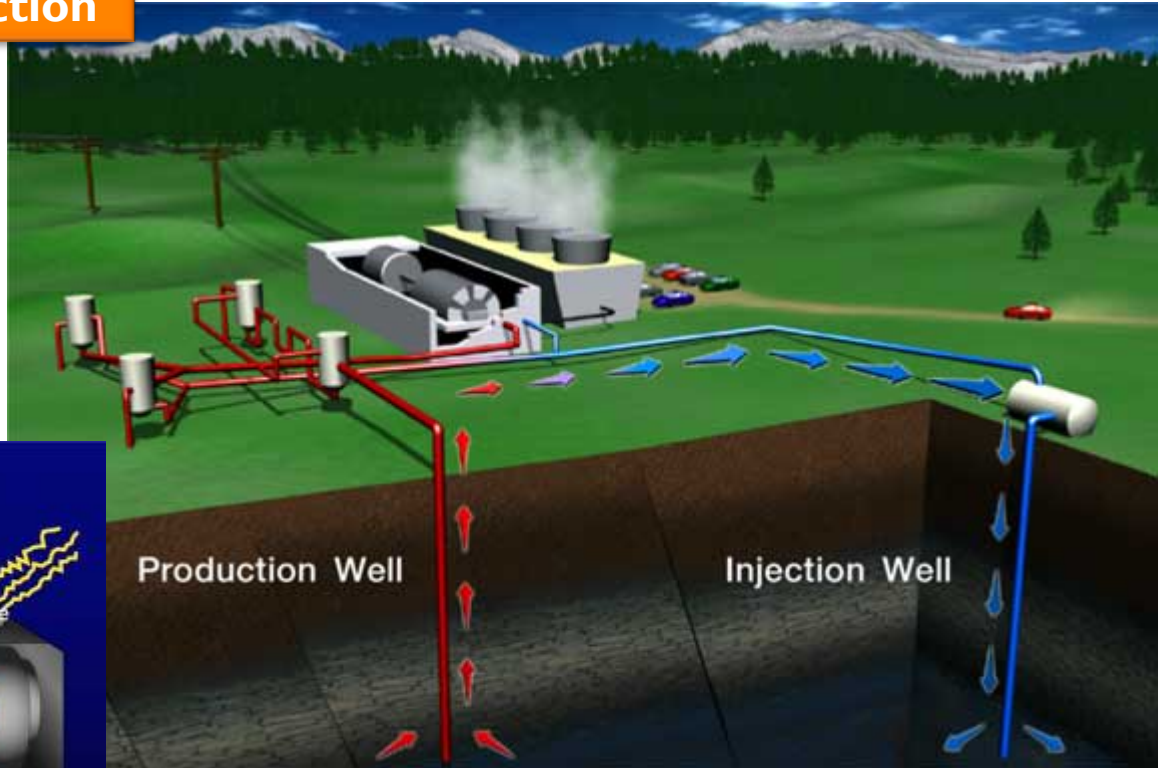
*Larderello, 1904*



# How Geothermal Energy is used

## Geothermal power production

By means of turbine generators, geothermal heat (high temperature) is converted in mechanical energy and then in electrical energy



# How Geothermal Energy is used

## Steam Dominated systems

vapourstatic pressure

Dry steam plants

Single or double flash plants  
separation of steam and liquid phase

## Liquid dominated systems

hydrostatic pressure

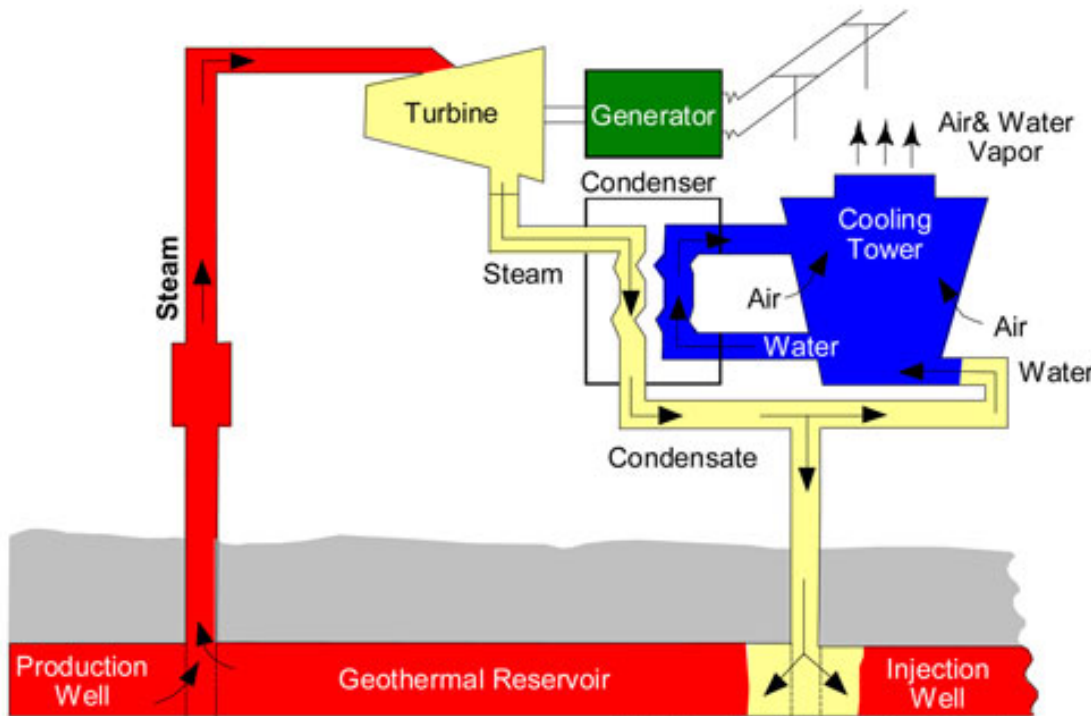
Binary plants

Combined plants  
flash and binary, cascade



# How Geothermal Energy is used

SCHEMATIC DIAGRAM OF A DRY STEAM GEOTHERMAL POWER PLANT



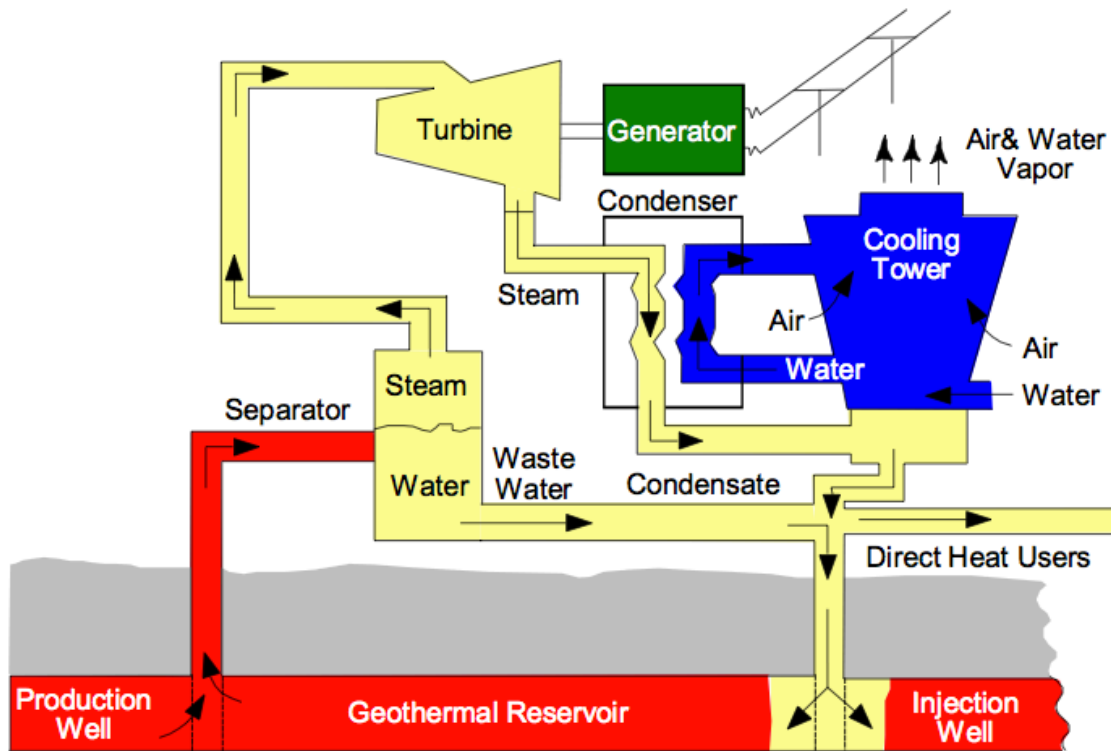
Modified from Geo-Heat Center

**Dry steam plants** use hydrothermal fluids that are primarily steam. The steam goes directly to a turbine, which drives a generator that produces electricity.



# How Geothermal Energy is used

Figure 27: Single Flash Steam Power Plant Schematic



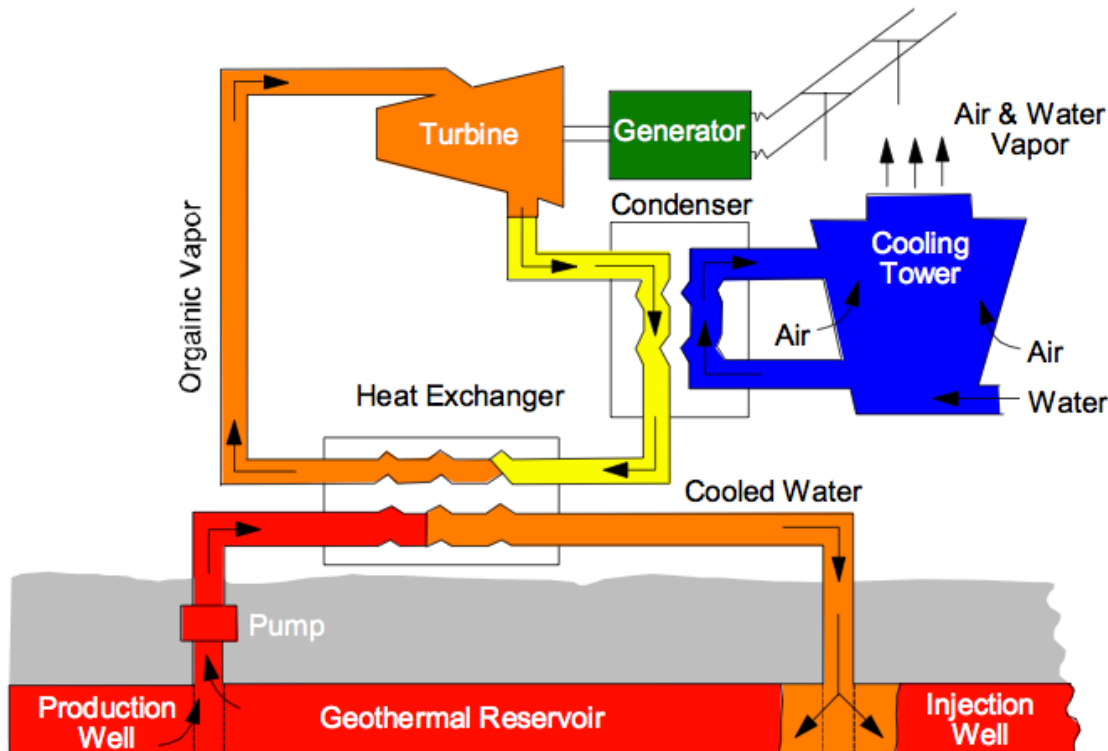
**Flash steam power plants** tap into reservoirs of water with temperatures higher than **180°C**. As it flows, the fluid pressure decreases and some of the hot water boils or "flashes" into steam. The steam is then separated at the surface and is used to power a turbine/generator unit





# How Geothermal Energy is used

Figure 30: Binary Power Plant Schematic



**Binary cycle power plants** operate on water at lower temperatures of about **105-180°C**. These plants use the heat from the geothermal water to boil a working fluid, usually an organic compound with a low boiling point.

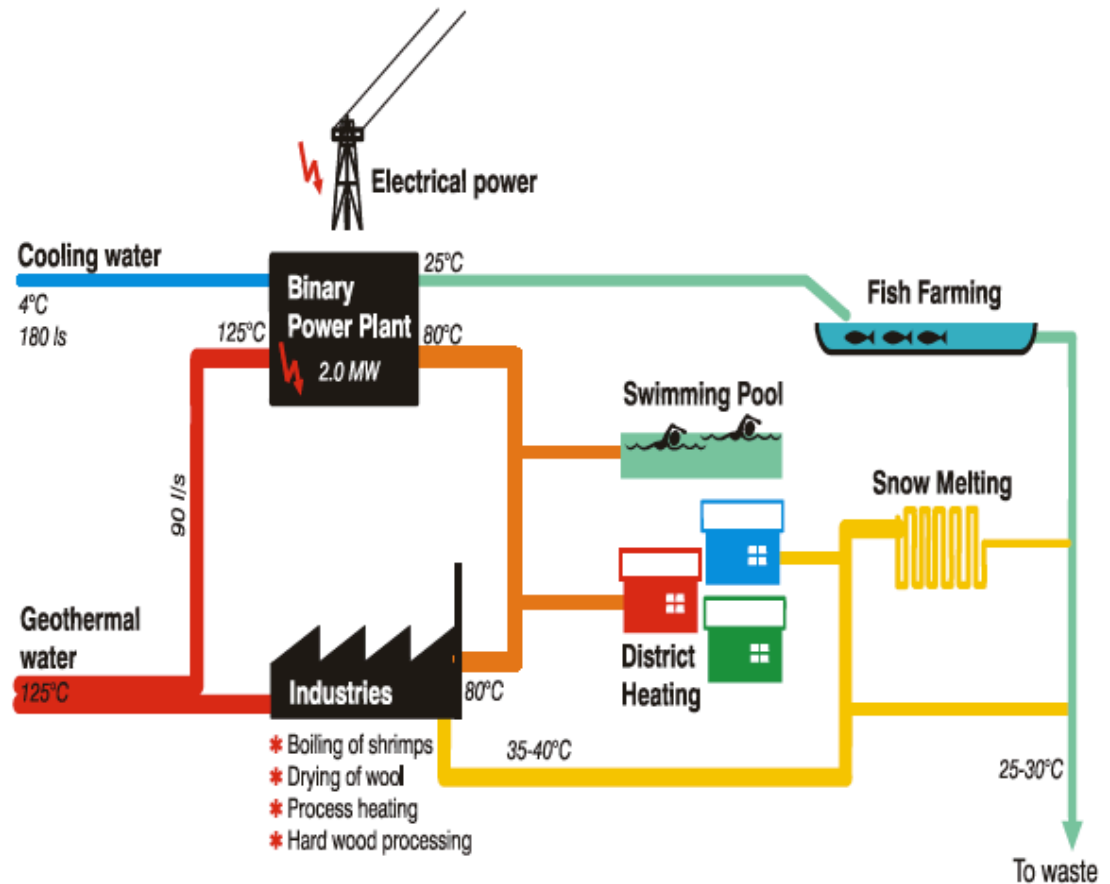
Source: Geo-Heat Center



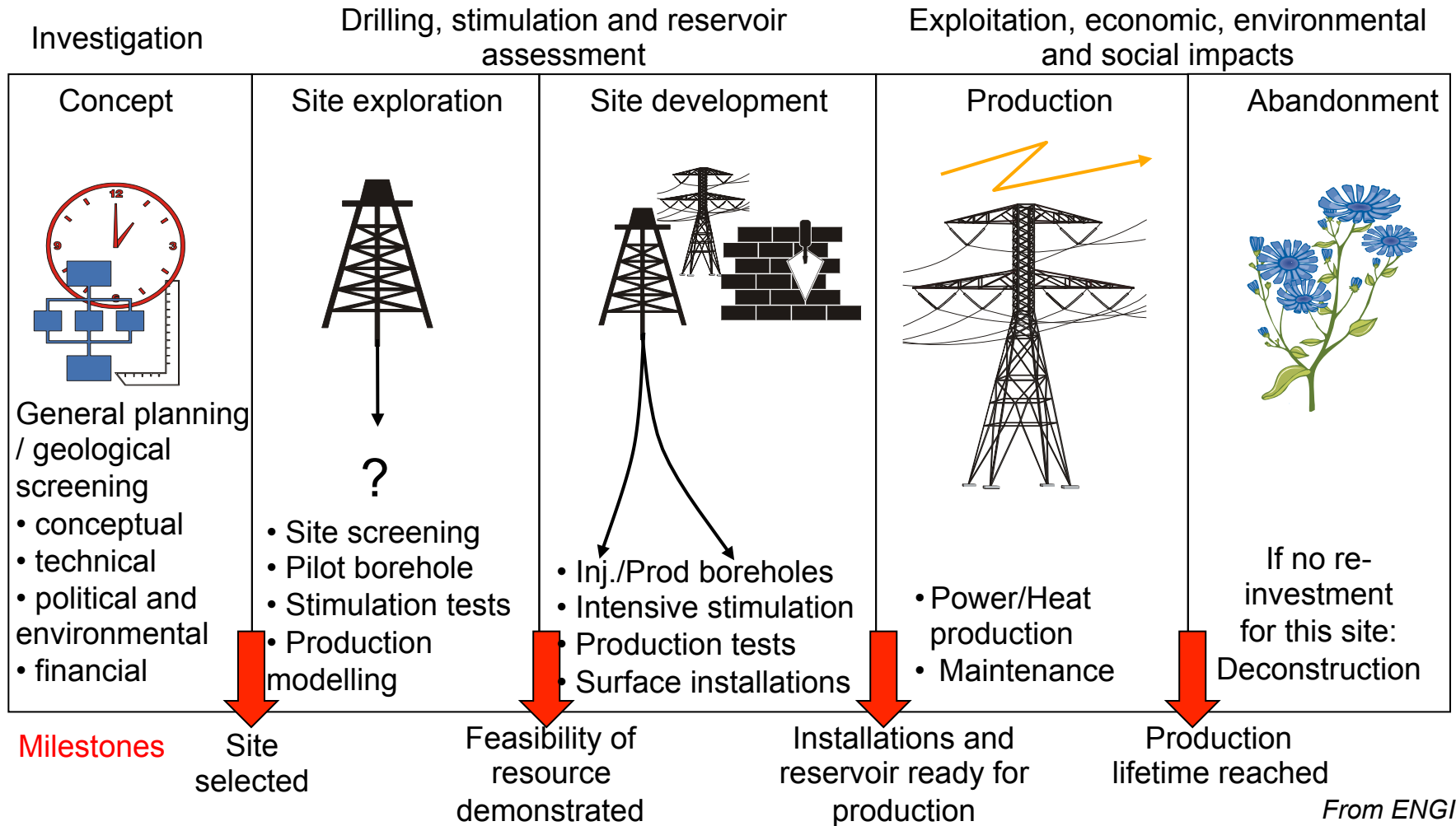
# How Geothermal Energy is used

The efficiency of geothermal utilisation is enhanced considerably by **cogeneration plants (combined heat and power plants)**, compared with conventional geothermal plants. A cogeneration plant produces both electricity and hot water which can be used for district heating as well as other direct uses.

A necessary condition for the operation is that a relatively large market for hot water exists at a distance not too far from the plant.



# How Geothermal Energy is used



From ENGINE



# How Geothermal Energy is used

A economically feasible geothermal reservoir should lie at depths that can be reached by drilling, possibly less than 4 km (**accessibility requirement**).

A geothermal system must contain great volumes of fluid at high temperatures - a reservoir - that can be recharged with fluids that are heated by contact with the rock.

**productivity requirement**

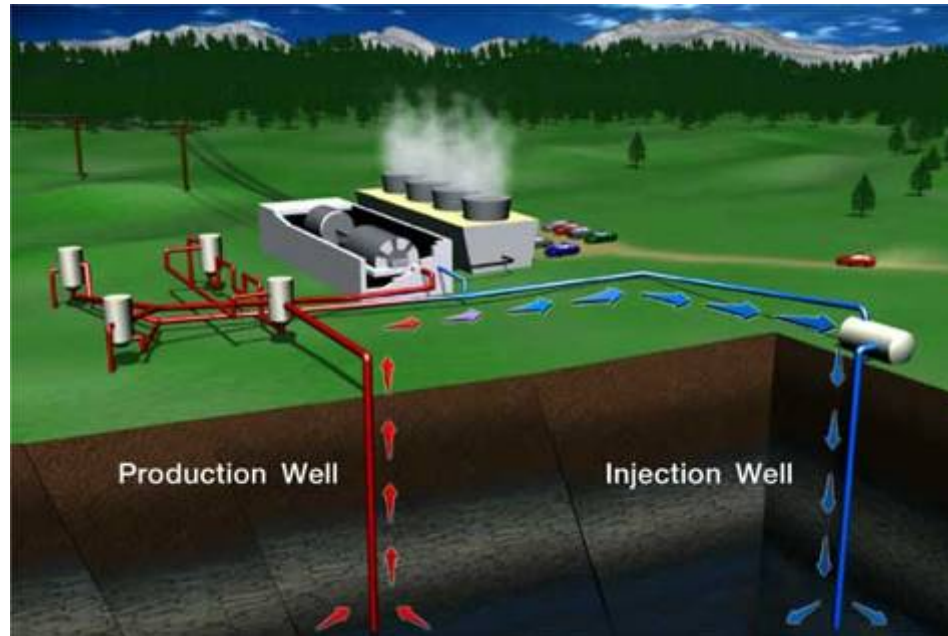
For most uses, a well must penetrate permeable zones, usually fractures, that can support a high flow rate.



# How Geothermal Energy is used

When sufficient natural recharge to the hydrothermal system does not occur, which is often the case, a reinjection scheme is necessary to ensure production rates will be maintained.

This would ensure the **sustainability** of the resource.



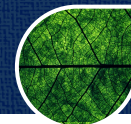
3

What is the production? What about the cost? And emissions?

# The advantages of using Geothermal Energy



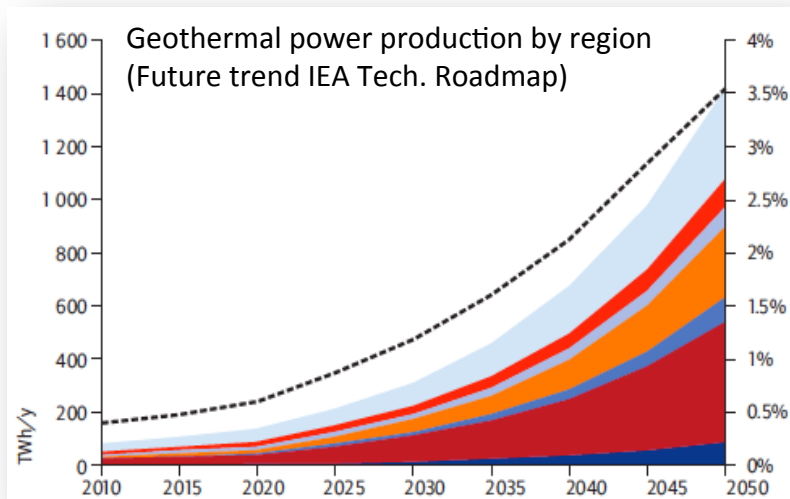
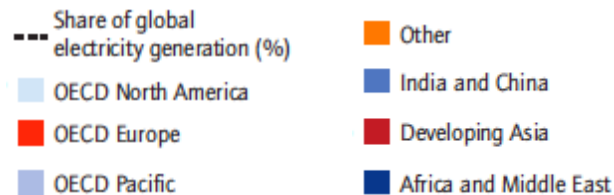
IGG – Institute of Geosciences and Earth Resources  
National Research Council of Italy



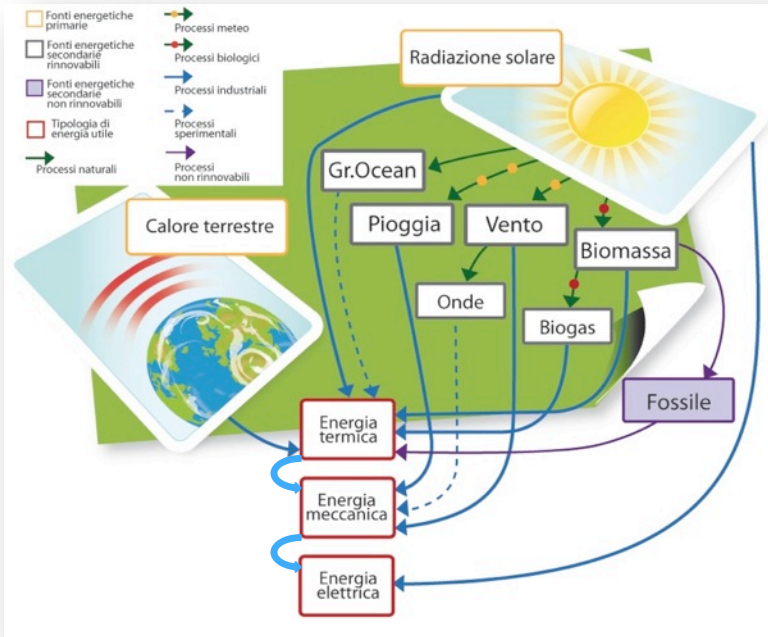
# Geothermal Energy pros

The two main applications of geothermal energy, electric power generation and direct use of heat, are currently producing more than 67 TWh/a<sub>e</sub> and 10 GW<sub>e</sub> of installed capacity, and about 300 TJ/yr with 30 GW<sub>th</sub>

And are **constantly growing**.

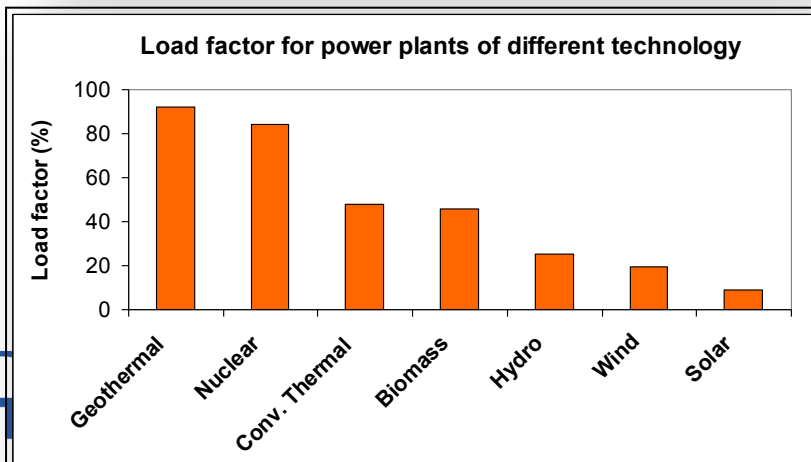


# Geothermal Energy pros



Not depending, directly or indirectly, on sun, geothermal may produce 24 hours per day: a **base-load energy** like fossil and nuclear sources.

It is most economical for geothermal power stations to serve as **base load** throughout the year.

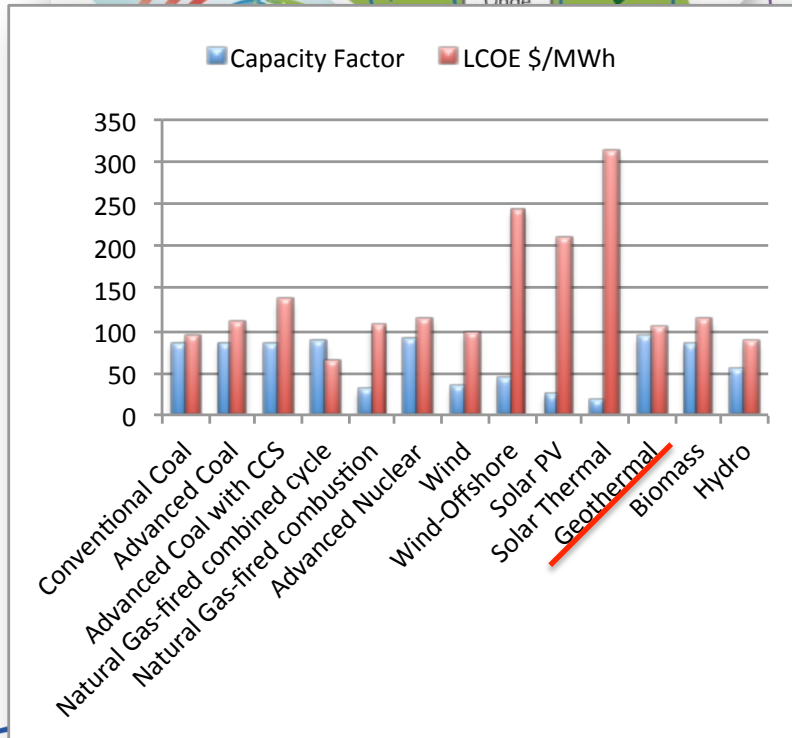




# Geothermal Energy pros



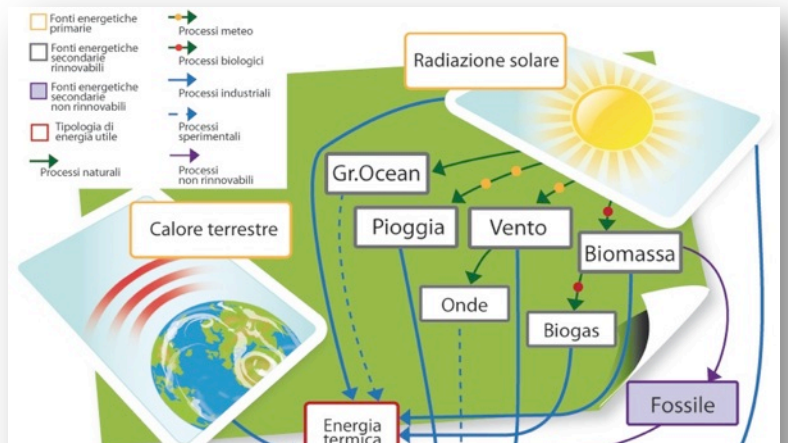
The **total cost (LCOE)** of geothermal power production is **cheap** if compared to those of others renewables



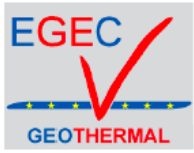
Levelized Cost of New Generation Resources in the Annual Energy Outlook 2011, EIA



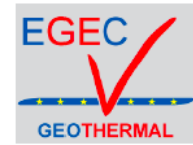
# Geothermal Energy pros



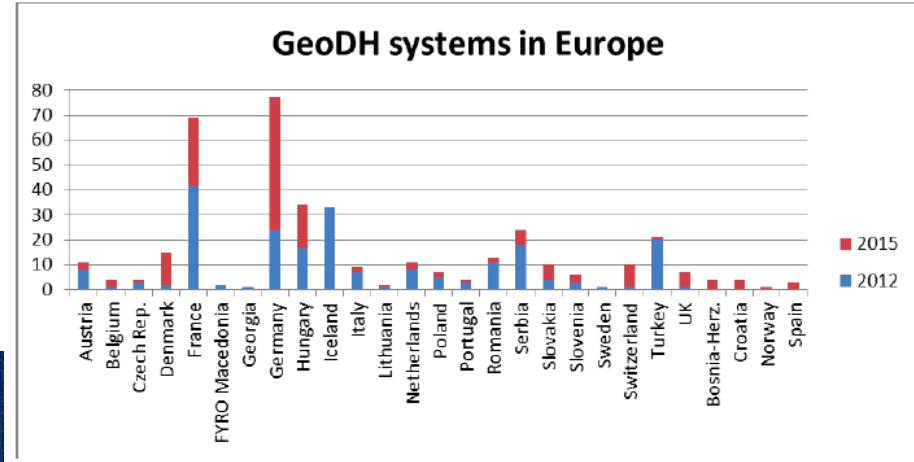
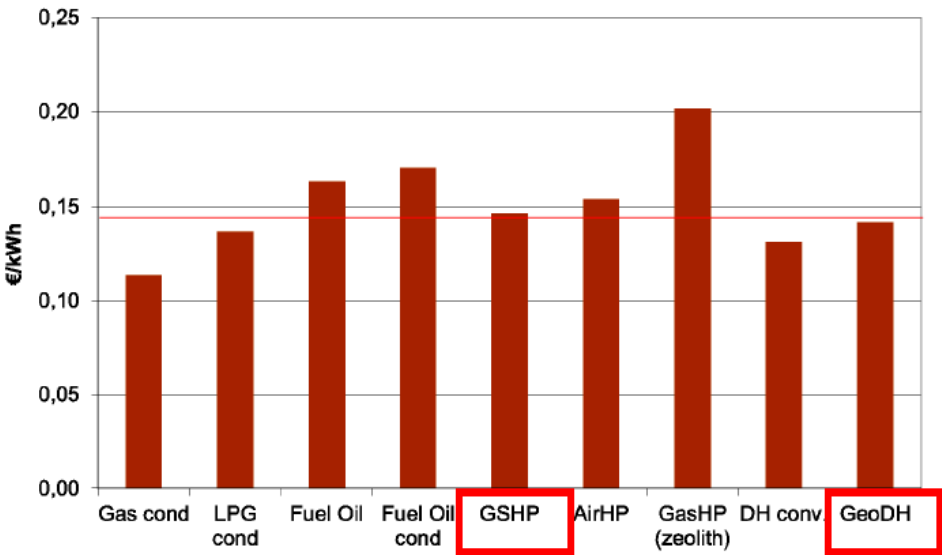
The **total cost (LCOE)** of geothermal power production is **cheap** if compared to those of others renewables and fuels



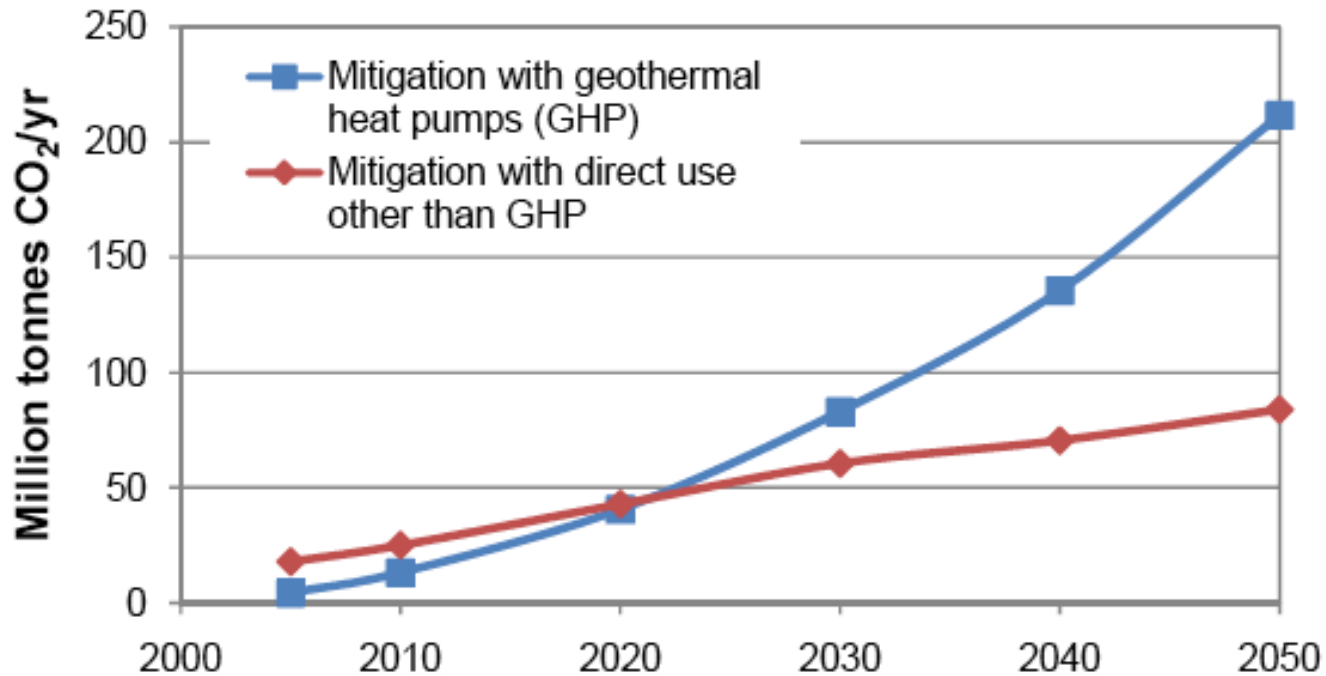
## Full cost of Heat, calculated for small building or flat



## GeoDH Systems in Europe



# Geothermal Energy pros



CO<sub>2</sub> emission mitigation of Geothermal Heat. For each Geothermal Heat Pump (blue) it assumes an emission of 50 tonnes CO<sub>2</sub>-equivalent/TJ. For other sources of geothermal heating (red) it assumes an emission of 4 tonnes CO<sub>2</sub>-equivalent/TJ. Both assume an emission of 100 tonnes CO<sub>2</sub> equivalent/TJ for fossil heat provision. Fridleifsson et al., 2008





What are the risks? Environmental impact?

# Disadvantages, needs and gaps of Geothermal Energy



# Geothermal Energy cons



Thanks to the high capacity factor, the total cost (LCOE) of geothermal power production is comparable or cheap if compared to those of others renewables.

However, the **capital, up-front costs remain too high**, due to the scarcity of on-site data, the difficulty to forecast the production prior to drill combined with the high drilling costs.



# Geothermal Energy cons

- The economics of electricity production is influenced by the drilling costs and resource development;
- The productivity of electricity per well is a function of reservoir fluid thermodynamic characteristics (phase and temperature);
- The higher the energy content of the reservoir fluid, the lesser is the number of required wells and as a consequence the reservoir CAPEX quota is reduced
- The small dimension of most plants enhance the risk of investment
- Environmental impact (details on Friday)





Thank you for your attention

*Jigokudani Hot Springs – Japan*



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