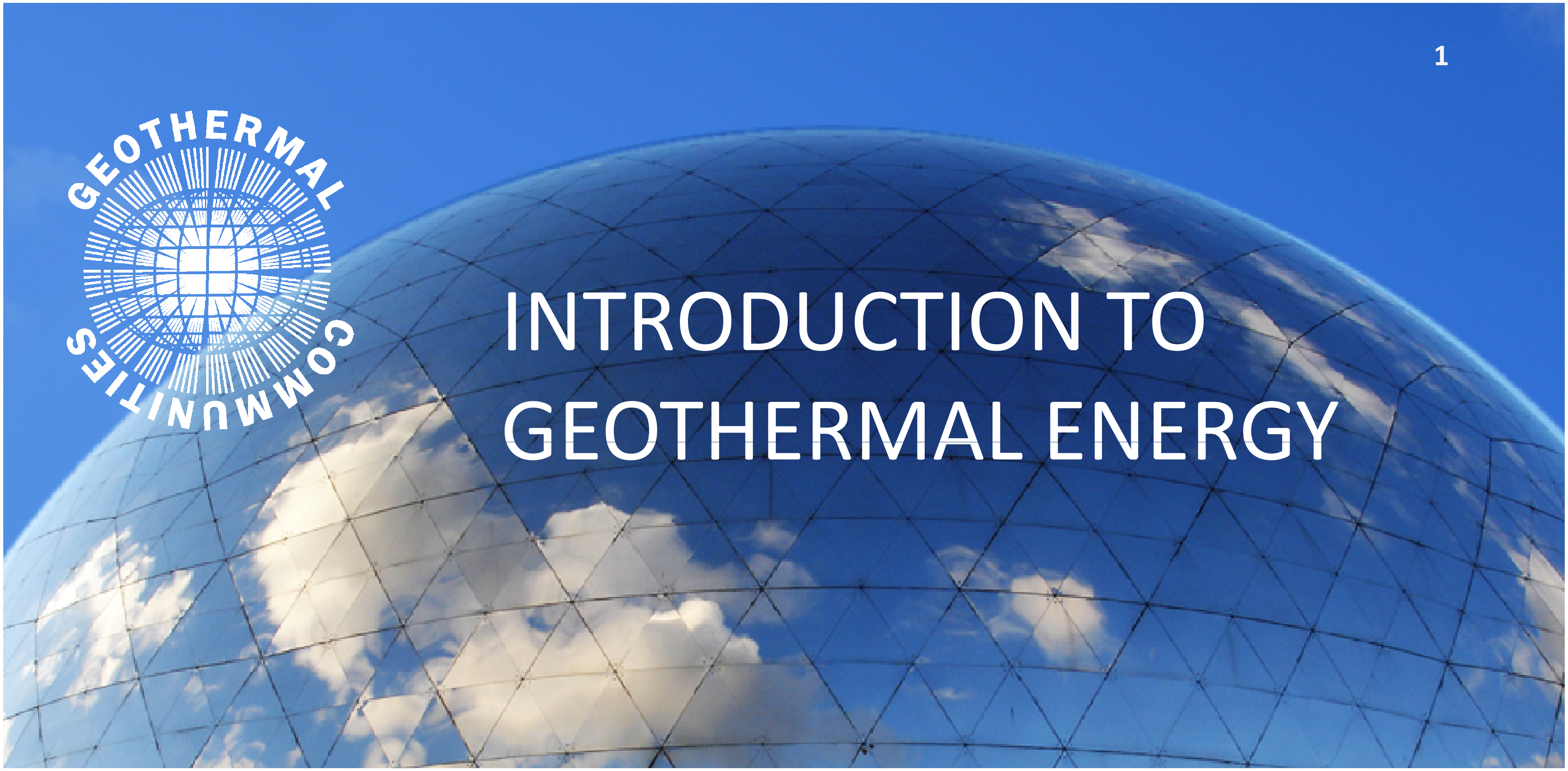


INTRODUCTION TO GEOTHERMAL ENERGY

Based on "What is Geothermal Energy?"
by Mary Dickson and Mario Fanelli

Contents

- Definition
- Brief Geothermal History
- Present Status of Geothermal Utilization
- Nature of Geothermal Resources
- Geothermal Systems
- Definition and Classification of Geothermal Resources
- Exploration
- Utilization of Geothermal Resources
- Environmental Impacts
- Present and Future

Definition

Heat is a form of energy and geothermal energy is the heat contained within the Earth that generates geological phenomena on a planetary scale.

'Geothermal energy' is most often used to indicate that part of the Earth's heat that can, or could, be recovered and exploited by man.

Brief Geothermal History

The presence of volcanoes, hot springs, and other thermal phenomena must have led our ancestors to surmise that parts of the interior of the Earth were hot.

Between 16th and 17th century, first mines were excavated to a few hundred meters below ground level ► man deduced, from simple physical sensations, that the Earth's temperature increases with depth.

The first measurements by thermometer - probably performed in 1740 by De Gensanne, in a mine near Belfort, in France.

By 1870, modern scientific methods were being used to study the thermal regime of the Earth.

Brief Geothermal History

In the 20th century the role of radiogenic heat, had been discovered.

All modern thermal models of the Earth, must take into account the continually generated heat by the decay of the long-lived radioactive isotopes of (U^{238}, U^{235}), (Th^{232}) and (K^{40}). Other potential sources of heat - the primordial energy of planetary accretion.

In the 1980s it had been demonstrated that there is no equilibrium between the radiogenic heat generated in the Earth's interior and the heat dissipated into space from the Earth, and that our planet is slowly cooling down.

Brief Geothermal History

Heat balance from Stacey and Loper (1988):

- Total flow of heat from the Earth estimated at 42×10^{12} W (conduction, convection, radiation)
- 8×10^{12} W come from the crust,
- 32.3×10^{12} W come from the mantle,
- 1.7×10^{12} W come from the core.

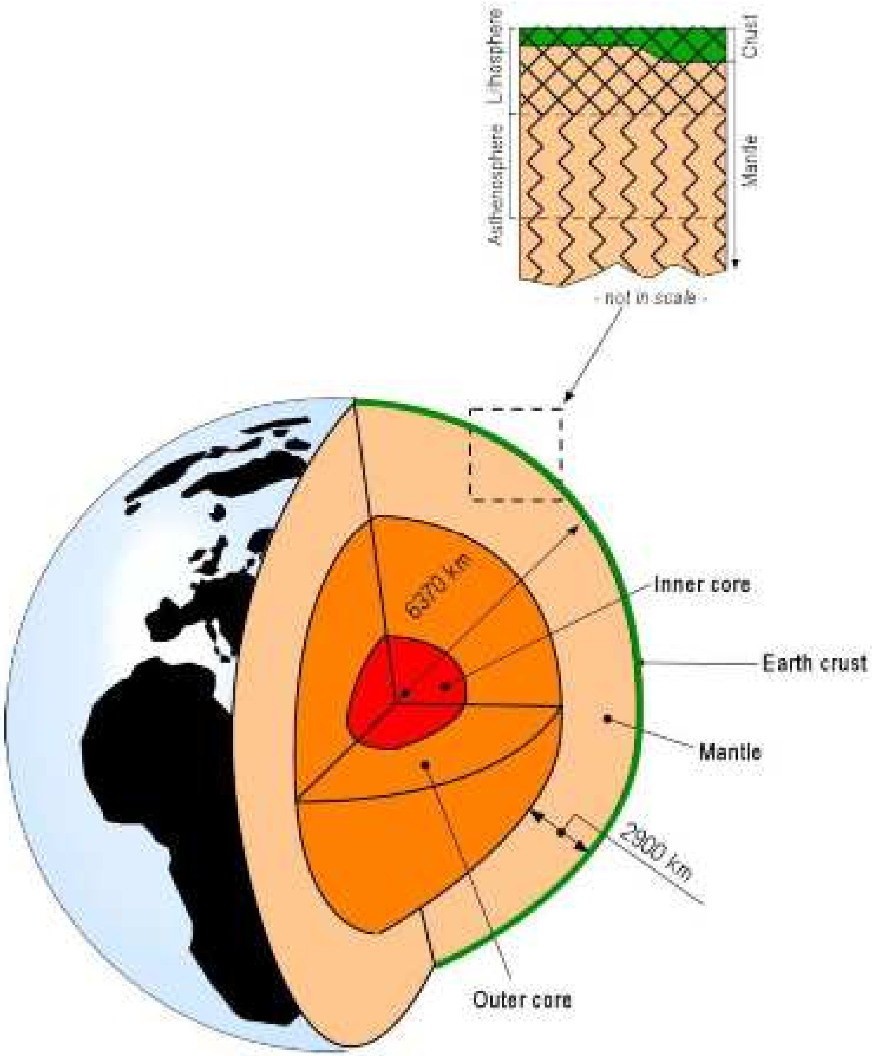
The radiogenic heat of the mantle is estimated at 22×10^{12} W ▶ the cooling rate of the mantle is 10.3×10^{12} W.

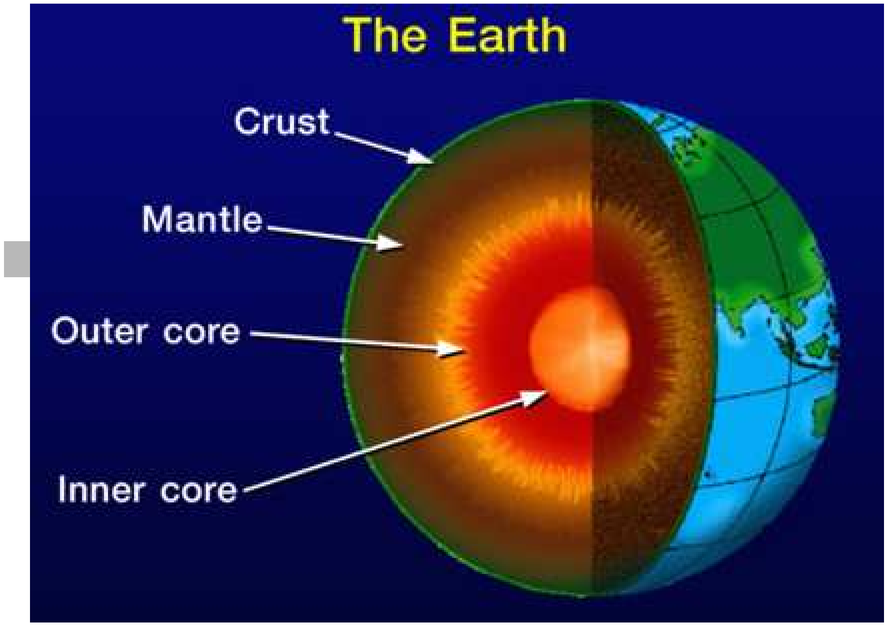
Brief Geothermal History

It has been estimated that the total heat content of the Earth, with assumed average surface temperature of 15°C, is of the order of 12.6 x 10^{24} MJ, and that of the crust 5.4 x 10^{21} MJ.

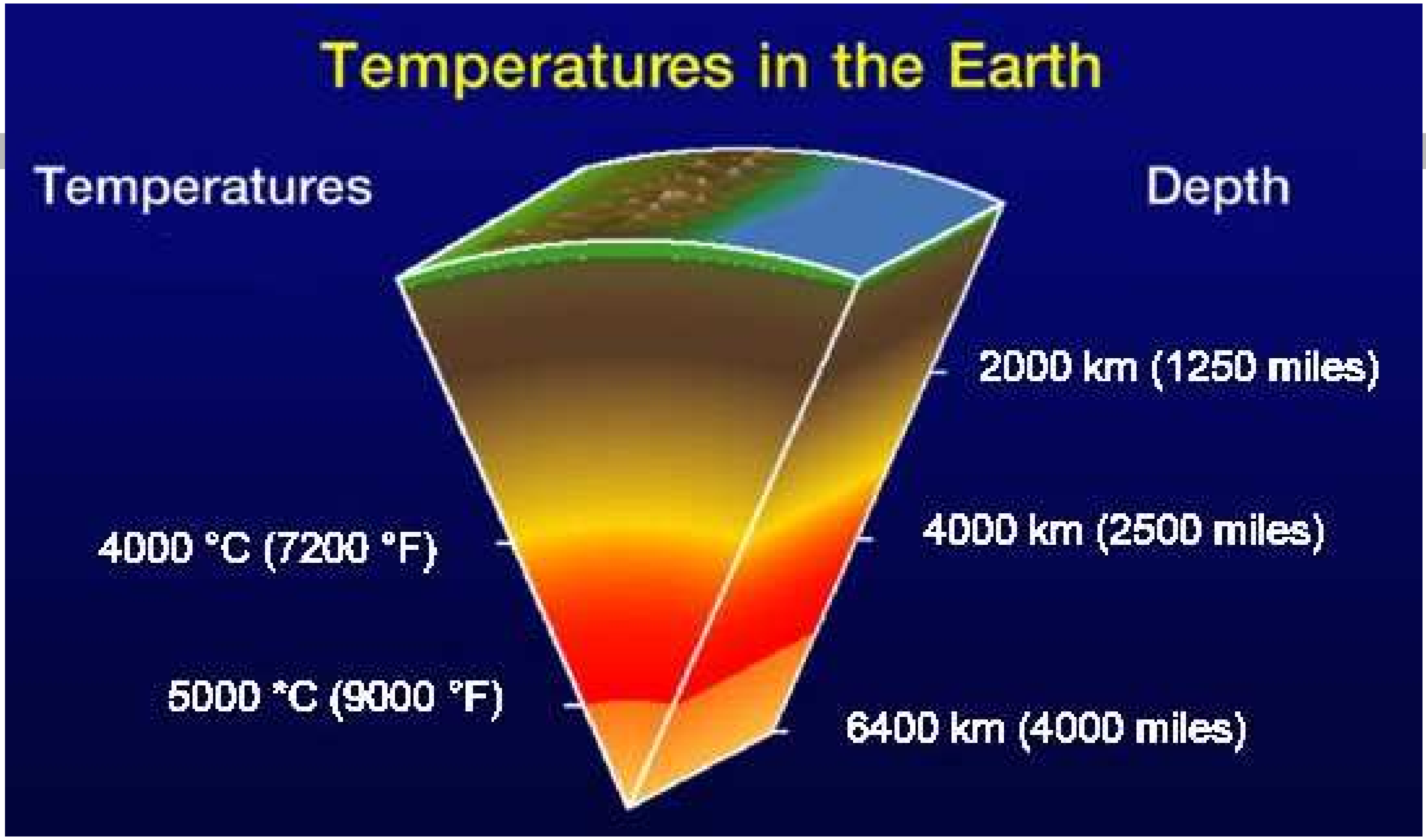
⇒ The thermal energy of the Earth is huge, but only a fraction could be utilized by mankind.

Our utilization so far is limited to areas in which geological conditions permit a carrier to 'transfer' the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources; innovative techniques in the near future, may offer new perspectives in this sector.



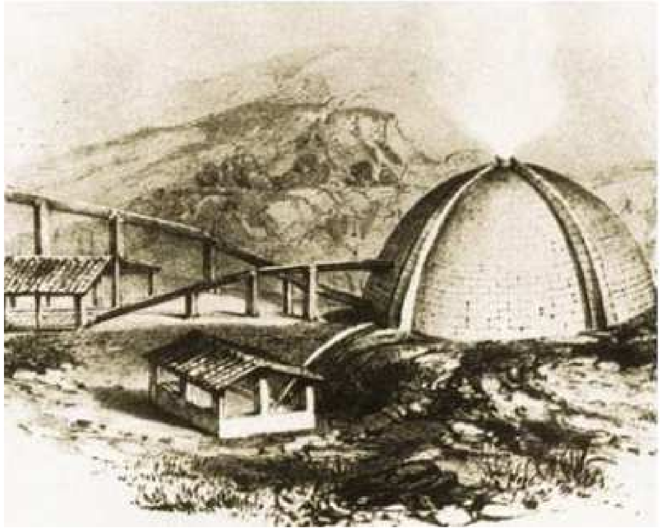


The Earth's crust, mantle and core


Temperatures in the Earth
Temperatures
Depth
2000 km (1250 miles)
4000 °C (7200 °F)
4000 km (2500 miles)
5000 °C (9000 °F)
6400 km (4000 miles)

Brief Geothermal History

In the early 19th century the geothermal fluids were already exploited for their energy content. Chemical industry in Italy - Larderello for extraction of boric acid from the boric hot waters (natural or shallow drilled boreholes).



In 1827 Francesco Larderel, founder of this industry, developed a system for utilizing the heat of the boric fluids in the evaporation process, rather than burning wood from the rapidly depleting forests.

"Covered lagoon"

Brief Geothermal History

1850 - 1875 - factory at Larderello held the monopoly in Europe for boric acid production.

1910 - 1940 - low-pressure steam used to heat industrial and residential buildings and greenhouses (Tuscany-Larderello).

1892 - first geothermal district heating system in Boise, Idaho (USA).

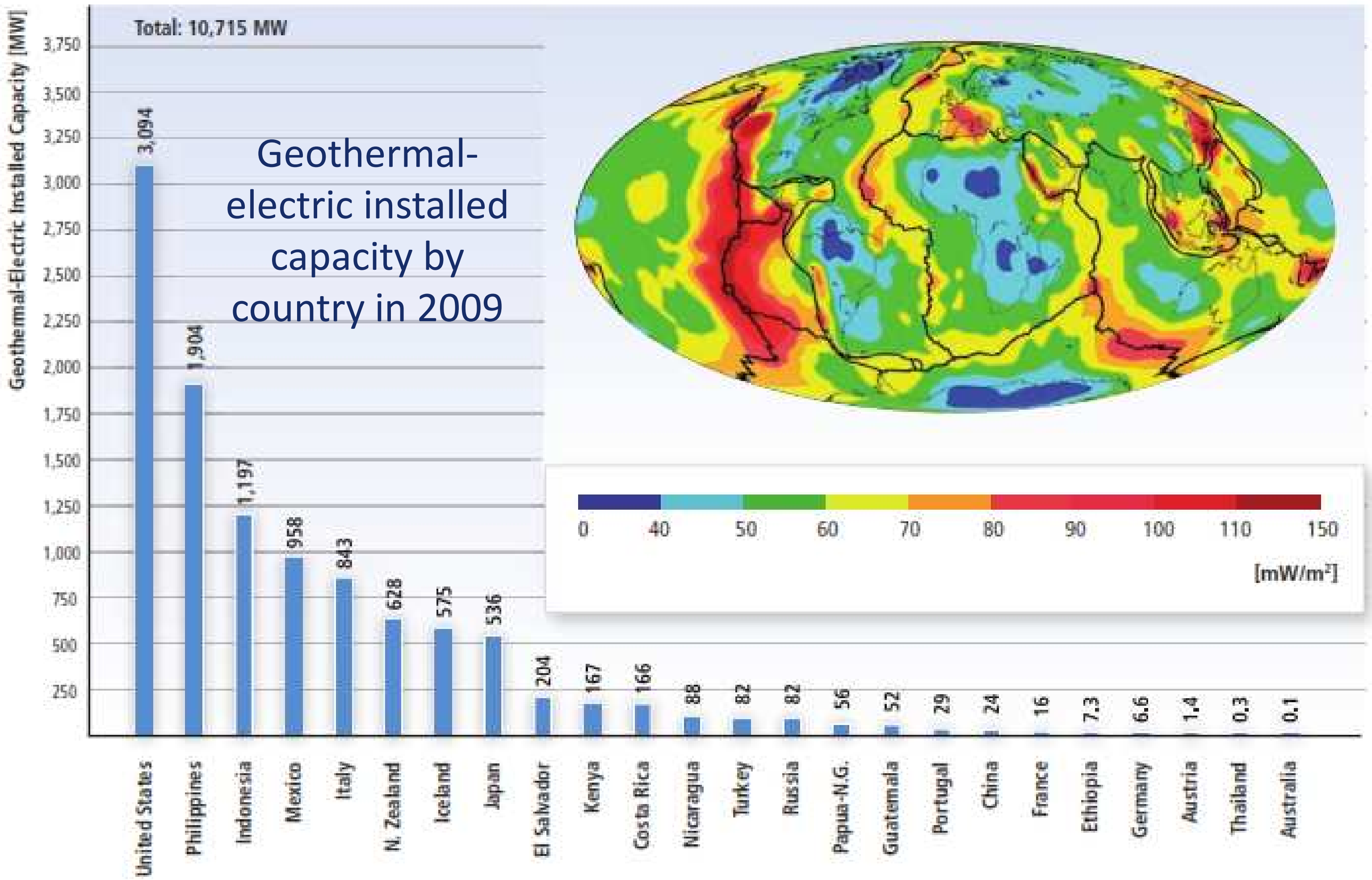
1928 - for domestic heating purposes in Iceland (mainly hot waters).

1904 - first attempt for generating electricity from geothermal steam (Larderello).

Brief Geothermal History

- By 1942 the installed geo-thermoelectric capacity had reached 127,650 kWe.
- In 1919 the first geothermal wells in Japan were drilled at Beppu, followed in 1921 by wells drilled at The Geysers, California, USA.
- In 1958 a small geothermal power plant began operating in New Zealand, in 1959 another began in Mexico, in 1960 in the USA, followed by many other countries in the years to come.

Present Status of Geothermal Utilization



Goldstein, B., et al., 2011: Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, et al. R.], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Non-Electric Uses

Geothermal electricity production		Geothermal direct use	
Country	GWh/yr	Country	GWh/yr*
United States	16 603	China	20 932
Philippines	10 311	United States	15 710
Indonesia	9 600	Sweden	12 585
Mexico	7 047	Turkey	10 247
Italy	5 520	Japan	7 139
Iceland	4 597	Norway	7 000
New Zealand	4 055	Iceland	6 768
Japan	3 064	France	3 592
Kenya	1 430	Germany	3 546
El Salvador	1 422	Netherlands	2 972
Costa Rica	1 131	Italy	2 762
Turkey	490	Hungary	2 713
Papua New Guinea	450	New Zealand	2 654
Russia	441	Canada	2 465
Nicaragua	310	Finland	2 325

Data source: Bertani, WGC 2010; Lund et al., WGC 2010

Top 15 countries
using geothermal energy

Nature of Geothermal Resources

Geothermal gradient (GG) expresses the increase in temperature with depth in the Earth's crust. Down to over 10,000 m (depths accessible by drilling), the average GG is about 2.5-3°C/100 m. E.g., if the temp. within the first few meters below ground-level, is 15°C, then it can be assumed that the temp. will be about 65-75°C at 2000 m depth, 90-105°C at 3000 m and so on for a further few thousand meters.

In areas in which the deep rock basement has undergone rapid sinking, and the basin is filled with geologically 'very young' sediments, the GG may be lower than 1°C.

Nature of Geothermal Resources

The ΔT between deep hotter zones and shallow colder zones generates a conductive flow of heat. The mean terrestrial heat flow of continents and oceans is 65 and 101 mWm^{-2}, which, yield a global mean of 87 mWm^{-2}. These values are based on 24,774 measurements at 20,201 sites covering about 62% of the Earth's surface. Empirical estimators, referenced to geological map units, enabled heat flow to be estimated in areas without measurements.

The temp. increase with depth, volcanoes, geysers, hot springs, etc., are the visible or tangible expression of the heat in the interior of the Earth. This heat creates other phenomena less visible, but of such magnitude that the Earth has been compared to an immense ‘thermal engine’.

Nature of Geothermal Resources

Plate Tectonics theory

The crust has a thickness of ∽ 20-65 km in continental areas and ∽ 5-6 km in oceanic areas, the mantle is roughly 2900 km thick, and the core, ∽ 3470 km in radius. Their physical and chemical characteristics vary from the surface of the Earth to its centre. The outermost shell of the Earth - lithosphere, is made up of the crust and the upper layer of the mantle; with thickness from < 80 km in oceanic zones to > 200 km in continental areas, and behaves as a rigid body. Below the lithosphere is the asthenosphere, 200-300 km in thickness, with 'more plastic' behavior.

Nature of Geothermal Resources

Due to ΔT between the different parts of the asthenosphere, convective movements were formed some tens of millions of years ago. Their extremely slow movement (a few cm per year) is maintained by the heat produced continually by the decay of the radioactive elements and the heat coming from the deepest parts of the Earth.

Immense volumes of deep hotter rocks, less dense and lighter than the surrounding material, rise with these movements towards the surface, while the colder, denser and heavier rocks near the surface tend to sink, re-heat and rise to the surface once again, very similar to what happens to water boiling in a pot or kettle.

Nature of Geothermal Resources

- spreading ridges
- transform faults
- subduction zones
- magmatic arcs
- plates

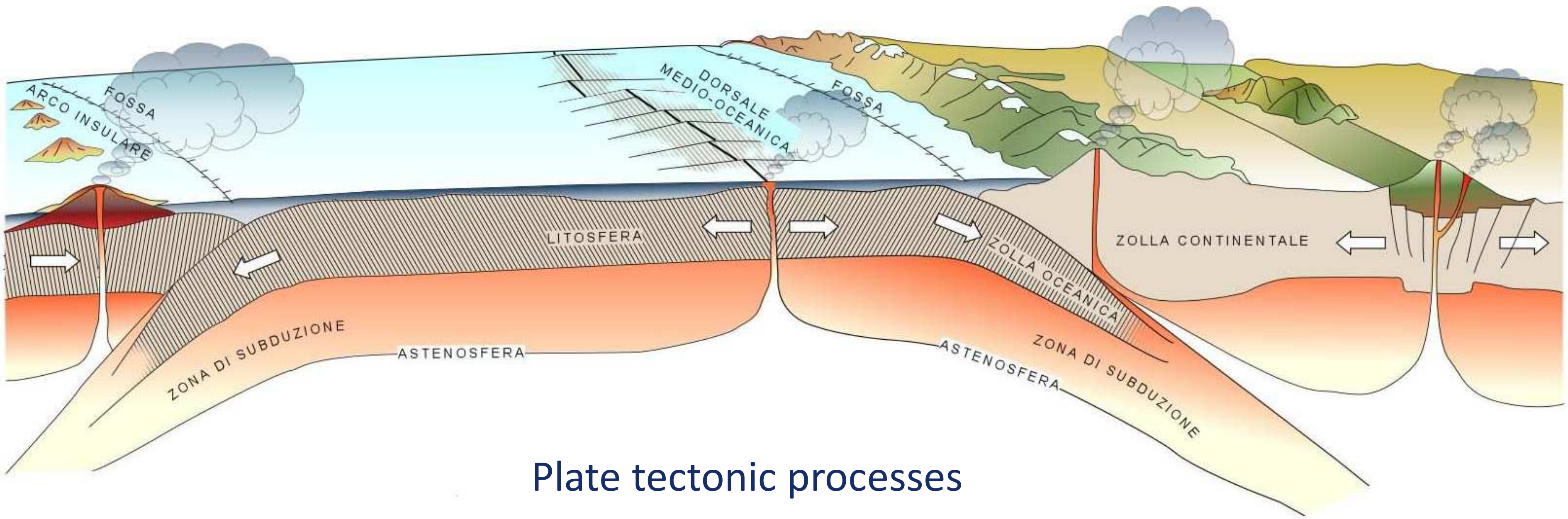
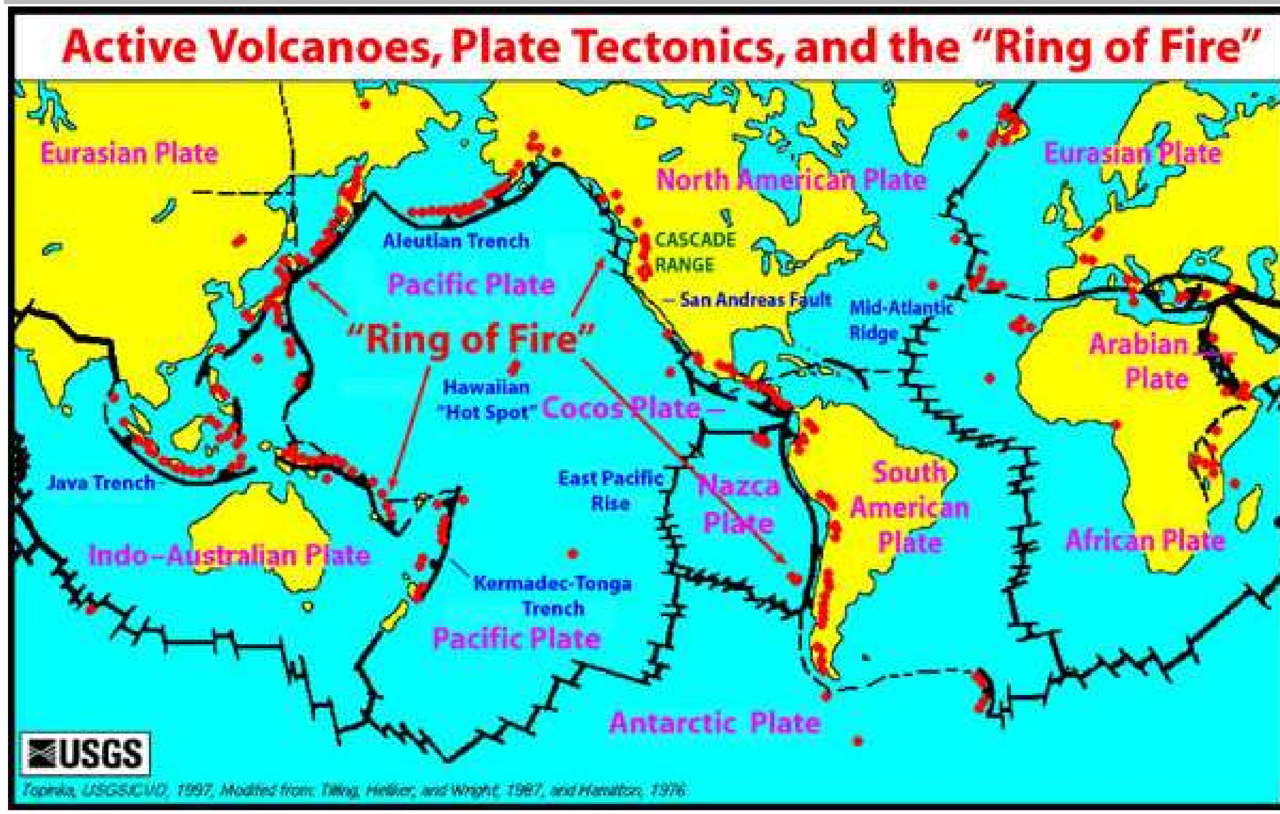


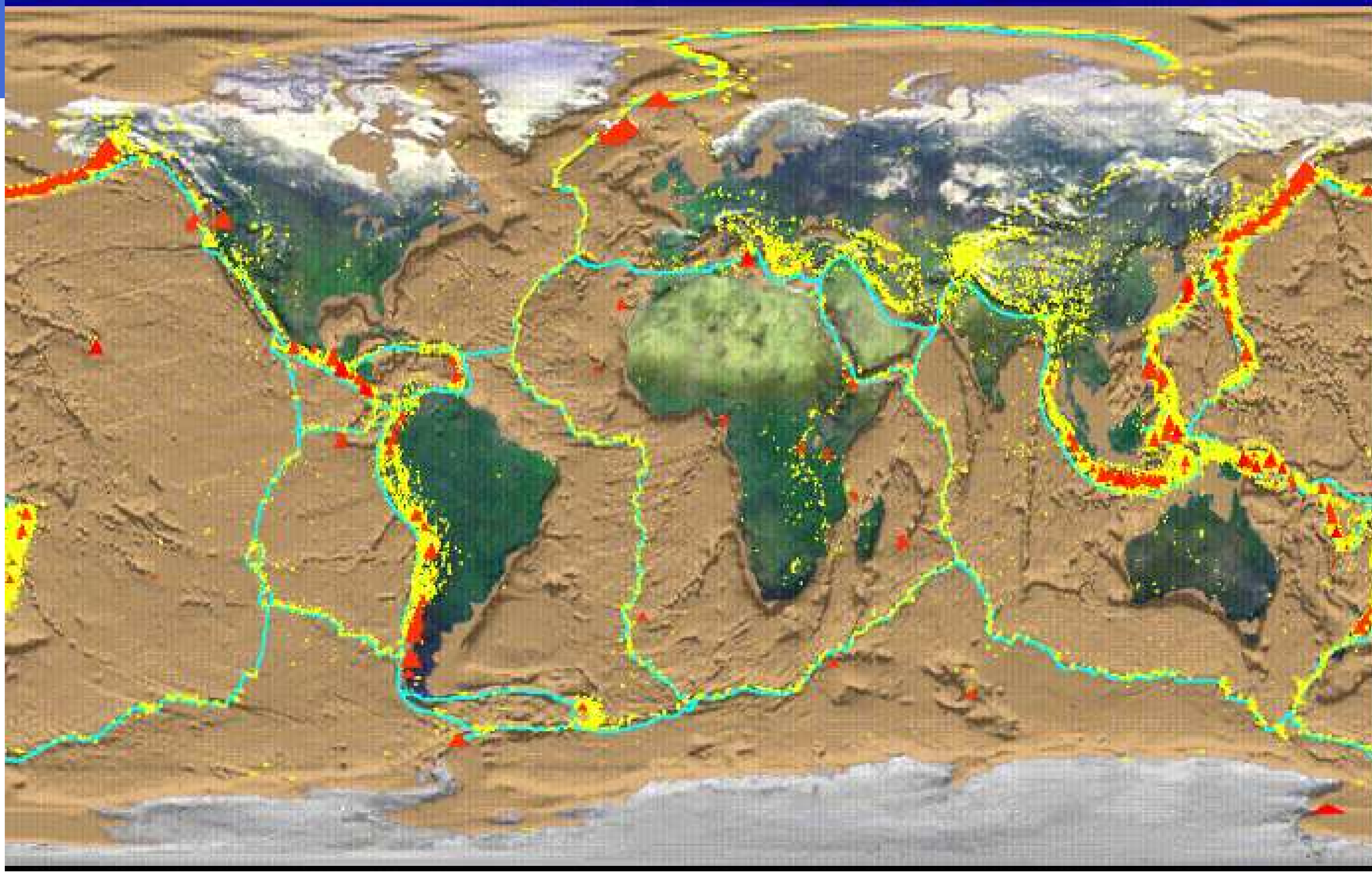
Plate tectonic processes

20

Nature of Geothermal Resources



Tectonic Plate Boundaries



Geothermal Systems

⇒ Geothermal systems can be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case the systems will be characterized by low temperatures, usually no higher than 100°C at economic depths; in the second case the temperatures could cover a wide range from low to very high, and even above 400°C.

⇒ Geothermal system can be described 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'.

Geothermal Systems

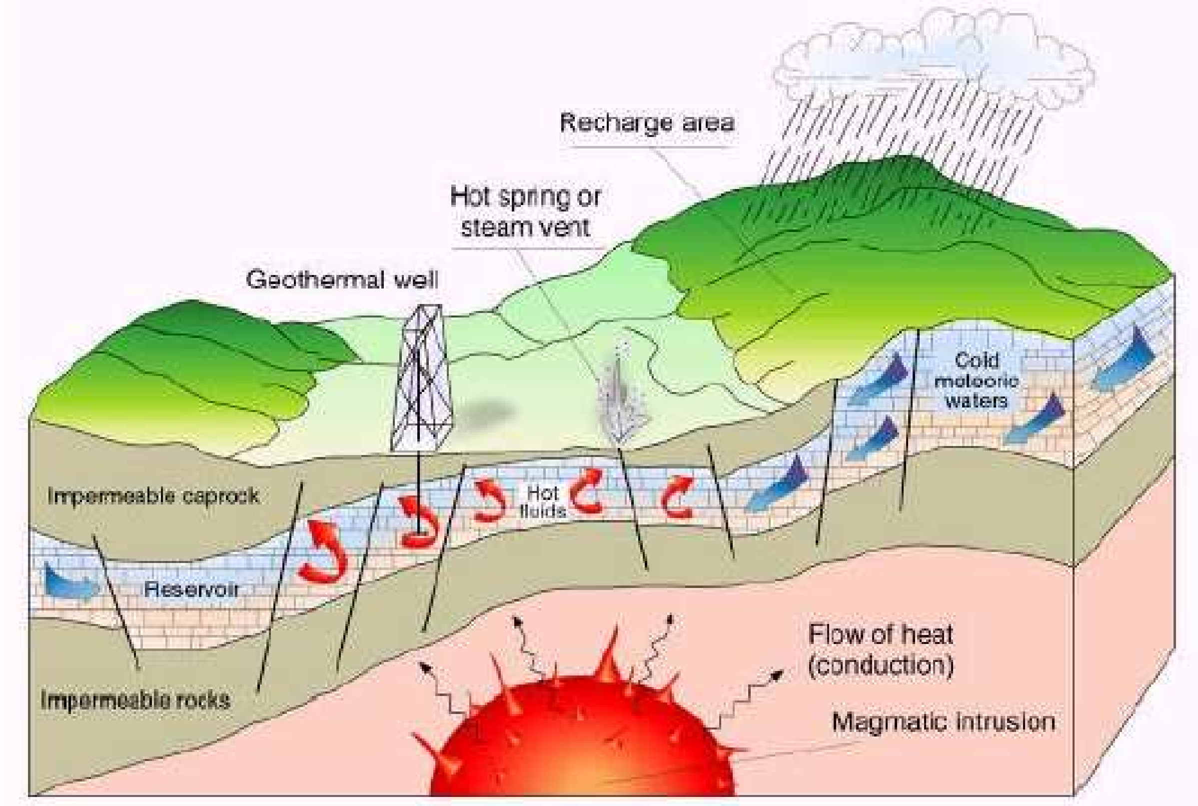
A geothermal system is made up of three main elements:

1. Heat source (either magmatic intrusion with T> 600°C at 5-10 km depth or low-temperature)
2. Reservoir and
3. Fluid (heat carrier/transporter).

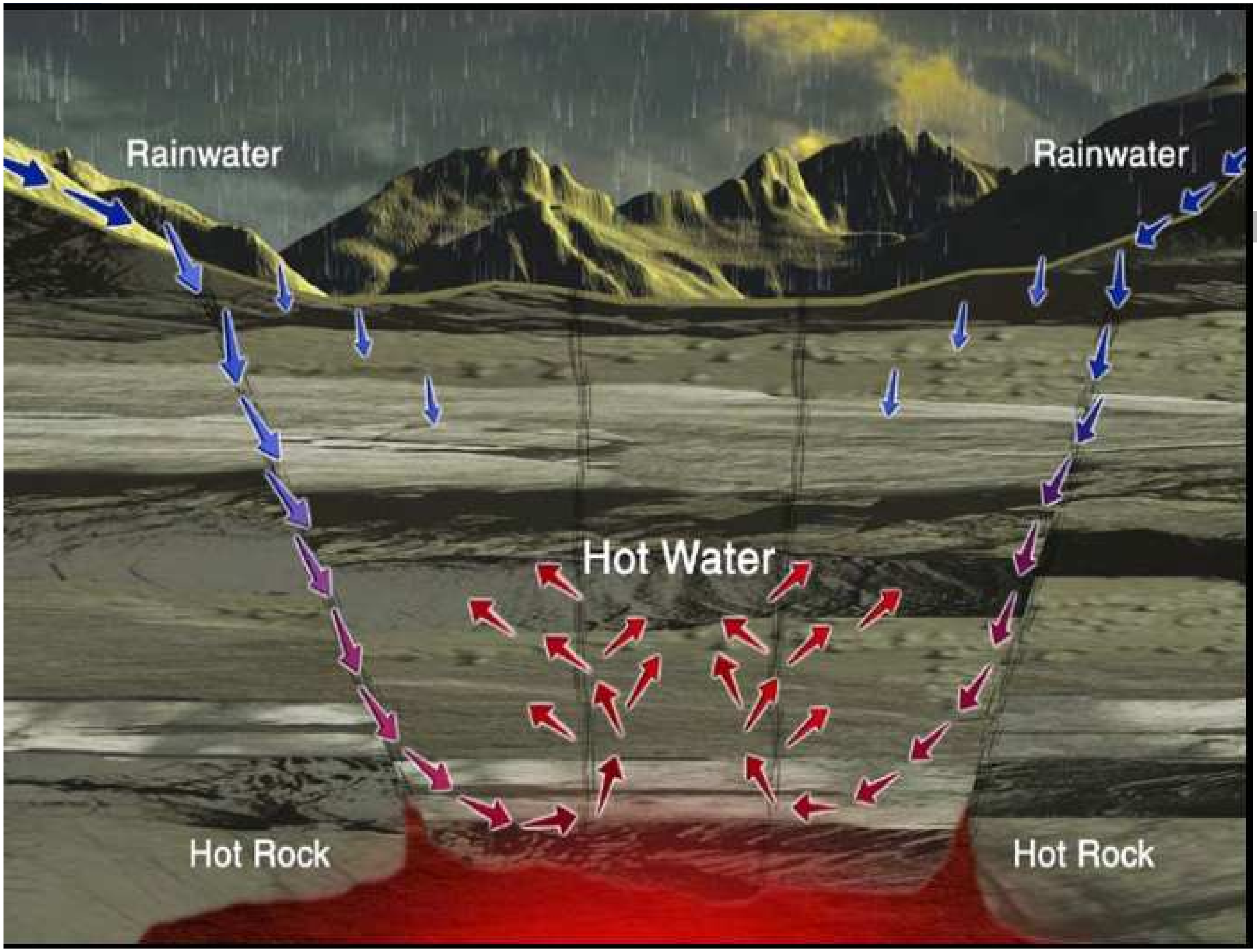
Reservoir - volume of hot permeable rocks from which the heat is extracted, overlaid by a cover of impermeable rocks and connected to a superficial recharge area.

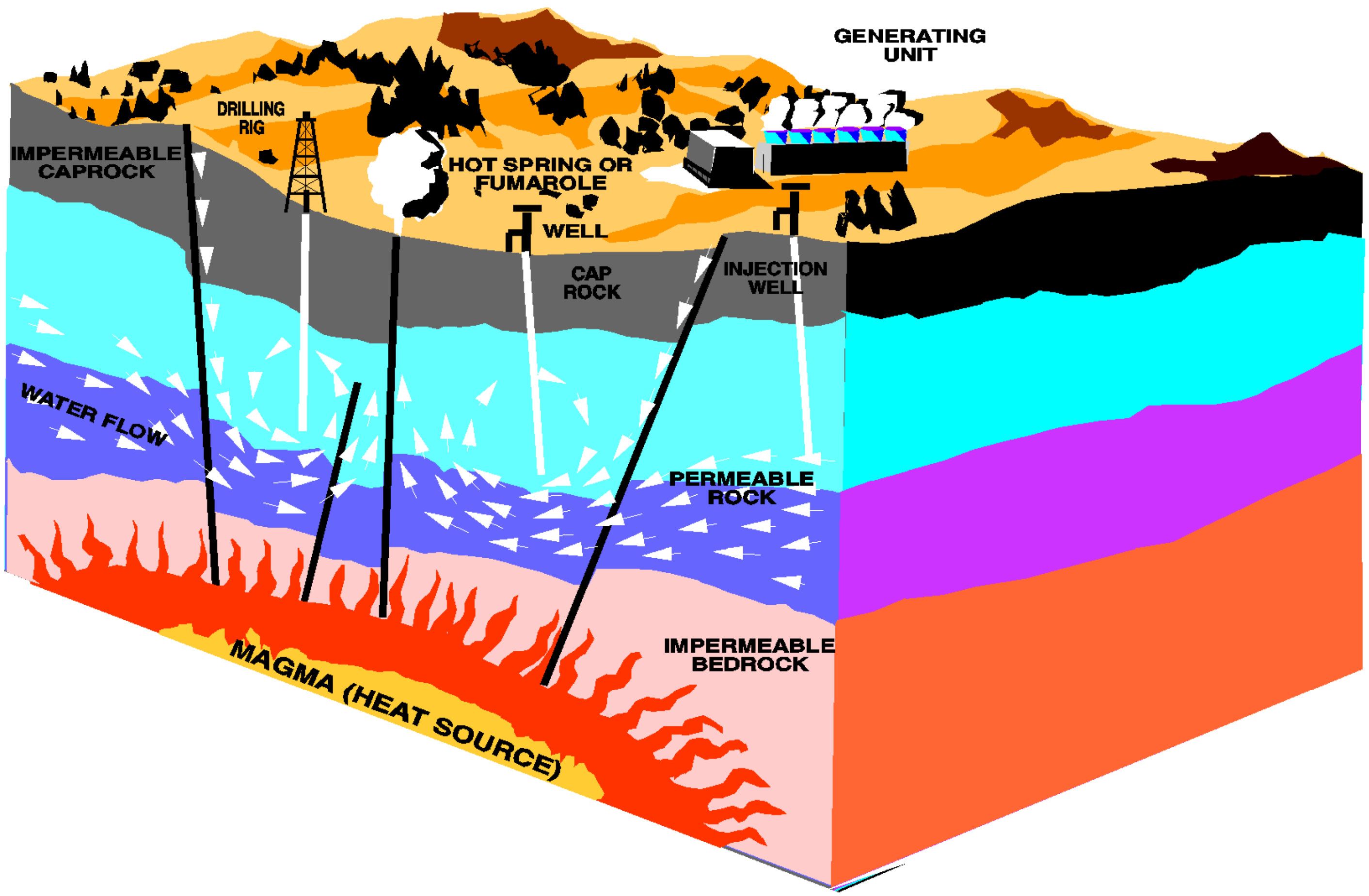
Geothermal fluid is water (mostly of meteoric origin), in liquid or vapor phase, depending on T and p; often carries chemicals and gases such as CO_2, H_2S, etc.

Geothermal Systems



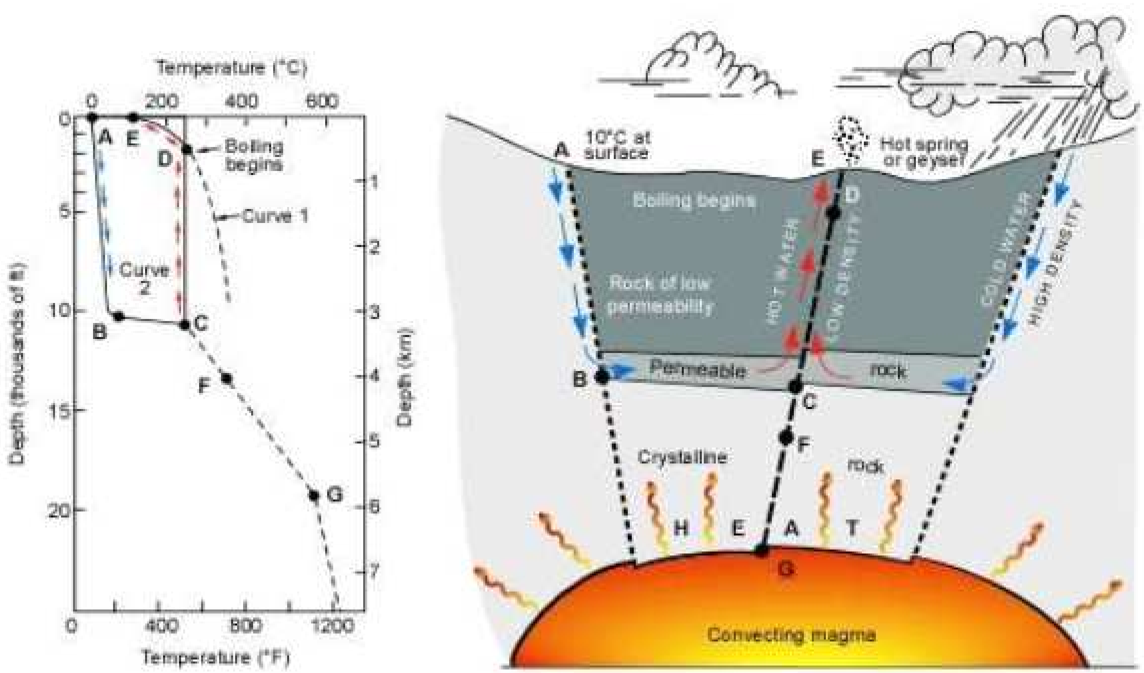
Schematic representation of an ideal geothermal system


Rainwater
Rainwater
Hot Water
Hot Rock
Hot Rock


GENERATING UNIT
DRILLING RIG
IMPERMEABLE CAPROCK
HOT SPRING OR FUMAROLE
WELL
CAP ROCK
INJECTION WELL
WATER FLOW
PERMEABLE ROCK
IMPERMEABLE BEDROCK
MAGMA (HEAT SOURCE)

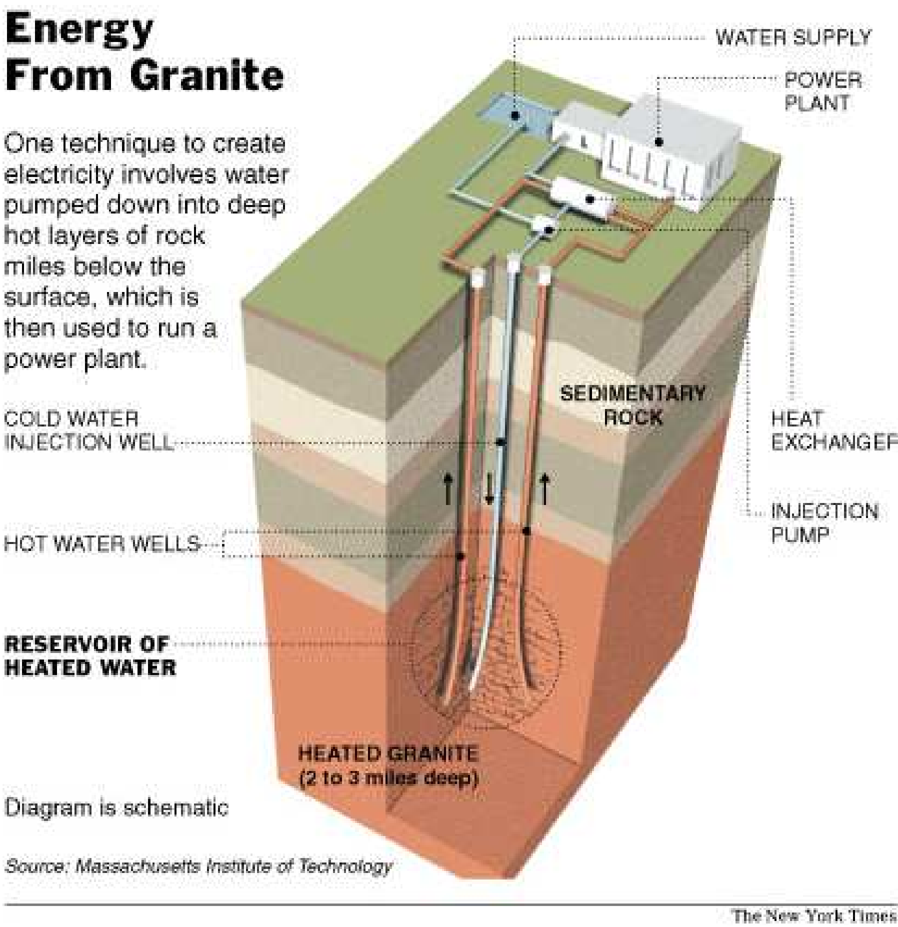
Geothermal Systems

Fluid convection governs the mechanism underlying geothermal systems.



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

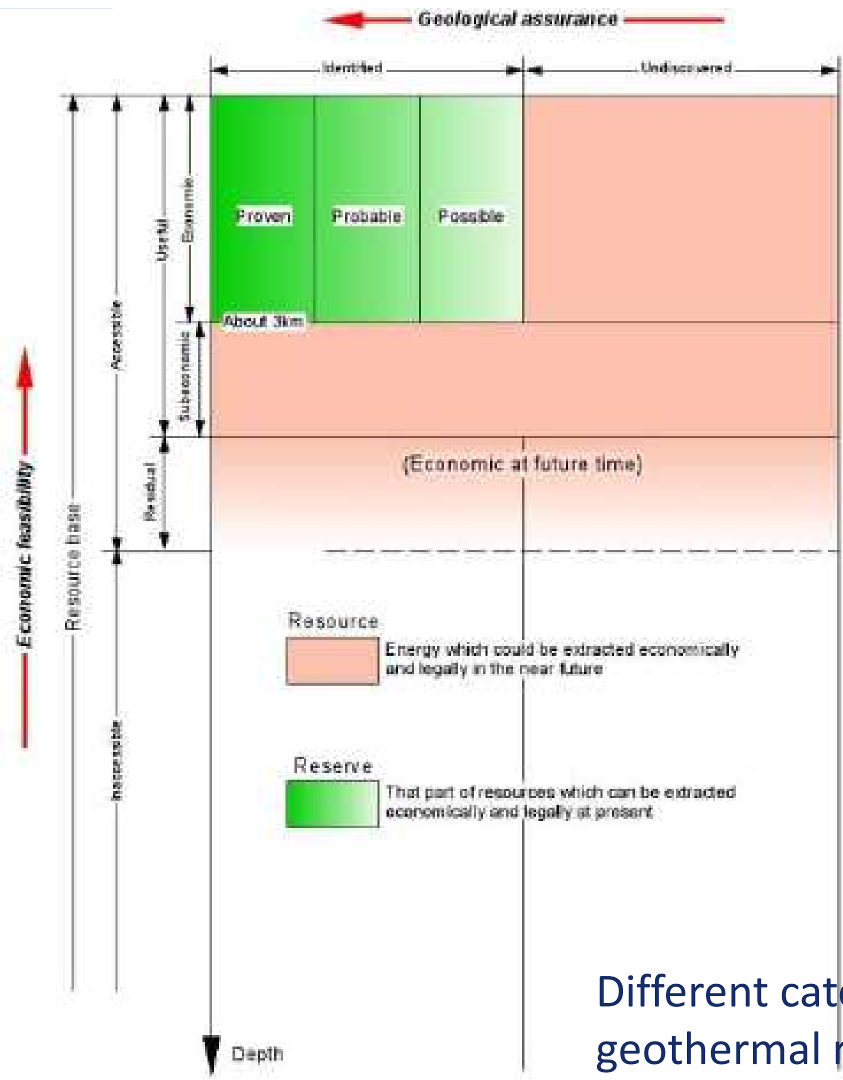
Geothermal Systems



Geothermal systems occur in nature in a variety of combinations of geological, physical and chemical characteristics, thus giving rise to several different types of system.

Re-injection / injection back the used geothermal fluid.

Hot Dry Rock or Enhanced Systems



Definition and Classification of Geothermal Resources

The accessible resource base - This category includes the identified economic resource (=Reserve) - that part of the resources of a given area that can be extracted legally at a cost competitive with other commercial energy sources and that are known and characterized by drilling or by geochemical, geophysical and geological evidence.

Different categories of geothermal resources

Definition and Classification of Geothermal Resources

The most common classification of geothermal resources is based on the enthalpy of the geothermal fluids. The resources are divided into low, medium and high enthalpy resources, according to criteria that are generally based on the energy content of the fluids and their potential forms of utilization.

Category	Temperature range [ºC]
Low enthalpy	< 90 - 190
Intermediate enthalpy	90 - 200
High enthalpy	> 150 - 190

Definition and Classification of Geothermal Resources

Distinction: water- or liquid-dominated geothermal systems and vapor-dominated (or dry steam) geothermal systems.

In liquid-dominated systems some vapor may be present as discrete bubbles; temperatures range from < 125 to > 225°C; the most widely distributed in the world. Depending on temperature and pressure conditions, they can produce hot water, water and steam mixtures, wet steam and, in some cases, dry steam.

In vapor-dominated systems liquid and vapor co-exist in the reservoir. Geothermal systems of this type, the best-known of which are Larderello in Italy and The Geysers in California, are somewhat rare, and are high-temperature systems. They normally produce dry-to-superheated steam.

Definition and Classification of Geothermal Resources

Another division based on the reservoir equilibrium state, where the circulation of the reservoir fluid and the mechanism of heat transfer are considered: dynamic and static systems.

In the dynamic systems the reservoir is continually recharged by water that is heated and then discharged from the reservoir; includes high-temp. (>150°C) and low-temp. (<150°C) systems.

In the static systems (stagnant or storage systems) there is only minor or no recharge to the reservoir; includes low-temp. and geo-pressured systems (found in large sedimentary basins (e.g. Gulf of Mexico, USA) at depths of 3 - 7 km).

Definition and Classification of Geothermal Resources

Geothermal field is a geographical definition, indicating an area of geothermal activity at the earth's surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below .

Renewable describes a property of the energy source (rate of energy recharge), whereas sustainable describes how the resource is utilized (no to be depleted in one generation).

Exploration

Objectives of geothermal exploration:

1. To identify geothermal phenomena.
2. To ascertain that a useful geothermal production field exists.
3. To estimate the size of the resource.
4. To determine the type of geothermal field.
5. To locate productive zones.
6. To determine the heat content of the fluids that will be discharged by the wells in the geothermal field.
7. To compile a body of basic data against which the results of future monitoring can be viewed.
8. To determine the pre-exploitation values of environmentally sensitive parameters.
9. To acquire knowledge of any characteristics that might cause problems during field development.

Exploration

Exploration methods

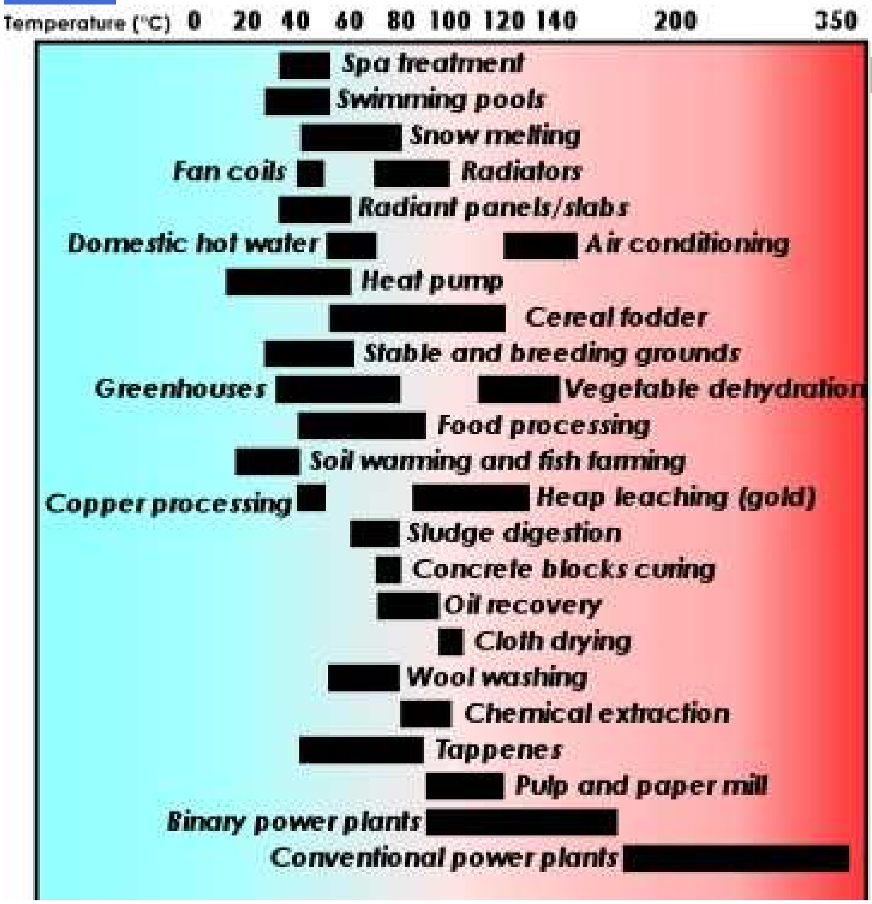
- Geological and hydrogeological studies (starting point – identification of location worth investigating in detail and recommendation of most suitable exploration methods).
- Geochemical surveys (including isotope geochemistry) – determination water or vapor dominated, origin of recharge, homogeneity of supply, minimum expected temperature, chemical composition, etc.
- Geophysical surveys (thermal, seismic, gravity, magnetic surveys, electrical and electromagnetic methods).
- Drilling exploratory wells – final phase.

Exploration

Before drawing up a geothermal exploration program (EP) all existing geological, geophysical and geochemical data must be collected and integrated with any data available from previous studies on water, minerals and oil resources in the study area and adjacent areas. This information frequently plays an important role in defining the objectives of the geothermal exploration program and could lead to a significant reduction in costs.

The EP is usually developed on a step-by-step basis: reconnaissance, pre-feasibility and feasibility.

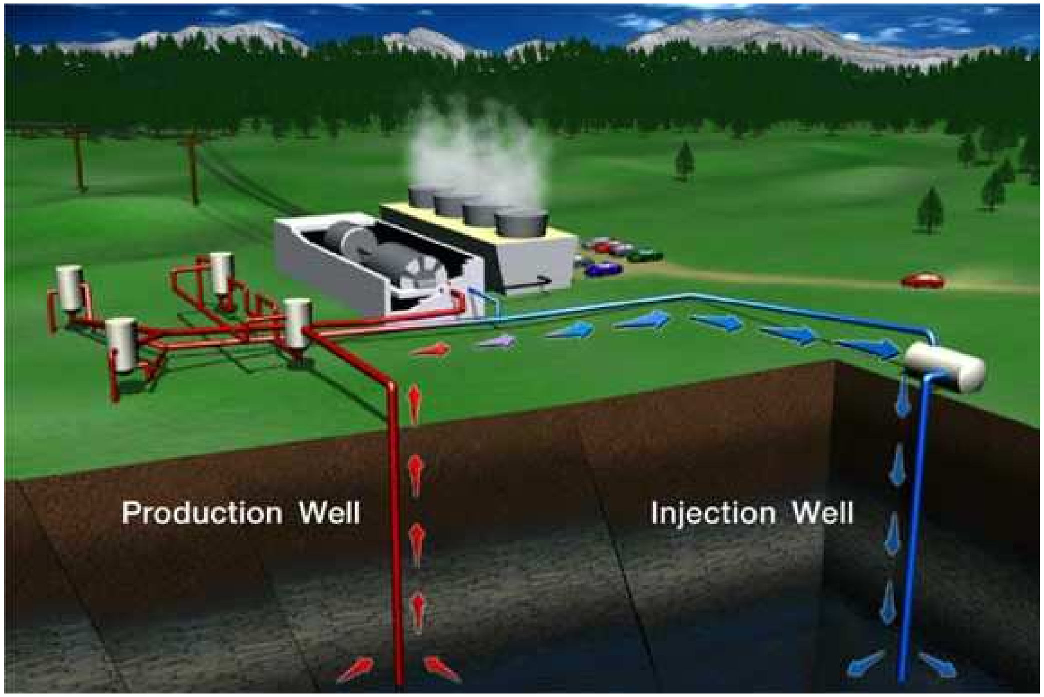
Utilization of Geothermal Resources



Lindal diagram

- ▶ with cascading and combined uses it is possible to enhance the feasibility of geothermal projects and
- ▶ the resource temperature may limit the possible uses.

Utilization of Geothermal Resources
Electricity Generation

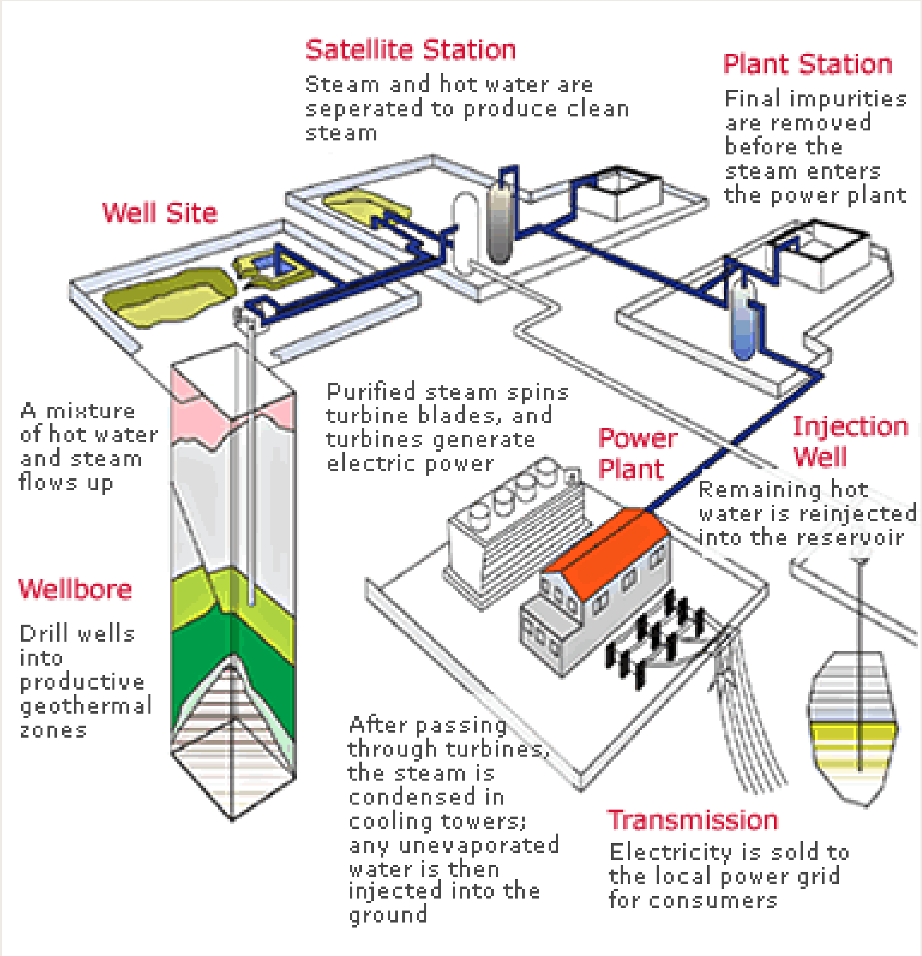


Electricity generation mainly takes place in conventional steam turbines and binary plants, depending on the characteristics of the geo-thermal resource.

Utilization of Geothermal Resources

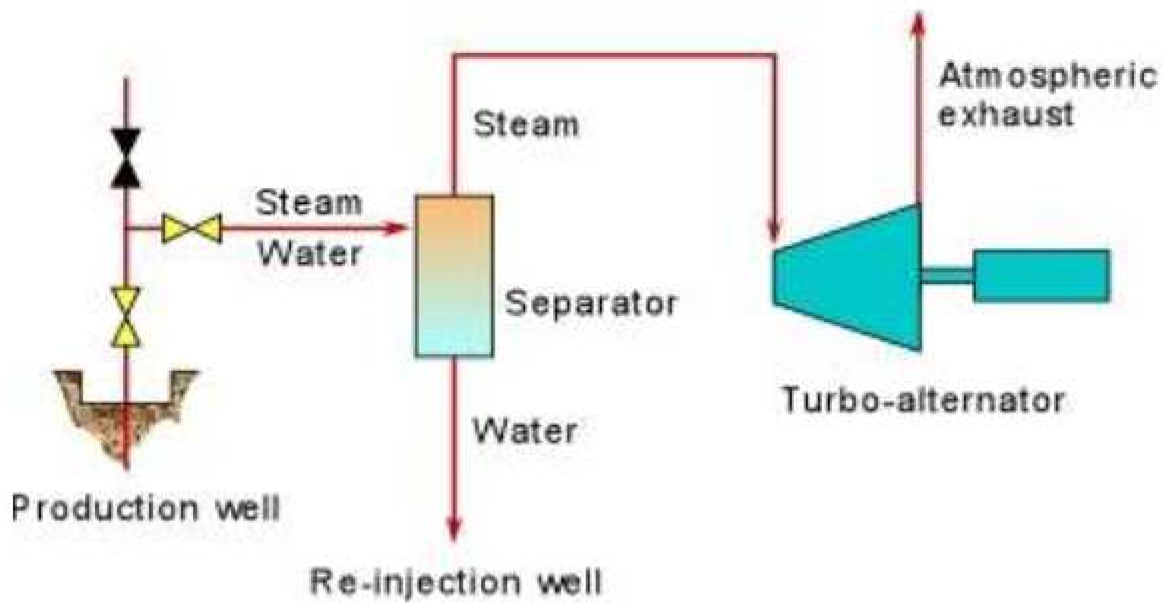
Electricity Generation

Conventional steam turbines require fluids at temperatures of at least 150°C and are available with either atmospheric (back-pressure) or condensing exhausts.



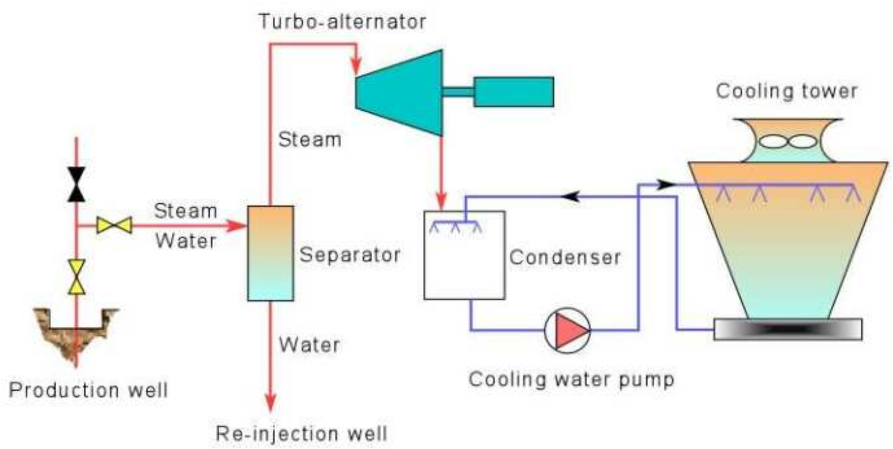
Utilization of Geothermal Resources
Electricity Generation

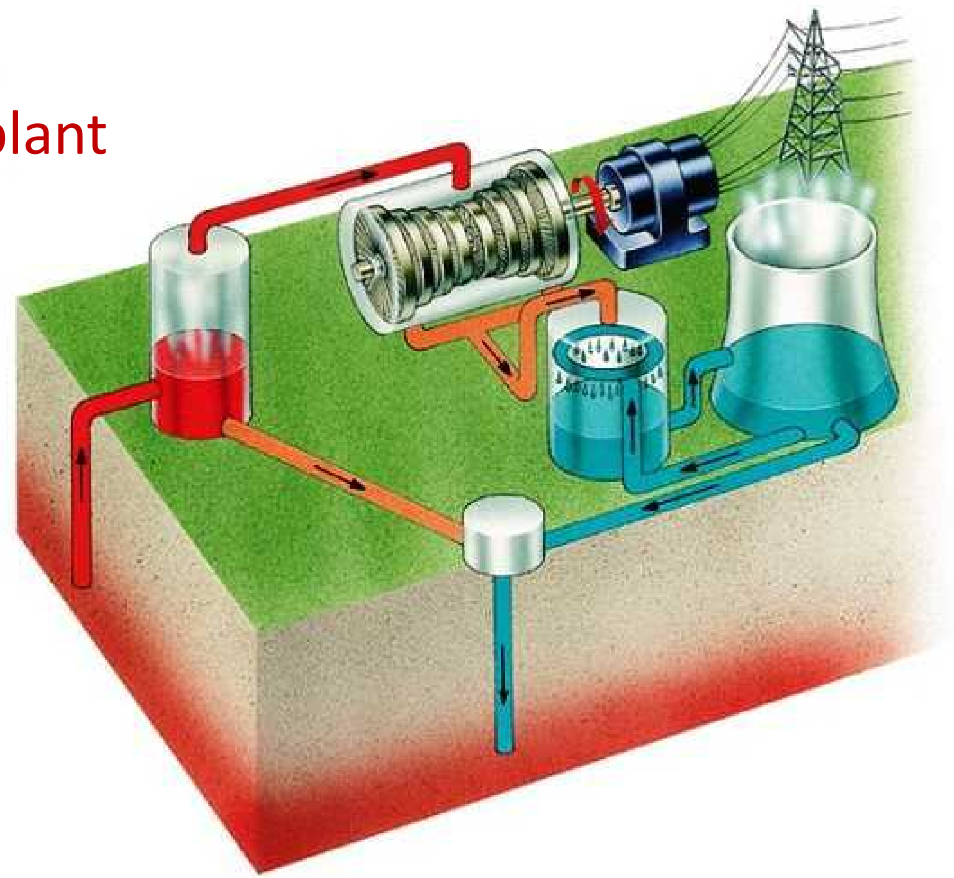
Atmospheric exhaust geothermal power plant
(2.5 – 5 MW_{el})



Utilization of Geothermal Resources
Electricity Generation

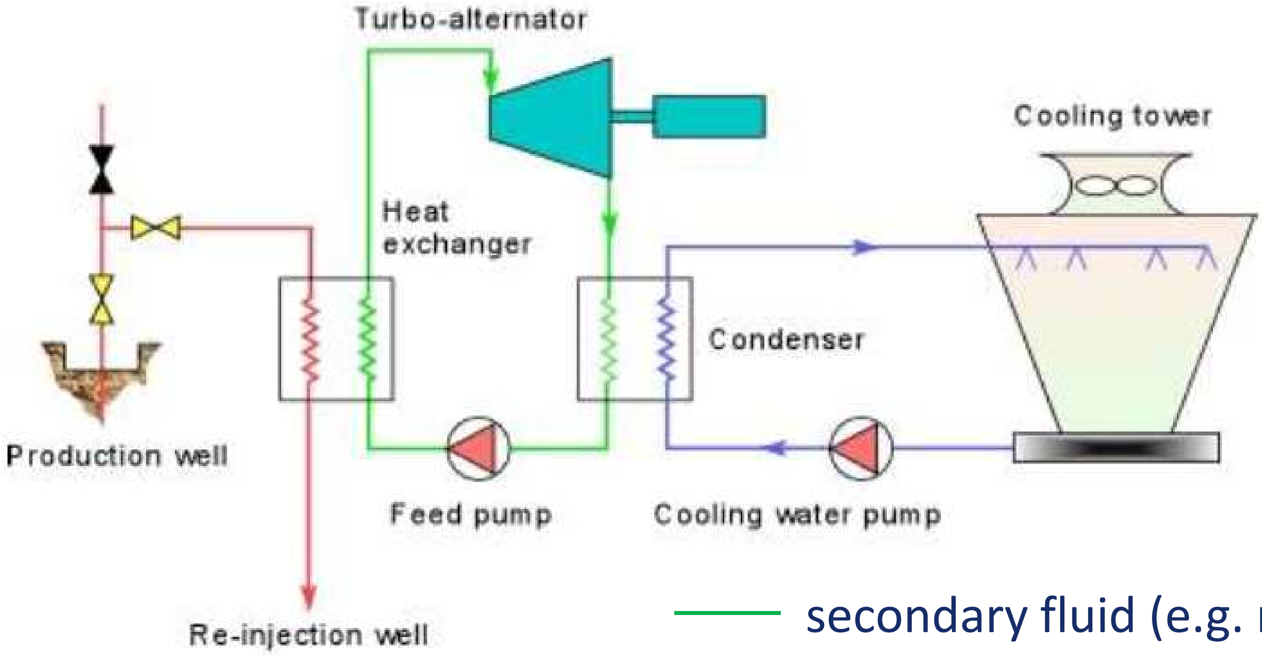
Condensing geothermal power plant
(55 – 60 (110) MW_{el})





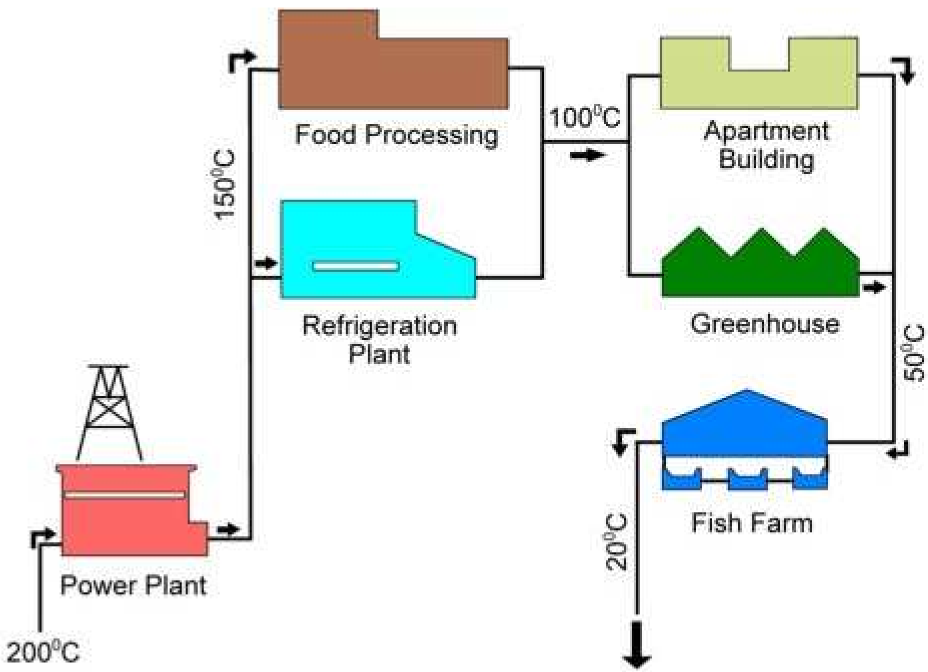
Utilization of Geothermal Resources
Electricity Generation

Geothermal binary power plant
(few hundreds kW_{el} to few MW_{el})



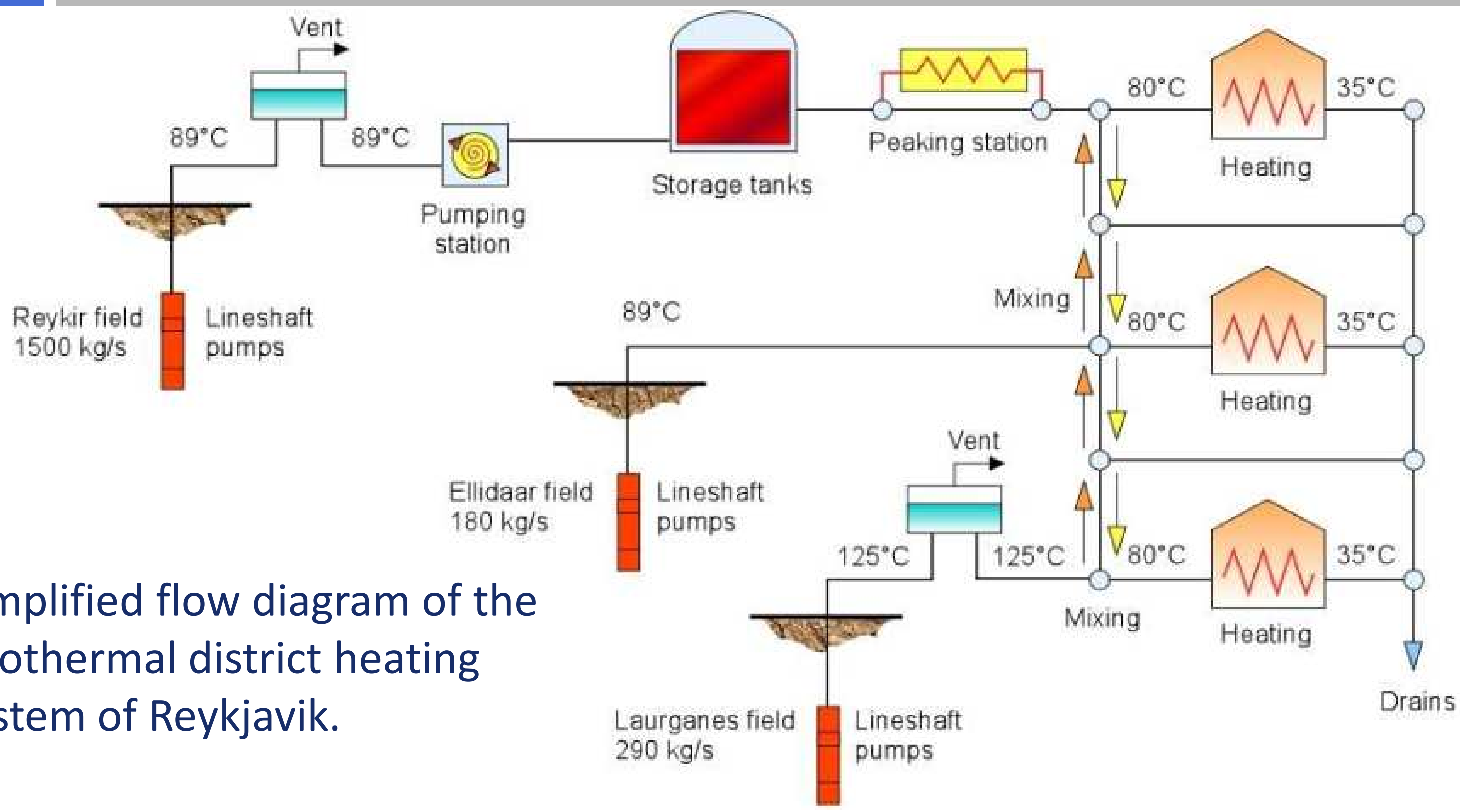
secondary fluid (e.g. n-pentane)

Utilization of Geothermal Resources
Direct Heat Uses



Direct heat use is one of the oldest, most versatile and also the most common form of utilization of geothermal energy: bathing, space and district heating, agricultural applications, aquaculture, some industrial uses, cooling, but heat pumps are the most widespread.

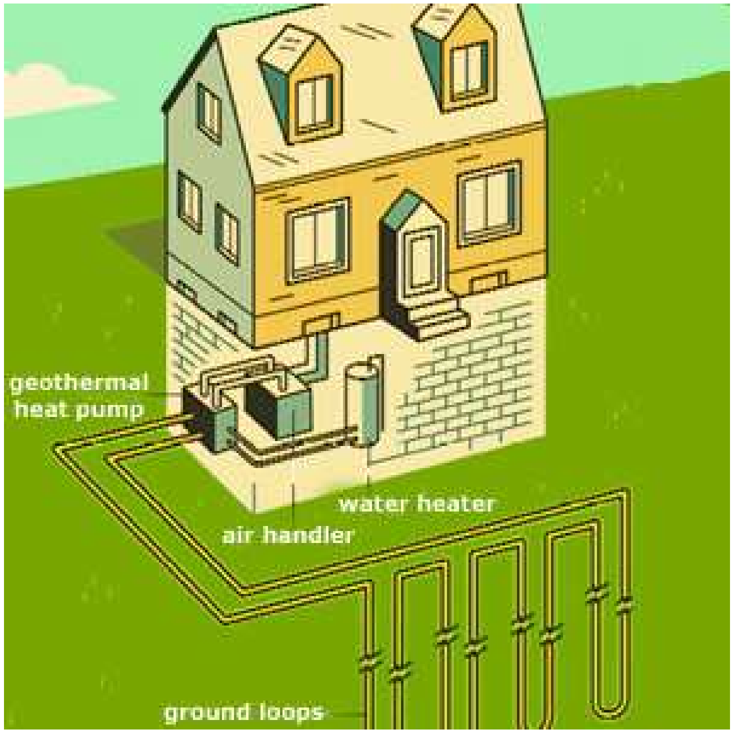
Utilization of Geothermal Resources
Direct Heat Uses

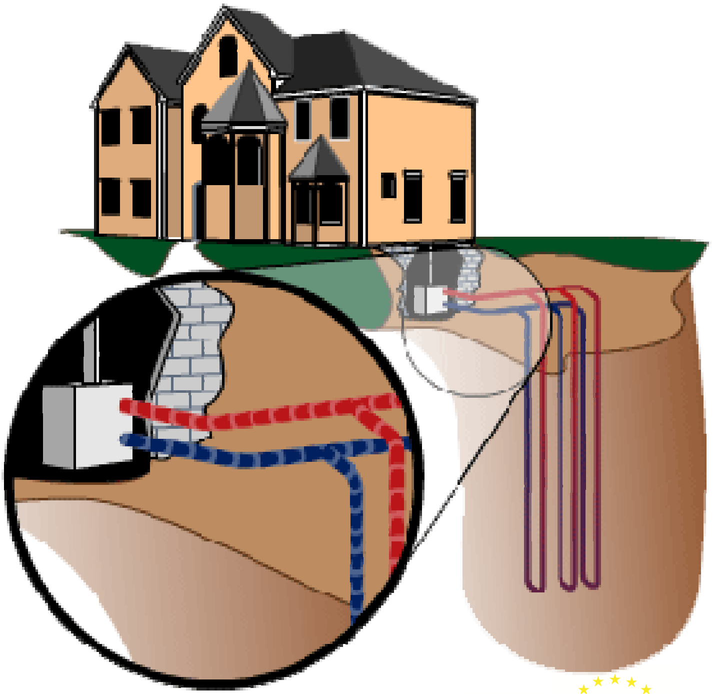


Simplified flow diagram of the geothermal district heating system of Reykjavik.

Utilization of Geothermal Resources
Direct Heat Uses

Geo-heat pumps

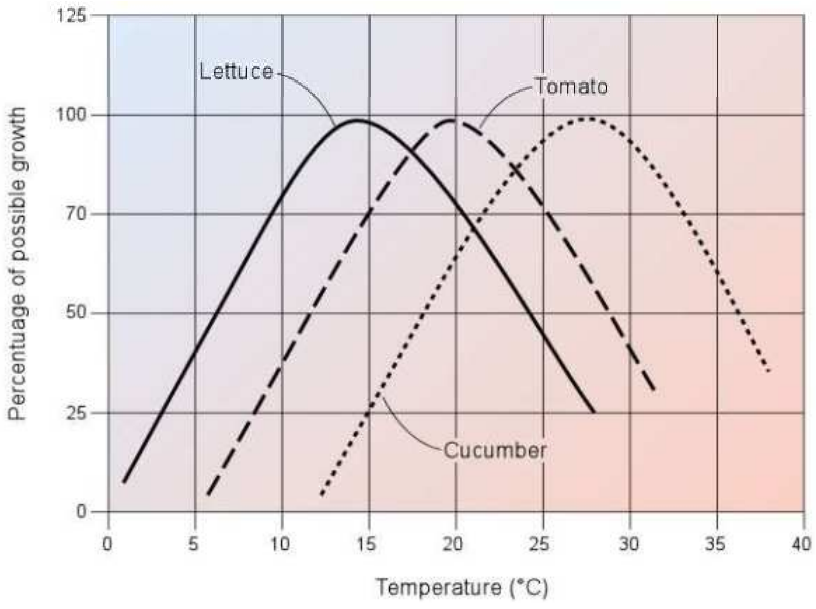


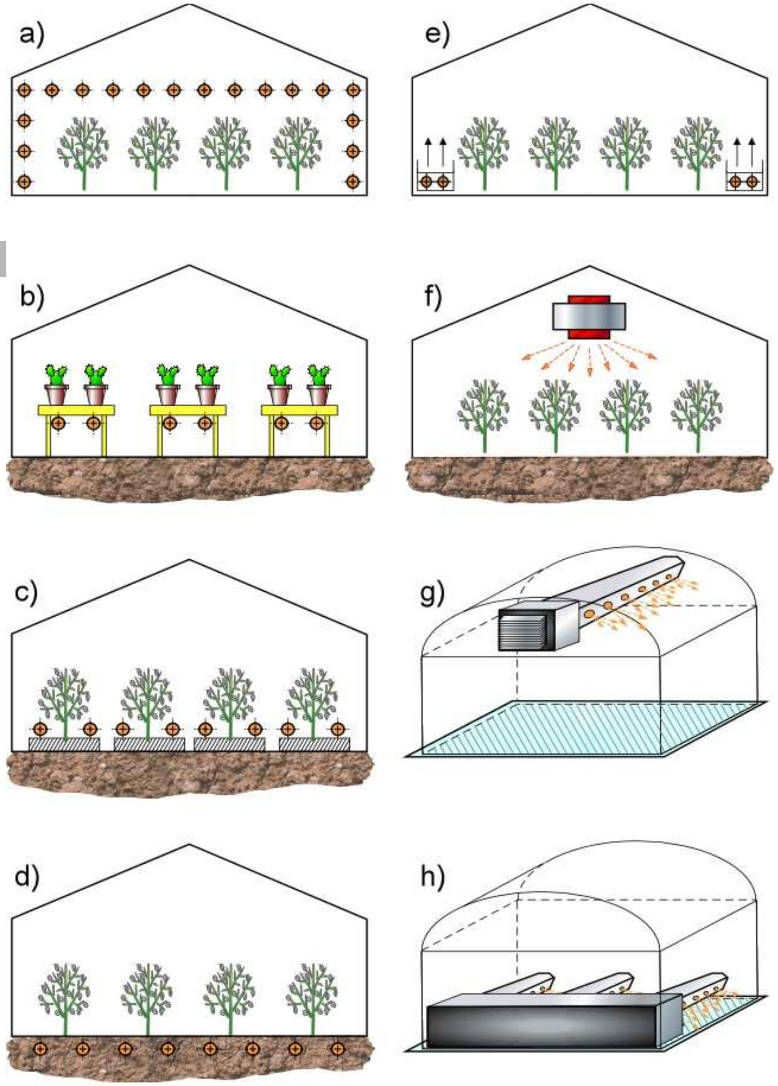


Ground coupled heat pump

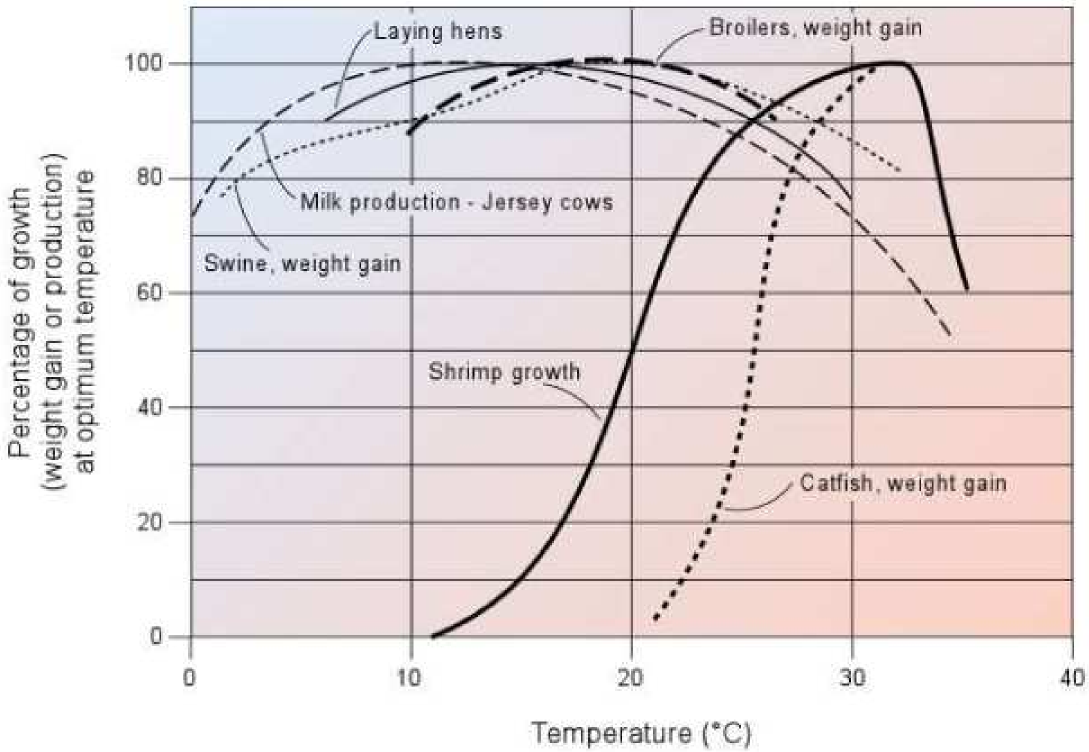
Utilization of Geoth. Resources
Direct Heat Uses

Heating greenhouses





Utilization of Geothermal Resources
Direct Heat Uses



Animal breeding, aquaculture

Utilization of Geothermal Resources
Economic Considerations

Numerous and complex elements that have to be considered in any cost estimate (plant or operating costs, price of the geo-thermal energy 'products'). All must be carefully evaluated before launching a geothermal project.

Few indications of general character - together with information on local conditions and on the value of the geothermal fluids available, should help the potential investor to reach a decision.

Utilization of Geothermal Resources
Economic Considerations

A resource-plant system consists of: geothermal wells, pipelines for geothermal fluids, utilization plant and injection system. They have heavy influence on investment costs ► careful analysis.

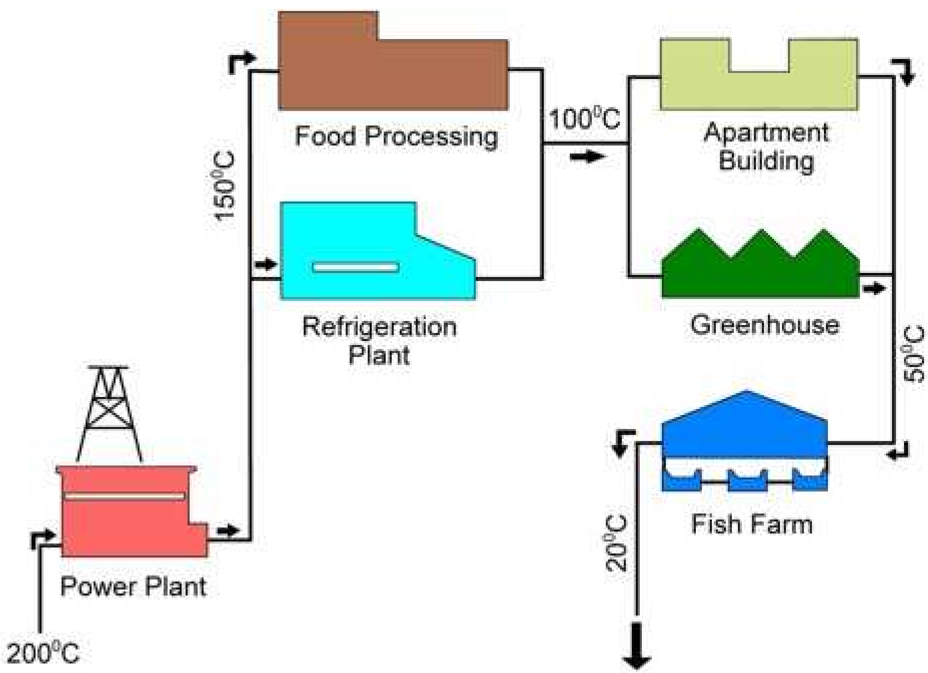
Example: In electricity generation, a discharge-to-the-atmosphere plant (DAP) is the simplest solution, therefore it is cheaper than a condensing plant (CP) of the same capacity, but it requires almost twice as much steam as the CP to operate, and, consequently, twice as many wells to feed it. Since wells are very expensive, a CP is effectively a cheaper option than the DAP (usually chosen for reasons other than economy).

Utilization of Geothermal Resources
Economic Considerations

Geothermal fluids can be transported over fairly long distances in thermally insulated pipelines (60 km), but pipelines, auxiliary equipment needed and the maintenance, are all quite expensive, and could weigh heavily on the capital cost and operating costs of a geothermal plant. The distance between the resource and the utilization site should therefore be kept as small as possible.

The capital cost of a geothermal plant is usually much higher than that of a similar plant run on a conventional fuel. The energy costs far less than conventional fuel. The higher capital outlay should be recovered by the savings in energy costs. Therefore, geothermal plant/system should be designed to last long enough to amortize the initial investment and, wherever possible, even longer.

Utilization of Geothermal Resources
Economic Considerations



Appreciable savings can be achieved by adopting integrated systems that offer a higher utilization factor or cascade systems, where the plants are connected in series, each utilizing the waste water from the preceding plant.

Utilization of Geothermal Resources
Economic Considerations

To reduce maintenance costs and shut-downs, the technical complexity of the plant should be on a level that is accessible to local technical personnel or to experts who are readily available.

If the geothermal plant is to produce consumer products, a careful market survey must be carried out beforehand to guarantee an outlet for these products. The necessary infrastructures for the economic transport of the end-product from the production site to the consumer should already exist, or be included in the initial project.

Utilization of Geothermal Resources
Economic Considerations

Energy and investment costs for electric energy production from RES (Fridleifsson, 2001)

	Current energy cost US¢/kWh	Potential future energy cost US¢/kWh	Turnkey investment cost US$/kW
Biomass	5 - 15	4 - 10	900 - 3000
Geothermal	2 - 10	1 - 8	800 - 3000
Wind	5 - 13	3 - 10	1100 - 1700
Solar (photovoltaic)	25 - 125	5 - 25	5000 - 10 000
Solar (thermal electricity)	12 - 18	4 - 10	3000 - 4000
Tidal	8 – 15	8 – 15	1700 - 2500

Utilization of Geothermal Resources
Economic Considerations

Energy and investment costs for direct heat from RES (Fridleifsson, 2001)

	Current energy cost US¢/kWh	Potential future energy cost US¢/kWh	Turnkey investment cost US$/kW
Biomass (including ethanol)	1 - 5	1 - 5	250 - 750
Geothermal	0.5 - 5	0.5 - 5	200 - 2000
Wind	5 - 13	3 - 10	1100 - 1700
Solar heat low temperature	3 - 20	2 - 10	500 - 1700

Environmental Impacts

There is no way of producing or transforming energy into a form that can be utilized by man without making some direct or indirect impact on the environment.

Exploitation of geothermal energy also has an impact on the environment, but there is no doubt that it is one of the least polluting forms of energy.

Environmental Impacts

Sources of pollution

In most cases the degree to which geothermal exploitation affects the environment is proportional to the scale of its exploitation.

Impact	Probability of occurring	Severity of consequences
Air quality pollution	L	M
Surface water pollution	M	M
Underground pollution	L	M
Land subsidence	L	L to M
High noise levels	H	L to M
Well blow-outs	L	L to M
Conflicts with cultural and archaeological features	L to M	M to H
Social-economic problems	L	L
Chemical or thermal pollution	L	M to H
Solid waste disposal	M	M to H

Probability and severity of potential environmental impact of direct-use projects

Environmental Impacts

Any modification to our environment must be evaluated carefully, in deference to the relevant laws and regulations, but also because an apparently insignificant modification could trigger a chain of events whose impact is difficult to fully assess beforehand.

Drilling

Installation of a drilling rig and all the accessory equipment entails the construction of access roads and a drilling pad, i.e. covering area 300-500 m^2 for a small truck-mounted rig (depth 300-700 m) to 1200-1500 m^2 for a small-to-medium rig (depth of 2000 m). These operations modify the surface morphology of the area and could damage local plants and wildlife. Blow-outs can pollute surface water; blow-out preventers should be installed when drilling geothermal wells where high T and p are anticipated. During drilling or flow-tests undesirable gases may be discharged into the atmosphere. The impact on the environment caused by drilling mostly ends once drilling is completed.

Environmental Impacts

Installation of pipelines and construction of utilization plants

Also affects animal and plant life and the surface morphology. The scenic view will be modified, although in some areas such as Larderello, Italy, the network of pipelines criss-crossing the countryside and the power-plant cooling towers have become an integral part of the panorama and are indeed a famous tourist attraction.

Environmental Impacts

During plant operation

Geothermal fluids (steam or hot water) usually contain gases such as CO_2, H_2S, NH_3, CH_4, and trace amounts of other gases, as well as dissolved chemicals whose concentrations usually increase with temperature. For example, NaCl, B, As and Hg are a source of pollution if discharged into the environment.

Some geothermal fluids, such as those utilized for district-heating in Iceland, are freshwaters, but this is very rare. The waste waters from geothermal plants also have a higher temperature than the environment and therefore constitute a potential thermal pollutant.

Environmental Impacts

Electricity generation - air pollution

Carbon dioxide is also present in the fluids used in the geothermal power plants, although much less CO_2 is discharged from these plants than from fossil-fuelled power stations: 13-380 g/kWh of electricity produced in the geothermal plants, compared to the 1042 g/kWh of the coal-fired plants, 906 g/kWh of oil-fired plants, and 453 g/kWh of natural gas-fired plants. Binary cycle plants for electricity generation and district-heating plants may also cause minor problems, which can virtually be overcome simply by adopting closed-loop systems that prevent gaseous emissions.

Environmental Impacts

Discharge of waste waters

Potential source of chemical pollution. Spent geothermal fluids with high concentrations of chemicals such as boron, fluoride or arsenic should be treated, re-injected into the reservoir, or both. However, the low-to-moderate temperature geothermal fluids used in most direct-use applications generally contain low levels of chemicals and the discharge of spent geothermal fluids is seldom a major problem. Some of these fluids can often be discharged into surface waters after cooling. The waters can be cooled in special storage ponds or tanks to avoid modifying the ecosystem of natural bodies of waters.

Environmental Impacts

Subsidence phenomena

Gradual sinking of the land surface after extraction of large quantities of fluids from geothermal reservoirs - irreversible phenomenon, but by no means catastrophic, as it is a slow process distributed over vast areas. Should be monitored systematically, as it could damage the stability of the geothermal buildings and any private homes in the neighborhood. In many cases subsidence can be prevented or reduced by re-injecting the geothermal waste waters.

Seismic events

Micro-seismic events that can only be detected by means of instrumentation. Unlikely to trigger major seismic events, and so far has never been known to do so.

Environmental Impacts

Noise

Associated with operating geothermal plants could be a problem where the plant in question generates electricity. During the production phase there is the higher pitched noise of steam travelling through pipelines and the occasional vent discharge.

These are normally acceptable. At the power plant the main noise pollution comes from the cooling tower fans, the steam ejector, and the turbine 'hum'.

The noise generated in direct heat applications is usually negligible.

Present and Future

Geothermal potential worldwide

	High-temperature resources suitable for electricity generation		Low-temperature resources suitable for direct use in million TJ/yr of heat (lower limit)
	Conventional technology in TWh/yr of electricity	Conventional and binary technology in TWh/yr of electricity	
Europe	1830	3700	> 370
Asia	2970	5900	> 320
Africa	1220	2400	> 240
North America	1330	2700	> 120
Latin America	2800	5600	> 240
Oceania	1050	2100	> 110
World potential	11 200	22 400	> 1400

Present and Future

If exploited correctly, geothermal energy could certainly assume an important role in the energy balance of some countries. In certain circumstances even small-scale geothermal resources are capable of solving numerous local problems and of raising the living standards of small isolated communities.

Of the total electricity produced from RES in 1998, 2826 TWh, 92% came from hydro power, 5.5% from biomass, 1.6% from geothermal, 0.6% from wind, 0.05% from solar, and 0.02% from tidal.

Biomass constitutes 93% of the total direct heat production from RES, geothermal represents 5% and solar heating 2%.