

BMM4753 RENEWABLE ENERGY RESOURCES



Chapter 4. Geothermal Energy

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Chapter 4. Geothermal Energy

Summary

- 4.1 Introduction**
 - 4.2 Interior of the earth structure**
 - 4.3 Geothermal resources**
 - 4.4 Utilization and environmental impact**
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Chapter 4. Geothermal Energy

4.1 Introduction

Geothermal energy is a cost-effective form of energy that neither contribute to global warming nor a threat to national security. It is the only form of 'renewable' energy that is independent of the sun, with the ultimate source from the center of the Earth where temperatures are approximately 6000°C.

- ☐ The heat can be used to generate steam and electricity.
- ☐ Heat from geothermal springs can be used directly to heat greenhouses for plants, to dry out fish and deice roads, for improving oil recovery, and to heat fish farms and spas.
- ☐ Geothermal water has been used to heat homes and buildings for over a century.
- ☐ In Iceland, virtually all the buildings in the country are heated by hot spring water and gets 45% of its energy from geothermal sources.

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4.2 Interior of the Earth Structure – Different Layers

Core itself has two layers

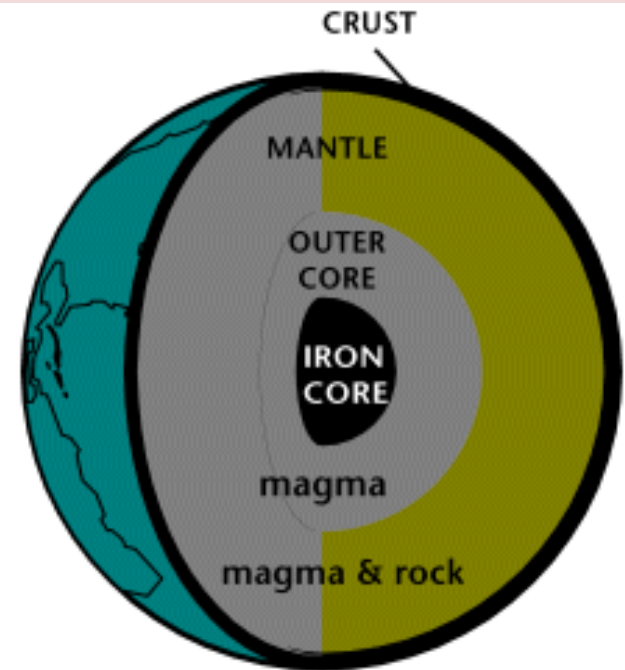
- inner core made of solid iron
- outer core made of very hot melted rock, called magma.

Mantle surrounds the core

- and is about 1,800 miles thick.
- made up of magma and rock.

Crust is the outermost layer of the Earth

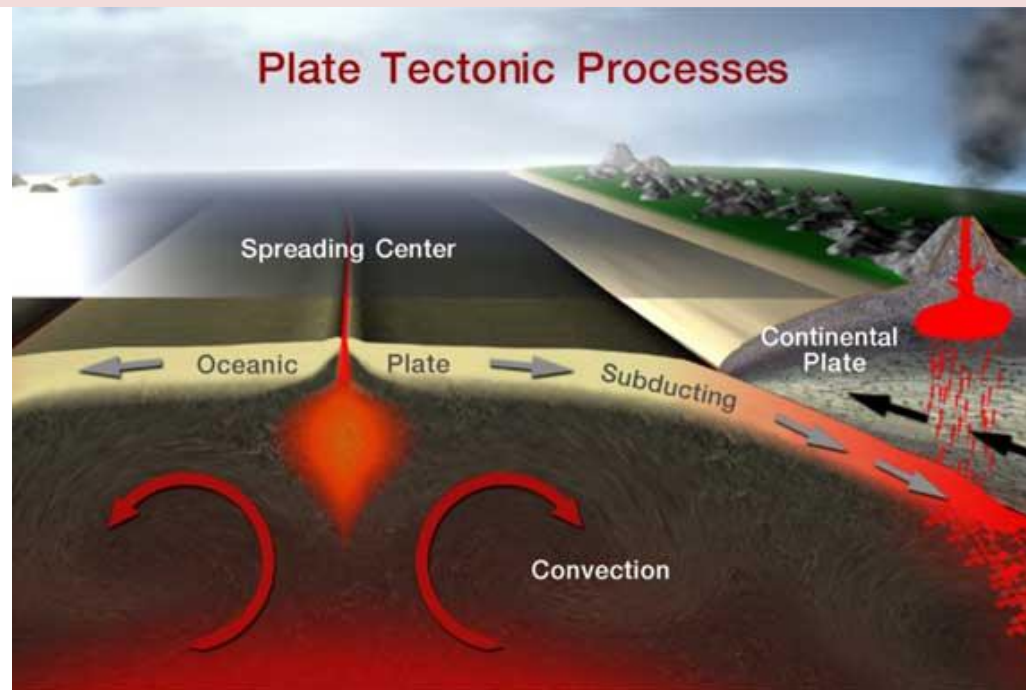
- the land that forms the continents and ocean floors
- 3 to 5 miles thick under the oceans
- 5 to 35 miles thick on the continents.



THE EARTH'S INTERIOR

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4.2 Interior of the Earth Structure – Tectonic Plate Formation



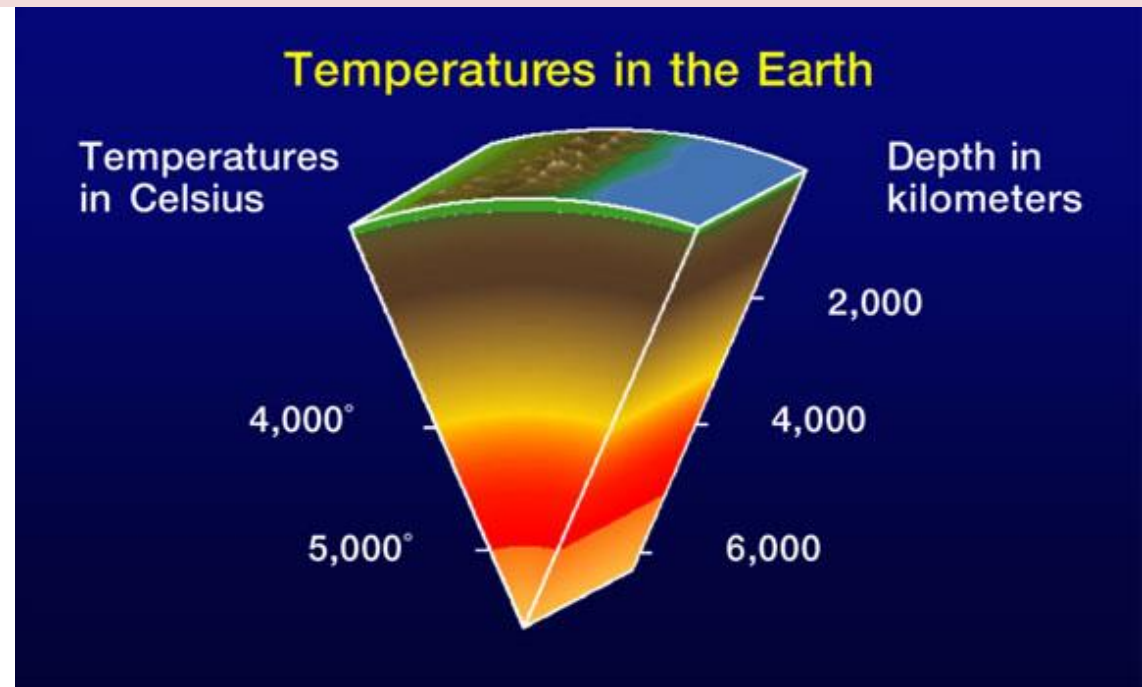
Earth's crust is broken into pieces called **tectonic plate**

- Magma comes close to the Earth's surface near the edges of these plate where volcanoes occur.
- The lava that erupts from volcanoes is partly magma. Deep underground, the rocks and water absorb the heat from this magma.

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4.2 Interior of the Earth Structure – Earth Temperature

- Temperature of rocks and water gets hotter as it gets deeper
- Radial temperature gradient increases proportionally to depth at a rate of about 30°C per km.
- At 3-4 km depth, water bubbles up
- At 10-15 km depth, the earth's interior is hot $1000^{\circ}\text{--}1200^{\circ}\text{C}$.
- The core of the earth consists of a liquid rock known as 'Magma' having a temperature of about 4000°C .



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4.3 Geothermal Resources

Geothermal are renewable energy sources that utilise the heat within the earth to create either a source of renewable heat or renewable electricity.

- i. Geothermal energy is generated in the Earth's core, mostly from the decay of naturally radioactive materials like uranium and potassium. The amount of heat within 10,000 meters of the surface contains 50,000 times more energy than all the oil and natural gas resources in the world.
- ii. The areas with highest underground temperatures are in regions with active or geologically young volcanoes. These "hot spots" occur at plate boundaries or at places where the crust is thin enough to let the heat through. The Pacific Rim, called the "ring of fire" for all of its volcanoes, has many hot spots, including some in Alaska, California, and Oregon.

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4.3 Geothermal Resources

- iii. These regions are also seismically active. The many earthquakes and the movement of magma break up the rock covering, allowing water to circulate. As the water rises to the surface, natural hot springs and geysers occur, such as "Old Faithful" at Yellowstone National Park. The water in these systems can be more than 200°C.
- iv. The current production of geothermal energy from various applications places third among renewable, following hydroelectric and biomass, and ahead of solar and wind. Despite these impressive statistics, the current level of geothermal use pales in comparison to its potential. The key to wider geothermal use is greater public awareness and technical support--two areas in which the Geo-Heat Center is very active.

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4.3 Geothermal Resources

Current Commercial Utilization

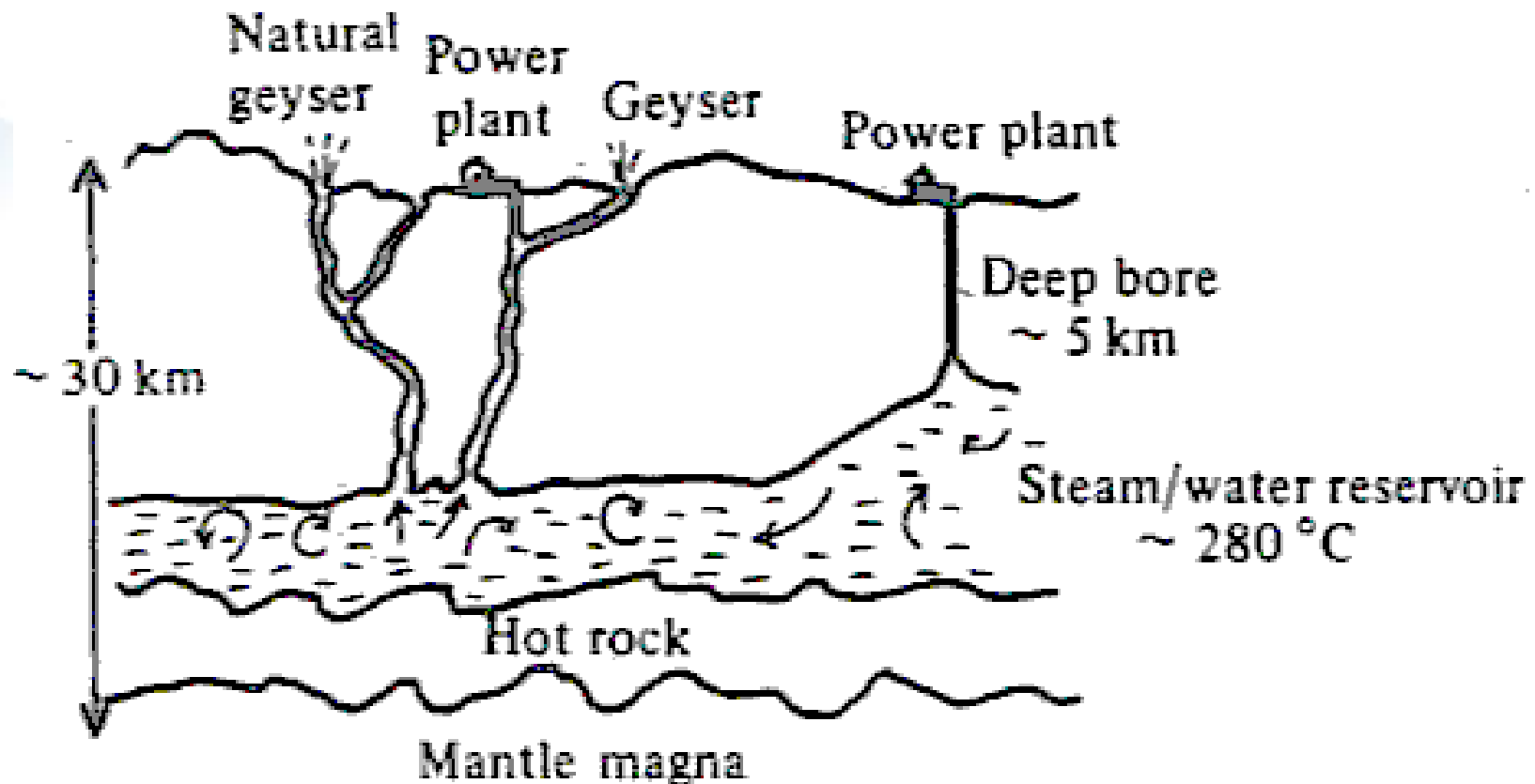
- i. Hydrothermal Reservoirs
- ii. Earth Energy

Advanced Technologies Yet To Be Developed

- iii. Hot Dry Rock
- iv. Geo-pressured Brines
- v. Magma

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4.3 Geothermal Resources – Current, Hydrothermal Reservoirs



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4.3 Geothermal Resources – Current, Hydrothermal Reservoirs

- Hydrothermal reservoirs are large pools of steam or hot water trapped in porous rock. The steam or hot water is pumped to the Earth's surface where it drives a turbine and electric generator. Steam resources are rare, instead hot water is used in most geothermal power plants. Steam and hot water power plants use different power production technologies and resources are classified accordingly
 - low temperature, less than 90°C
 - moderate temperature, 90°C- 150°C, and
 - high temperature greater than 150°C.
- Generally, the highest temperature resources are used for electric power generation. Approximately, current U.S. geothermal electric power generation totals 2200 MW or the equivalent of four large nuclear power plants.
- Low and moderate temperature resources can be classified into two categories namely **direct use** and ground-source **heat pumps**.

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4.3 Geothermal Resources – Current, Hydrothermal Reservoirs

a) Dry Steam

Steam is routed directly to the turbines, eliminating the need for the boilers used by conventional natural gas and coal plants.

b) High-temperature Hot Water

Hot water with temperatures above 200°C are usually utilized using a flash technology where hot water is sprayed into a low-pressure tank. The water vaporizes to steam, which is routed to the turbine.

c) Moderate-temperature Hot Water—hot water resources below 200°C are utilized using a binary cycle technology where the hot water vaporizes a secondary working fluid, which then drives the turbine.

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4.3 Geothermal Resources – Current, Earth Energy

- Direct use, involves using the water for direct heating buildings, industrial processes, greenhouses, aquaculture (growing of fish) and resorts with resource temperatures 38°C-149°C . Current U.S. installed capacity of direct use systems totals 470 MW or enough to heat 40,000 average-sized houses.
- The heat contained in shallow ground is used to directly heat or cool homes and commercial buildings through technologies such as geothermal heat pumps (GHP) and district heating systems. The U.S. is somewhat privileged, earth energy is found throughout the U.S.

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4.3 Geothermal Resources – Current, Earth Energy

a) Geothermal Heat Pumps (GHPs)

- Ground-source heat pumps use the earth or groundwater as a heat source in winter and a heat sink in summer. Using resource temperatures of 4°C-38°C, the heat pump, a device moves heat from one place to another, transfers heat from the soil to the house in winter and from the house to the soil in summer. Current estimates, the rate of installation is 10,000-40,000 per year.
- GHPs use the Earth's relatively constant ground temperature to provide low-cost heating and cooling. GHPs can cut heating costs by 50%, and cooling costs by 25%. More than 200,000 GHPs are operating in U.S. homes, schools and commercial buildings.
 - Winter, transfer heat from the ground into homes and buildings
 - Summer, cool homes and buildings by transferring indoor heat into the ground.

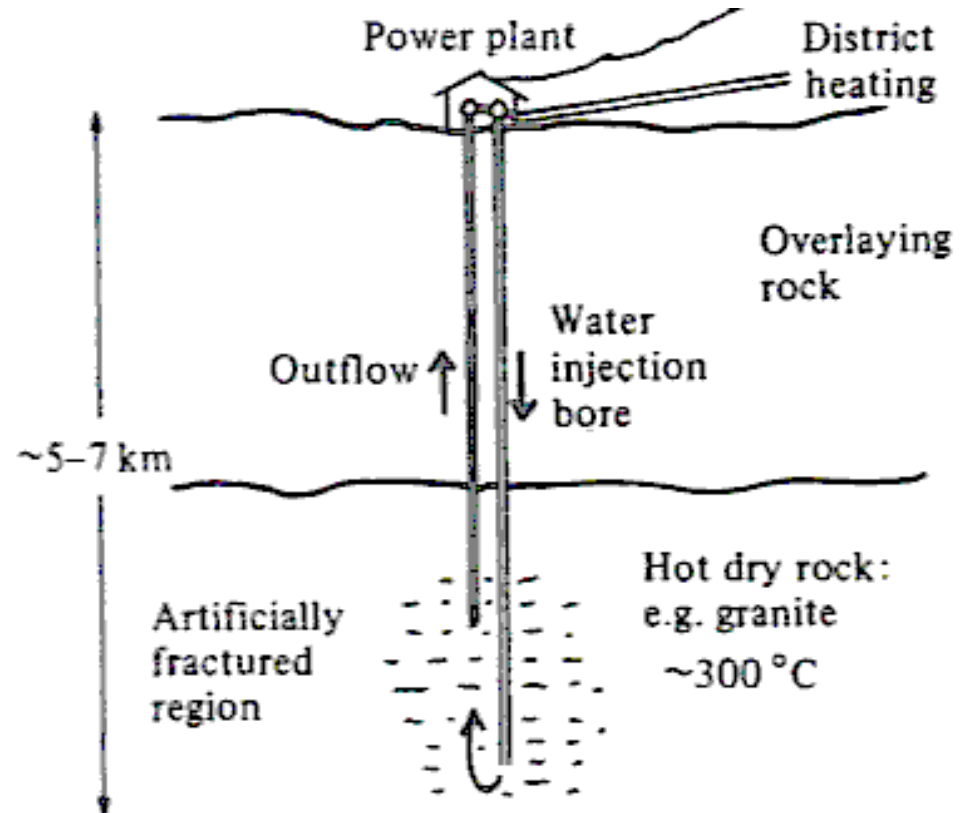
b) District Heating Systems

Communities use district-heating systems for homes or public buildings by circulating hot water through pipes. Overall, direct-use applications use geothermal energy to supply the energy equivalent of nearly 1 million barrels of oil.

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4.3 Geothermal Resources – Advanced Technologies, Hot Dry Rock

- a) Consists of dry, impermeable rock in which water must be pumped into the rock at high pressures to widen existing fissures and create an underground reservoir of steam or hot water
- b) Geothermal heat occurs everywhere under the surface of the earth, but the conditions that make water circulate to the surface are found only in less than 10% of the land area of the earth.



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4.3 Geothermal Resources – Advanced Technologies, Hot Dry Rock

- d) Capturing the heat in "hot dry rock" involves breaking up the rocks by pumping high pressure water through them. Water is then pumped from the surface down through the broken hot rocks. The water when heated up is brought back to the surface through a second well to drive turbines or use for heating.
- e) Studies have shown a well drilled 3,500 m into rock at 220°C, water pumped down the well at 30°C returned to the surface at 180°C, equivalent to plant producing 5 megawatts of power.
- f) Barriers to be overcome include the wells must be quite deep, deeper than for conventional geothermal plants. Also, the flow of heat through dry rock is slow hence, the heat removed through the well will be slow to be renewed.
- g) Drawback, water may be hard to come by in dry areas of the West, the most promising sites.

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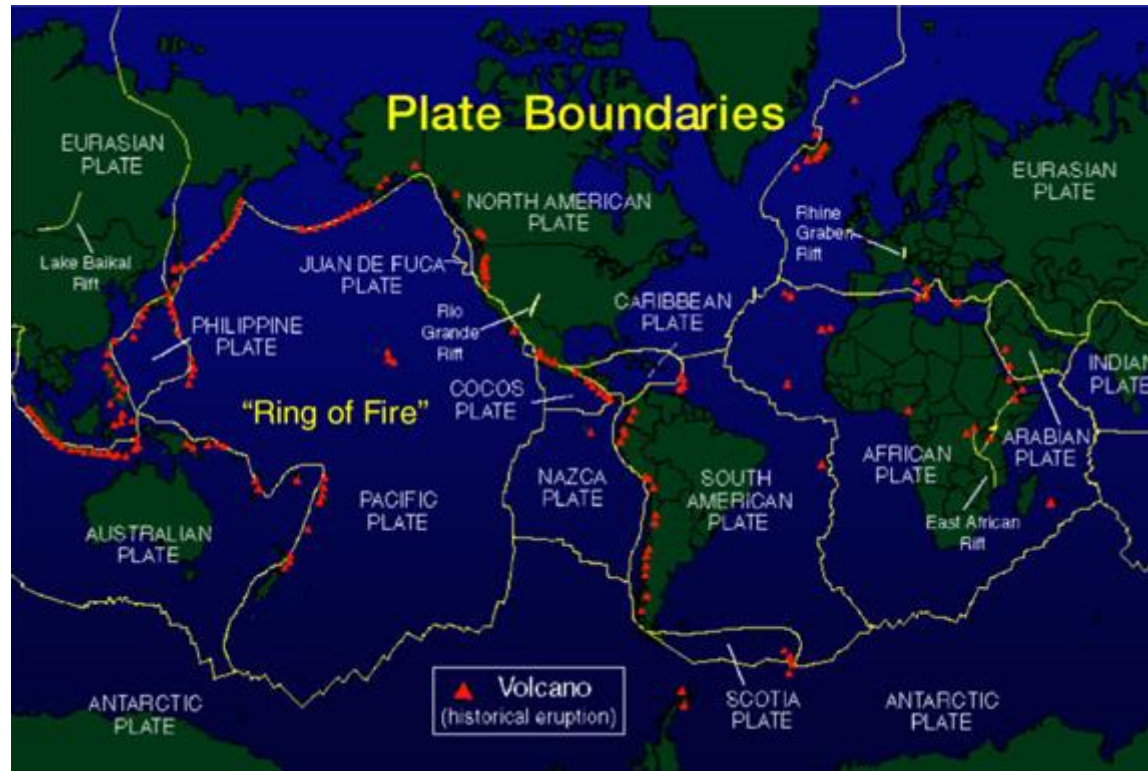
4.3 Geothermal Resources – Advanced Technologies

Geo-pressured Brines, hot, pressurized waters containing dissolved methane. Both heat and methane can be used for power generation.

Magma is the molten or partially molten rock found below the Earth's crust with temperature reaching up to 1200°C. While some magma bodies exist at accessible depths but a practical way to extract magma energy has yet to be developed.

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4.3 Geothermal Resources – Tectonic Plate Location



"Hot Spots" at plate boundaries and places where the crust is thin enough to let the heat through. The Pacific Rim, called the "ring of fire" for all of its volcanoes, has many hot spots, including Alaska, California, and Oregon.

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4.3 Geothermal Resources – World Geothermal Power Plants



People living in these areas are receiving electricity from geothermal power plants.

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4.3 Geothermal Resources – World Geothermal Power Production

World Geothermal Power Production 8,217MW

Production > 100 MW		Production < 100 MW	
United States	2850.0	Nicaragua	70.0
Philippines	1848.0	Kenya	45.0
Italy	768.5	China	32.0
Mexico	743.0	Turkey	21.0
Indonesia	589.5	Portugal	11.0
Japan	530.0	Russia	11.0
New Zealand	345.0	Guatemala	5.0
Iceland	140.0	France	4.0
Costa Rica	120.0	Taiwan	3.0
El Salvador	105.0	Thailand	0.3
		Zambia	0.2

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4.4 Application and Environmental Impact

- i. Worldwide, direct uses of geothermal water avoids the combustion of fossil fuels equivalent to burning of 830 million gallons of oil or 4.4 million tons of coal per year.
- ii. Worldwide electrical production from geothermal reservoirs avoids the combustion of 5.4 billion gallons of oil or 28.3 million tons of coal
- iii. Direct use facilities of geothermal energy have minimal impacts on the environment.
- iv. Geothermal power plants are relatively easy on the environment and have been successfully operated in the middle of crops, in sensitive desert environments and in forested recreation areas.

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4.4 Application and Environmental Impact

Direct Use Geothermal Water

1. Hot Spring / Bathing
2. Agriculture
3. Aquaculture
4. Industry
5. Heating/District Heating

Indirect Use Geothermal Steam/water

6. Electrical Power Generation

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4.4 Utilization and Environmental Impact – Hot Spring Bathing



Since Roman times, hot water has been piped into pools to better control the temperature. Photos of outdoor and indoor pool and spa bathing in Japan, the US, and Europe

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4.4 Utilization and Environmental Impact – Agriculture



Peppers, tomatoes, and flowers are commonly grown in geothermal heated greenhouses

4.4 Utilization and Environmental Impact – Aquaculture



Geothermal water to speed the growth of fish
in a hatchery at Mammoth Lakes, California

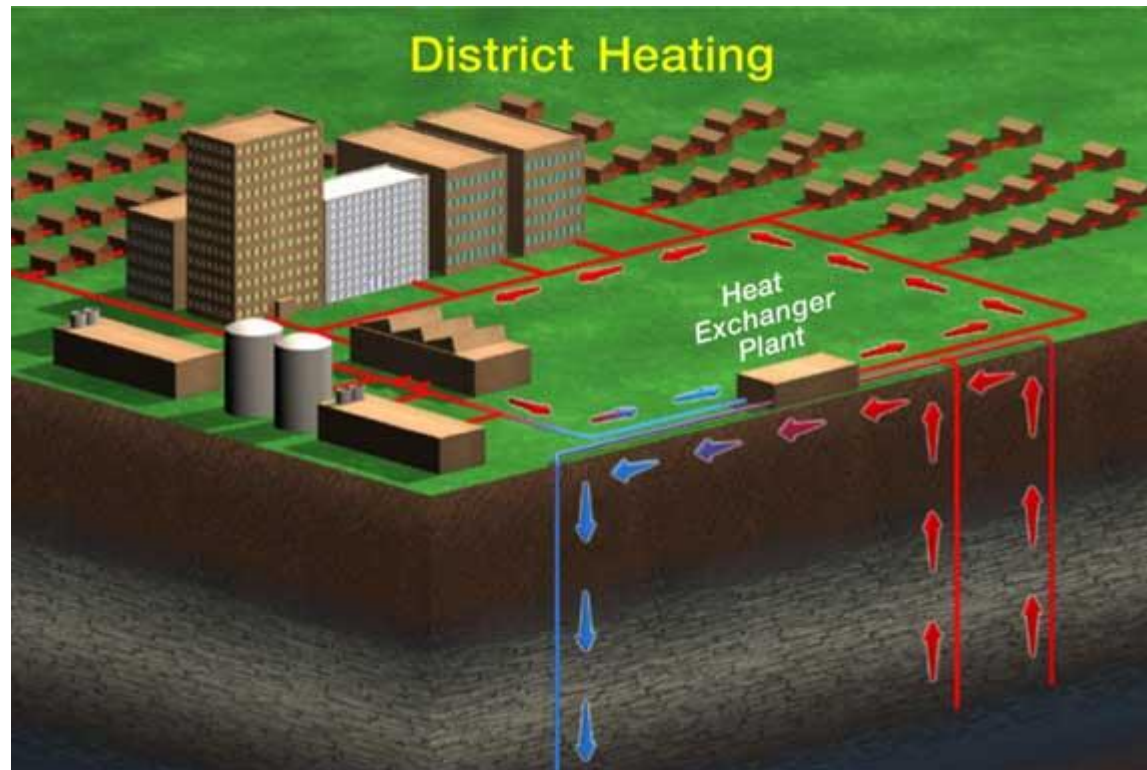
4.4 Utilization and Environmental Impact – Industry



High mineral contents of some southern California geothermal reservoirs provide salable byproducts like silica and zinc in the middle of crops in Imperial Valley, California.

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4.4 Utilization and Environmental Impact – District Heating



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

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4.4 Utilization and Environmental Impact – Electrical Generation



The first modern geothermal power plants in Lardello, Italy. They were destroyed in World War II, rebuilt and still in operation till today.

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4.4 Utilization and Environmental Impact – Electrical Generation



The first geothermal power plants in the U.S was built in 1962 at The Geysers dry steam field, California. It is still the largest producing geothermal field in the world.

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4.4 Utilization and Environmental Impact – Electrical Generation



The power plant provides about 25% of the electricity used on the Big Island of Hawaii.

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4.5 Application of Geothermal Energy – Power Generation Plants

- i. The most common current way of capturing the energy from geothermal sources is to tap into naturally occurring "hydrothermal convection" systems. When heated water is forced to the surface, it is a relatively simple matter to capture that steam and use it to drive electric generators. Geothermal power plants drill their own holes into the rock to more effectively capture the steam.
- ii. There are three designs for geothermal power plants, all of which pull hot water and steam from the ground, use it, and then return it as warm water to prolong the life of the heat source. In the simplest design, the steam goes directly through the turbine, then into a condenser where the low-temperature steam is condensed into water. In a second approach, the steam and hot water are separated as they come out of the well; the steam is used to drive the turbine while the water is sent directly back underground.

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4.5 Application of Geothermal Energy – Power Generation Plants

- iii. In the third approach, called a binary system, the hot water and steam mixture is passed through a heat exchanger, where it heats a second liquid (like isobutane) in a closed loop. The isobutane boils at lower temperatures than water, so as steam it is used to drive the turbine. The three systems are shown in the graphics here.
- iv. The choice of which design to use is determined by the resource. If the water comes out of the well as steam, it can be used directly, as in the first design. If it is hot water, it must go through a heat exchanger. Since there are more hot water resources than pure steam, there is more growth potential in the heat exchanger design.

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4.5 Application of Geothermal Energy – Power Generation Plants

- v. The largest geothermal system now in operation is a steam-driven plant in an area called The Geysers, north of San Francisco. Despite the name, there are actually no geysers, and the heat that is used for energy is all steam, not hot water. Although the area was known for its hot springs as far back as the mid-1800s, the first well for power production was drilled in 1924. Deeper wells were drilled in the 1950s, but real development didn't occur until the '70s and '80s. By 1990, 26 power plants had been built, for a capacity of over 2,000 megawatts. In 1992, the area produced enough power for a city of 1.3 million.

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4.5 Application of Geothermal Energy – Power Generation Plants

- vi. Because of the rapid development of the area in the '80s, and the technology used, the steam resource has been declining since 1988. In the Geysers, the plants use an evaporative water-cooling process to create a vacuum that pulls the steam through the turbine, producing power more efficiently. But this process loses 60 to 80 percent of the steam to the air, not re-injecting it underground. While the steam pressure may be declining, the rocks underground are still hot. Some efforts are under way to remedy the situation, including re-injecting water pumped in through a 26-mile pipeline, and replacing the water-cooled systems with air-cooled.

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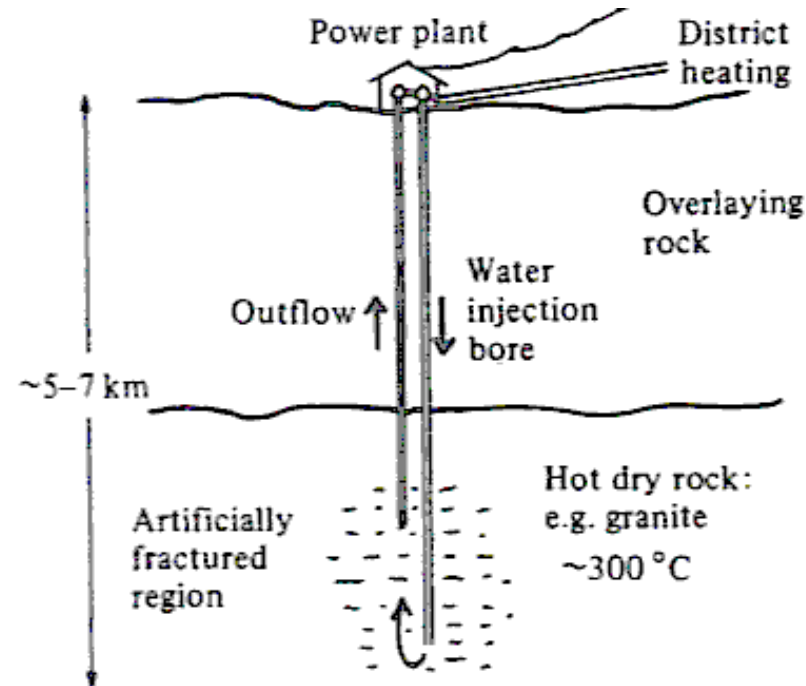
4.5 Application of Geothermal Energy – Power Generation Plants

- vii. Another problem with open systems like the one at the Geysers is that they produce some air emissions. Hydrogen sulfide, along with small amounts of arsenic and minerals, is released in the steam. At a power plant at the Salton Sea reservoir in California, a significant amount of salt builds up in the pipes and must be removed. While the plant initially started to put the salts into a landfill, they now re-inject the salt back into a different well. With closed-loop systems, such as the binary system, there are no emissions; everything brought to the surface is returned underground.

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4.6 Estimation of Geothermal Energy – Dry Hot Rock/Aquifer

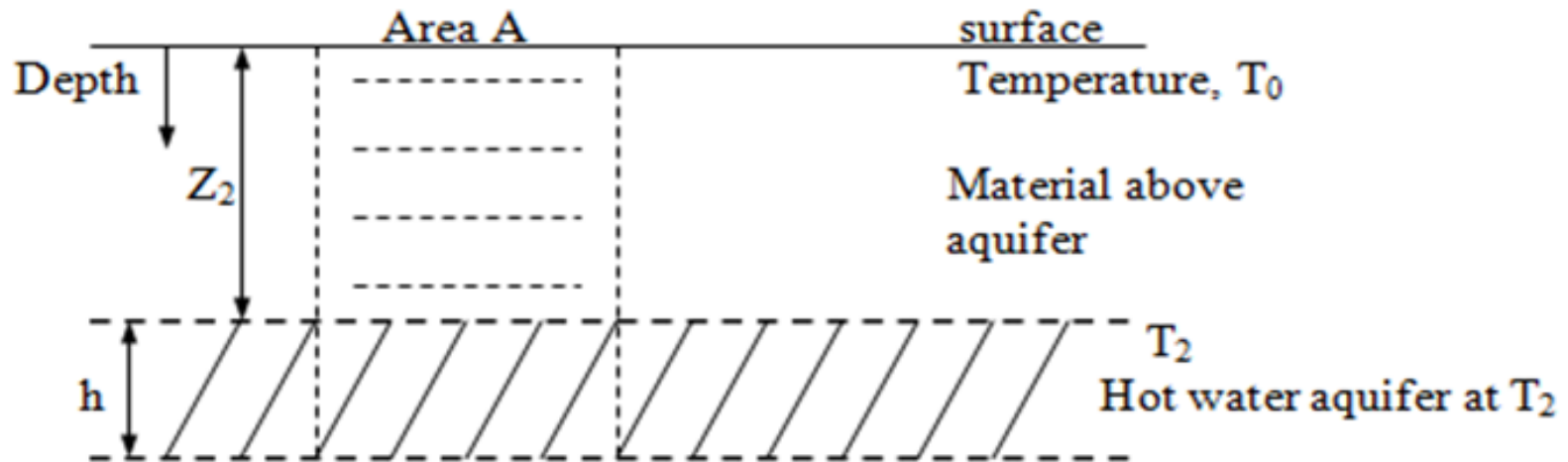
Consider a large mass of dry material extending from near the earth's surface to deep inside the crust



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4.6 Estimation of Geothermal Energy – Dry Hot Rock/Aquifer

The heat source within a layer of water beneath the ground is called a hot aquifer whose thickness h is assumed much less than depth Z_2 below ground level as shown



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4.6 Estimation of Geothermal Energy – Dry Hot Rock/Aquifer

Let, the water temperature = T_2

The porosity of the fraction of the aquifer containing water = p^1

The rock density of the remaining space = ρ_r

The minimum useful temperature = T_1

$$T_2 = T_0 + \frac{dT}{dZ} Z = T_0 + GZ$$

$$\frac{E_0}{A} = \zeta_a (T_2 - T_1)$$

where ζ_a , the thermal capacity of the hot aquifer is given by

$$\zeta_a = [p^1 \rho_w C_w + (1 - p^1) \rho_r C_r] h$$

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4.6 Estimation of Geothermal Energy Availability - Hot Dry Rock

Let the volume flow of water = \dot{V} at θ above T_1 .

Let τ_a be the time constant.

The removal of heat by this water is calculated thus:

$$\dot{V} \rho_w C_w \theta = -\zeta_a \frac{d\theta}{dt}$$

$$E = E_0 \cdot \exp(-t/\tau_a)$$

$$\frac{dE}{dt} = -(E_0/\tau_a) \exp(-t/\tau_a)$$

$$\tau_a = \frac{\zeta_a}{\dot{V} \rho_w C_w} = \frac{[p^1 \rho_w C_w + (1 - p^1) \rho_r C_r] h}{\dot{V} \rho_w C_w}$$

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4.7 Geothermal Energy in Malaysia

In Malaysia, Tawau has an electricity generation potential of up to 67 MW from geothermal resources following the discovery of a geothermal site in Apas



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4.7 Geothermal Energy in Malaysia

- a) Tenaga Nasional Bhd (TNB) has identified four potential geothermal power generation sites that could collectively generate more than 2 MW of electricity. Once exploratory testing prove satisfactory, TNB would begin drilling. The projects are expected to be on line by 2016. TNB's move into geothermal energy was part of its long-term strategy to diversify into renewable energy sources, given the environment of rising coal and gas prices. TNB had earmarked the four sites to set up geothermal power plants which will utilize steam generated from hot springs. There are more than 40 thermal springs in Peninsular Malaysia, most of which are good potential sites to generate geothermal power as part of the nation's plan to enhance its renewable energy potential.

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4.7 Geothermal Energy in Malaysia

- b) Each geothermal plant would have the potential to generate more than two megawatts of electricity. A large hot spring can generate up to 20 megawatts of power. The need to look at other viable renewable energy options is gaining importance, given adverse public opinion on the use of nuclear power, post-nuclear disaster in Japan. The foray into geothermal power is in line with the government's plan to increase renewable energy's contribution to Malaysia's power generation mix from less than one per cent currently to 5.5 per cent (985MW) by 2015. Tawau has an electricity generation potential of up to 67 MW from geothermal resources following the discovery of a geothermal site in Apas in a study by the Mineral and Geoscience Department. The study has found a reservoir about 2,000 to 3,000 m below the earth's surface with water at 220°C–236°C which was more than sufficient to generate electricity.

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4.8 Recent Developments in Geothermal Application

1. Comparing statistical data for end-1996 (SER 1998) and the present Survey, there has been an increase in world geothermal power plant capacity (+9%) and utilization (+23%) while direct heat systems show a 56% additional capacity, coupled with a somewhat lower rate of increase in their use (+32%).
2. Geothermal power generation growth is continuing, but at a lower pace than in the previous decade, while direct heat uses show a strong increase compared to the past.
3. Six countries with the largest electric power capacity are: USA with 2 228 MWe is first, followed by Philippines (1 863 MWe); four countries (Mexico, Italy, Indonesia, Japan) had capacity (at end-1999) in the range of 550-750 MWe each. These six countries represent 86% of the world capacity and about the same percentage of the world output, amounting to around 45 000 GWe.

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4.8 Recent Developments in Geothermal Application

4. Strong decline in the USA in recent years, due to overexploitation of the giant Geysers steam field, has been partly compensated by important additions to capacity in several countries: Indonesia, Philippines, Italy, New Zealand, Iceland, Mexico, Costa Rica, El Salvador. Newcomers in the electric power sector are Ethiopia (1998), Guatemala (1998) and Austria (2001). Total of 22 nations are generating geothermal electricity sufficient for 15 million houses.
5. Three countries with the largest amount of installed power: USA (5,366 MWt), China (2,814 MWt) and Iceland (1,469 MWt) cover 58% of the world capacity, which has reached 16,649 MWt, enough to provide heat for over 3 million houses. Out of about 60 countries with direct heat plants, beside the three above-mentioned nations, Turkey, several European countries, Canada, Japan and New Zealand have sizeable capacity.

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4.8 Recent Developments in Geothermal Application

6. With regard to direct use applications, a large increase in the number of GHPs installations for space heating (presently estimated to exceed 500 000) has put this category in first place in terms of global capacity and third in terms of output. Other geothermal space heating systems are second in capacity but first in output. Third in capacity (but second in output) are spa uses followed by greenhouse heating. Other applications include fish farm heating and industrial process heat. The outstanding rise in world direct use capacity since 1996 is due to the more than two-fold increase in North America and a 45% addition in Asia. Europe also has substantial direct uses but has remained fairly stable: reductions in some countries being compensated by progress in others.

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4.8 Recent Developments in Geothermal Application

7. In R & D, the hot dry rock (HDR) project at Soultz-sous-Forêts near the French-German border has progressed significantly. Besides the ongoing Hijiori site in Japan, another HDR test has just started in Switzerland (Otterbach near Basel).
8. The total world use of geothermal power is giving a contribution both to energy saving (around 26 million tons of oil per year) and to CO₂ emission reduction (80 million tons/year if compared with equivalent oil-fuelled production).

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4.8 Recent Developments in Geothermal Application

Malaysia's First Geothermal Power Plant

- ❑ To be built at Apas Kiri in Sabah's Tawau district, is expected to have the capability of generating more than 100-MW of electricity, once all its development phases are completed.
- ❑ Tawau Green Energy Sdn Bhd (TGE), the project's developer, is building the first, which is expected to begin operation in 2014 with a generation capacity of 30-MW.
- ❑ The project is being supported by Malaysia's federal government which will provide a 35 million Ringgit (USD11.1 million) in funding under public-private partnership agreement signed at the weekend.
- ❑ The total phase one project investment is estimated at RM419 million (USD133 million) with the preliminary infrastructure and interconnection accounting to almost RM120 million (USD38 million).
- ❑ Last November TGE signed a power purchase agreement with state utility Sabah Electricity Sdn Bhd, giving at a 21-year concession to provide 30-MW of electricity to the Sabah grid at a fixed tariff of RM0.21/kWh (7 US cents).

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4.8 Recent Developments in Geothermal Application

Malaysia's First Geothermal Power Plant

- ❑ The project will also qualify to receive carbon credits under the Clean Development Mechanism of the United Nations Framework Convention on Climate Change.
- ❑ The Apas Kiri geothermal prospect had been identified by Malaysia's Minerals and Geosciences Department as having the potential for electricity generation through studies commissioned by the department in the early 1990s and more recently, in 2008-2009. The survey covered an area of about 50-km, leading the discovery of a 12 square kilometers sub-surface heat water field.

NB: United Nations Framework Convention on Climate Change under its Clean Development Mechanism program and is enabled to earn certified emission reduction ("**CER**") credits during its first ten years of operations. Each CER may be sold and traded on carbon credit exchanges such as BlueNext at a quoted market price (current spot CER price is euro 3.55 each). When operating at its rated capacity of 30 megawatts, the power plant is expected to reduce CO₂ emissions by 282,400 metric tonnes per year and earn the same number of CERs (1 CER = 1 tonne CO₂ reduction). Under its agreement with a third party carbon credit solutions provider, TGE will be entitled to 75% of the CER revenue or about euro 750,000 per year at current CER spot prices. Take exchange rate at RM4.12 estimated revenue RM3.09 million.

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Problem 4.1: Hot Dry Rock

Example:

An aquifer has the following data is available:

Thickness = 0.5 km;

depth = 3 km;

porosity 5 %;

under sediments density = 2700 kg/m^3

Specific heat capacity = 840 J/kg-k ;

temperature gradient = 30° C/km .

- Assume the average surface temperature to be 10° C calculate the initial temperature and heat content per sq.km above 40° C .
- Determine the time constant for useful heat extraction of $100 \text{ l/s} - \text{km}$
- Determine the thermal power extracted initially and after 10 years.

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Problem 4.1: Hot Dry Rock

Solution:

- a) Initial temperature, $T_2 = 10 + (30 \times 3) = 100^\circ C$
The thermal capacity

$$\begin{aligned}\zeta_a &= [0.05 \times 1000 \times 4200 + 0.95 \times 2700 \times 840] \times 0.5 \times 10^9 \\ &= 1.18 \times 10^{15} J / K - km^2\end{aligned}$$

The quality of energy is suitable as process heat or for district heating

$$\begin{aligned}E_0 &= 1.18 \times 10^{15} \times (100 - 40) \\ &= 7.1 \times 10^{16} J / km^2\end{aligned}$$

- b) Time constant for useful heat extraction

$$\tau_a = \frac{1.18 \times 10^{15}}{0.1 \times 1000 \times 4200} = 2.8 \times 10^9 s = 90 \text{ yrs}$$

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Problem 4.1: Hot Dry Rock

c) Determine the thermal power

$$\left(\frac{dE}{dt}\right)_{t=0} = \frac{7.1 \times 10^{16}}{2.8 \times 10^9} = 25.2 \text{ MW} / \text{km}^2$$

or

$$\begin{aligned} \left(\frac{dE}{dt}\right)_{t=0} &= \dot{V} \rho_w C_w (T_2 - T_1) \\ &= \frac{0.1 \times 1000 \times 4200 \times 60}{10^6} = 25.2 \text{ MW} / \text{km}^2 \end{aligned}$$

$$\left(\frac{dE}{dt}\right)_{t=10y} = 25.2 \exp\left(\frac{-10}{90}\right) = 22.55 \text{ MW} / \text{km}^2$$

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Problem 4.2: Hot Dry Rock

A geothermal power plant uses geothermal water extracted at 160°C at a rate of 440 kg/s as the heat source and produces 22 MW of net power. If the environment temperature is 25°C, determine (a) the actual thermal efficiency, (b) the maximum possible thermal efficiency, and (c) the actual rate of heat rejection from this power plant.

SOLUTION

From property table A-4 @ 160°C, $h_f = 675.47$ kJ/kg; 25°C, $h_f = 104.83$ kJ/kg

(a) Heat input $\dot{Q}_{in} = \dot{m}_{geo}(h_{geo} - h_{env}) = 440(675.47 - 104.83) = 251$ MW

Actual thermal efficiency, $\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{22}{251} = \mathbf{8.76\%}$

(b) Maximum thermal efficiency, $\eta_{Carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{298}{433} = \mathbf{31.2\%}$

(c) Heat rejection, $\dot{Q}_{out} = \dot{Q}_{in} - \dot{W}_{net} = 251 - 22 = \mathbf{229}$ MW

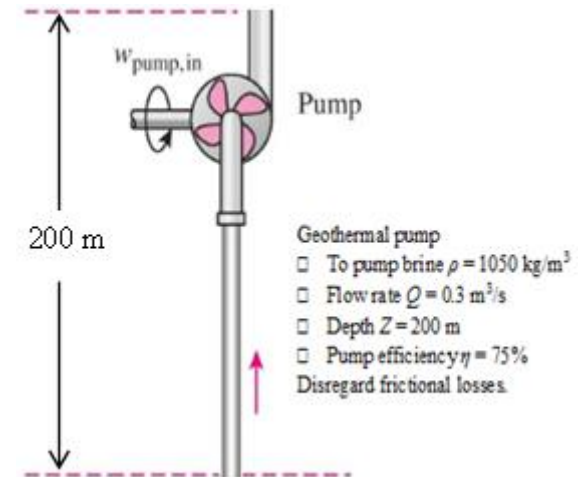
Chapter 4. Geothermal Energy

Problem 4.3: Geothermal Pump

A geothermal pump is used to pump brine whose density is 1050 kg/m^3 at a rate of $0.3 \text{ m}^3/\text{s}$ from a depth of 200 m . For a pump efficiency of 75% , determine the required power input to the pump. Disregard frictional losses in the pipes, and assume the geothermal water to be exposed to the atmosphere.

SOLUTION

Mechanical energy of water is equal to the change in its potential energy, $E_{mech} = \dot{m}gZ = (\rho Q)gZ = (1050 \times$



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Problem 4.4: Geothermal Power Plant

A geothermal plant withdraw saturated liquid at 230°C from a production well at a rate of 230 kg/s and flash it to a pressure of 500 kPa in an isenthalpic flashing process. The resulting vapor is separated from the liquid in a separator and directed to the turbine as shown. The steam leaves the turbine at 10 kPa with a moisture content of 5 percent and enters the condenser prior to reinjection well. Assume the dead state enthalpy of water h_o is 105 kJ/kg at standard temperature of 25°C . Determine the enthalpy h_4 , turbine power output and the plant thermal efficiency.

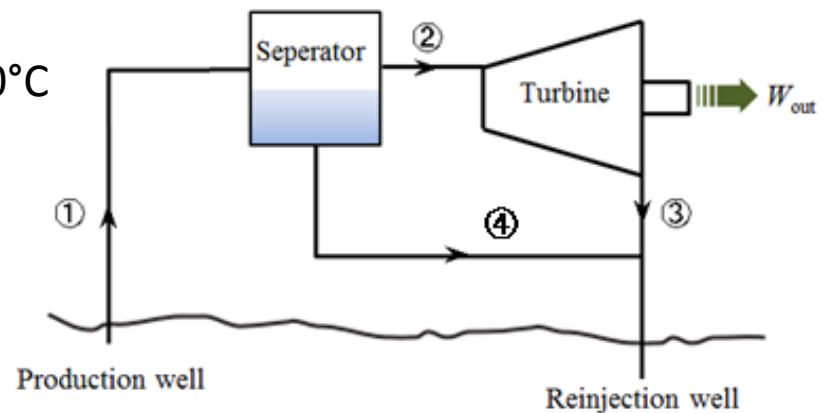
Given:

$h_1 = 990\text{ kJ/kg}$, enthalpy saturated water 230°C

$h_2 = 2748\text{ kJ/kg}$, enthalpy dry saturated steam 230°C

$h_3 = 2345\text{ kJ/kg}$, enthalpy wet vapor 10 kPa

$m_2 = 38\text{ kg/s}$, mass flow rate through turbine



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Problem 4.4: Geothermal Power Plant

A geothermal plant withdraw saturated liquid at 230°C from a production well at a rate of 230 kg/s and flash it to a pressure of 500 kPa in an isenthalpic flashing process. Determine the enthalpy h_4 , the turbine power output and the plant thermal efficiency.

SOLUTION

Mass flow rate \dot{m}_4 kg/s and enthalpy h_4 kJ/kg at state 4

From mass balance $\dot{m}_4 = \dot{m}_1 - \dot{m}_2 = 230 - 38 = 192 \text{ kg/s}$

From energy balance, $\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_4 h_4$

$$h_4 = \frac{\dot{m}_1 h_1 - \dot{m}_2 h_2}{\dot{m}_4} = \frac{230 \times 990 - 38 \times 2748}{192} = 642 \text{ kJ/kg}$$

Power output from the turbine W_{out}

$$W_{\text{out}} = \dot{m}_2 (h_2 - h_3) = 38.2(2748 - 2345) = 15,390 \text{ kW} = 15.39 \text{ MW}$$

Geothermal water heat input

$$Q_{\text{in}} = \dot{m}_1 (h_1 - h_0) = 230(990 - 105) = 203.55 \text{ MW}$$

Thermal efficiency

$$\eta_{th} = \frac{W_{\text{out}}}{Q_{\text{in}}} = \frac{15.39}{203.55} = 7.56\%$$

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