5

Geothermal Power Generation: Global Perspectives, Technology, Direct Uses, Plants, Drilling and Sustainability Worldwide

This Chapter discusses the state of art in harnessing geothermal power for medium- and large-scale generation of electricity and for space heating worldwide. It reviews current, probable, possible and potential developments both in developed and developing countries in near future and long term.

First, world energy consumption is reviewed. Then relative contribution of energy sources in the world in OECD countries with respect to renewables is discussed. Installed geothermal capacities for electricity generation worldwide are summarized. Direct use of geothermal energy worldwide is examined together with the technical potential of renewable energy sources.

Geothermal energy in USA is evaluated. Highlighted is heat flow, tectonic controls, types of geothermal systems, US geothermal potential, geothermal energy, operating conditions for electricity generation, and environmental constraints. The Chapter then examines the Geothermal Technologies Program in USA, reviewing the goals: geo-science and supporting technologies, exploration and drilling research, and energy systems research and testing. Discussed also is direct use of geothermal energy where district heating, agriculture and aquaculture applications, and future developments are considered.

Also examined is improving geothermal power plants where typical R&D projects are reviewed. Geothermal drilling R&D aimed at reducing drilling costs by 25%~50%, which often account for more than half of the total capital required for a project, is then discussed.

Enhanced power cycles for enhancing geothermal sustainability are reviewed. Deep drilling projects in Iceland--exploration of deep unconventional geothermal resources that requires drilling wells to depths of 3.5 to 5 km and at temperatures of 450-600^{o}C and which will exceed by an order of magnitude the power typically obtained from conventional wells are examined. The phases of development of a 400 MW_{el} scheme in the Hengill area of Iceland is discussed. Geothermal schemes in NE Iceland are also discussed as are geothermal development in reducing CO_2 emissions. Perspectives on the future of geothermal energy in the United States is indicated as is technology of harnessing geothermal power now and future. Economics, availability, and reliability of geothermal plants are reviewed.

5.1 Introduction

Energy consumption in the world is now a little over 400 EJ per year. Available energy resources in the world are large, and energy shortage is not expected in the foreseen future. On the other hand, most of the energy used in the world at present is coming from finite energy resources, whereas renewable energy sources are more suitable for sustainable development. The highest share of the use of renewable energy resources is in Iceland, where renewable energy comprises approximately 70% of the primary energy resources and approximately 30% is derived from fossil fuels. This unique position has been achieved by an extensive and advanced use of geothermal energy.

The state of art in harnessing geothermal power for medium- and large-scale generation of electricity (and for space heating) worldwide is examined. It gives a global perspective on geothermal power where world energy consumption, consumption of renewable energy, consumption of geothermal energy, direct use of geothermal energy, geothermal resources, and cost is indicated. An in-depth review of geothermal energy in USA: the technology for harnessing geothermal energy, direct use of geothermal energy, improving geothermal plants, and drilling is made. On the worldwide basis, geothermal energy is considered to have the largest technical potential of the renewable energy sources. Furthermore, the production price of geothermal energy is favorable in comparison to all other energy sources.

5.2 Global Perspective on Geothermal Energy

Most of the renewable energy sources presently used and under development in the world are in one way or another connected to the energy that the Earth is receiving from the Sun (hydro, biomass, solar- and wind energy). Most of the energy resources used in the world at present are coming from finite energy sources embedded in the crust of the Earth (oil, gas, coal, and uranium). Only one energy resource of the crust is renewable, namely geothermal energy. The source of geothermal energy is the continuous energy flux flowing from the interior of the Earth towards its surface.

The use of finite energy sources is not in good harmony with the concept of sustainable development and most countries are aiming at increasing the use of renewable energy sources at the expense of the finite energy resources (the UK is aiming for 80% of its energy to come from renewables by 2050). Geothermal energy has many desirable properties that make it suitable as a replacement for fossil fuels. The technical potential of geothermal energy is very large and the production price of geothermal energy is very favorable in comparison with other energy sources.

5.2.1 World Energy Consumption

Consumption of energy is one of the characteristics of the present society. Table 5.1 shows the worldwide consumption of primary energy in the year 1999.

	EJ	**Gtoe**	**%**
Fossil Fuels	322	7.68	79.2
Nuclear	28	0.66	6.8
Renewables	57	1.36	14.0
Total	**407**	**9.70**	**100**

Source: IEA 2001[1]

Table 5.1. World Energy Consumption in 1999

For the world in 1999, the use of renewable energy sources was only 14% of the primary energy sources, whereas finite energy sources (fossil fuels and nuclear) comprised 86%. The consumption of renewable energy sources is even lower in the developed countries than in the world as a whole. This is because the use of traditional fuel wood is more common in the developing countries than in the more affluent OECD countries. Most of the worldwide use of nuclear energy takes place in the OECD countries.

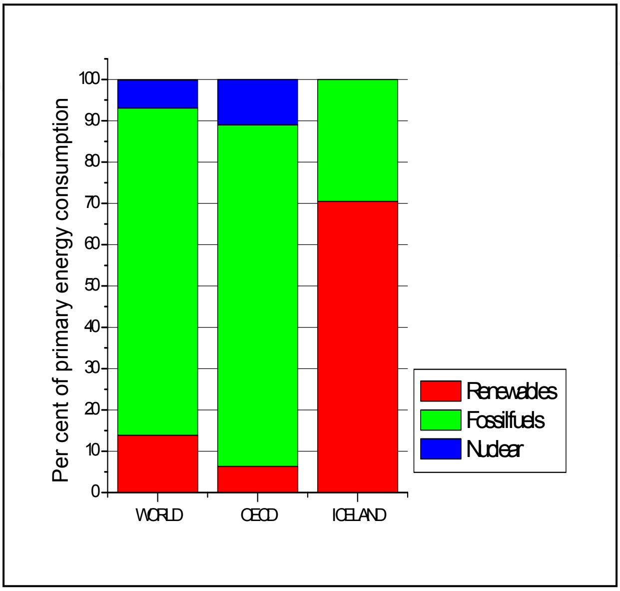


Fig. 5.1. Relative Contribution of Energy Sources in the World, OECD Countries, and Iceland.

Figure 5.1 shows relative contribution of energy sources in the world, in the OECD countries, and in Iceland. The highest share of the use of renewable energy resources is in Iceland. Table 5.2 illustrates primary energy supply in the OECD countries in 1999.

It is desirable to increase use of renewable energy sources at the expense of use of finite energy resources. Such development promotes the idea of sustainable development [2] and at the same time is expected to reduce the man-made emission of greenhouse gases.

	EJ	**Gtoe**	**%**
Fossil fuels	181	4.32	82.7
Nuclear	24	0.58	11.0
Renewables	14	0.33	6.3
Total	**219**	**5.23**	**100**

Source: IEA 2001[1]

Table 5.2. Primary Energy Supply in OECD Countries in 1999

5.2.2 Consumption of Renewable Energy Sources

Traditional biomass (fuel-wood) and hydro contribute the largest share to the use of "renewables" in the world (Table 5.1). Table 5.3 gives a further breakdown of the use of renewables.

	Electricity TWh	**Heat TWh**	**EJ**
Traditional biomass			38
Biomass-electricity	160		0.576
Biomass-heat		>700	>2.52
Biomass-ethanol			0.42
Wind-electricity	18		0.065
Solar-PHV-electricity	0.5		0.002
Solar-thermal-electricity	1		0.004
Solar-heat		14	0.05
Hydro	2,600		9.36
Geothermal-electricity	46		0.166
Geothermal-heat		40	0.144
Tidal	0.6		0.002
TOTAL	**2,826.1**	**>754**	**>51.3**

Source: WEA 2000 [3]

Table 5.3. Consumption of Renewable Energy in 1998

For the world, the share of renewable energy sources is about 14%. For the OECD countries, this ratio is only about 6% (see Tables 5.1 and 5.2). This is because about 80% of consumption of renewable energy sources in the world is the use of biomass (Table 5.3) and that use of traditional biomass is more common in the developing countries than in the OECD countries. Aside from hydro and biomass, the contribution of renewable energy sources at present is a very small fraction of the energy consumption in the world.

5.2.3 Consumption of Geothermal Energy

The use of geothermal energy is usually divided into the part used for electricity generation and the part used directly for heating purposes (direct use). Huttrer [4] has made a review of the electricity generation from geothermal energy, and Lund and Freestone [5] have reviewed the direct use of geothermal energy.

There are 21 countries in the world that use geothermal steam to generate electricity. Installed geothermal capacities for electricity generation worldwide is illustrated in Table 5.4. The largest installed capacities are in USA (2850 MWe in 2005: source US Information Agency) and the Philippines (1909 MWe in 2001: source Huttrer [4]) with lower values in other countries. The importance of this kind of electricity generation is different for these two countries. In the Philippines, electricity generated from geothermal is about 22% of the electricity generated in the country, whereas in USA it is only 0.36% of US annual electrical generation (16,010 GWh, see section 5.11). Table 5.5 lists the countries with the highest ratio of electricity generation from geothermal energy.

Country	Installed MWe	Generated GWh/a	Capacity Factor
Australia	0.17	0.9	0.60
China	29	100	0.39
Costa Rica	142	592	0.48
El Salvador	161	800	0.57
Ethiopia	8.5	30	0.40
France	4.2	25	0.68
Guatemala	33	216	0.75
Iceland	170	1,138	0.76
Indonesia	589	4,575	0.89
Italy	785	4,403	0.64
Japan	547	3,532	0.74
Kenya	45	366	0.93
Mexico	755	5681	0.86
New Zealand	437	2,268	0.59
Nicaragua	70	583	0.95
Philippines	1,909	9,181	0.55
Portugal	16	94	0.67
Russia	23	85	0,42
Thailand	0.3	1.8	0.68
Turkey	20	120	0.68
USA	2,228	1,5470	0.79
Totals	**7,972**	**49,262**	**0.71**

from Huttrer, 2001 [4]

Table 5.4. Installed Geothermal Capacities for Electricity Generation

Capacity factors for electricity generation for different renewable energy sources worldwide are: Geothermal 0.71, Hydro 0.42, Solar-thermal 0.30, Solar PV 0.15, and Wind 0.19 [6].

The main types of direct use of geothermal energy are bathing, space heating, greenhouses, fish farming, and in industry. Direct application can use both high- and low-temperature geothermal resources and is therefore much more widespread in the world than for electricity production. Direct application is, however, more site specific for the market, as steam and hot water is rarely transported over long distances. The longest geothermal hot water pipeline in the world is in Iceland (63 km). The production cost for direct utilization is highly variable, but is commonly lower than 2 US cents/kWh.

Table 5.6 shows direct use of geothermal energy worldwide in the in the year 1999 [5].

The large variation in the capacity factors in Table 5.6 is due to the different utilization mode of the direct use of geothermal energy. In USA and Switzerland, ground coupled heat pumps are the main sources of geothermal energy and the capacity factors for those countries are relatively low. Where geothermal energy is used for heating purposes in a moderate climate, the capacity factors are frequently in the range 0.4-0.7. The high capacity factors reported for India and Serbia might not be realistic.

Country	**Ratio of Electricity Generated from Geothermal Resources, %**
Philippines	22
El Salvador	20
Nicaragua	17
Iceland	15
Costa Rica	10
Kenya	8
New Zealand	6
Indonesia	5

Table 5.5. Countries with the Highest Share of Electricity Generated from Geothermal.

Country	**Installed MWt**	**Production, GWh/a**	Capacity **Factor**
China	2,282	10,531	0.53
Japan	1,167	7,482	0.73
USA	3,766	5,640	0.17
Iceland	1,469	603	0.44
Turkey	820	4,377	0.61
New Zealand	308	1,967	0.73
Georgia	250	1,752	0.80
Russia	308	1,707	0.63
France	326	1,360	0.48
Sweden	377	1,147	0.35
Hungary	473	1,135	0.27
Mexico	164	1,089	0.76
Italy	326	1,048	0.37
Romania	152	797	0.60
India	80	699	1.00
Switzerland	547	663	0.14
Serbia	80	660	0.94
Slovak Republic	132	588	0.51
other countries	2,118	4,731	0.25
Total	**15,145**	**52,976**	**0.40**

Source: Lund and Freeston, 2001 [5]

Table 5.6. Direct use of Geothermal Energy

5.2.4 World Energy Resources

In dealing with availability of energy resources, distinction has to be made between renewable energy sources and finite energy sources. The finite sources, fossil fuels and nuclear, are fixed amounts of energy stored in the Earth's crust; whereas the renewables are more or less a continuous current of energy. The finite sources can only be used once, but the exploitation of renewables will not affect the size of the energy current and this kind of energy can be utilized continuously without changing the amount of the available energy.

The term "reserves" means identified and economic resources and the term "resources" cover sub-economic and undiscovered resources. The sum of reserves and resources is denoted as a "resource base". For these resources, the reserves are best known, but the size of the resource base is more uncertain.

Due to the dynamic nature of the renewables, it is not possible to use the same classification for them as for the finite sources. For the renewable energy resources, names like "theoretical potential", "technical potential", and "economical potential" are frequently used. For these resources, it is usually easy to determine the size of the theoretical potential, but it is usually difficult to estimate how much of this energy is economical.

It can be convenient to compare the size of the resource base of the finite energy sources to the technical potential of the renewables. However, the resource base is a finite number whereas the technical potential is the yearly availability of the renewable energy source.

The resource base of the finite energy sources is shown in Table 5.7. Table 5.8 shows the technical potential of the renewables.

	EJ
Oil	32,422
Gas	49,805
Coal	199,666
Uranium	325,000
TOTAL	**606,893**

Source: WEA 2000 [3]

Table 5.7. Resource Base of Finite Energy Resources

It should be noted that during 100 years, the technical potential of renewables would produce the same amount of energy as stored in the resource base of the finite energy sources.

If it is assumed that 10% of the resource base is economical, Table 5.7 indicates that the present world energy consumption (407 EJ, see Table 5.1) could be maintained for some 150 years by the finite energy resources. Furthermore, if it is also assumed that 10% of the technical potential is economic; the renewable energy sources could maintain the present world energy consumption for a very long time.

	EJ per year
Hydropower	50
Biomass	276
Solar energy	1,575
Wind energy	640
Geothermal energy	5,000
TOTAL	**7,600**

Source: WEA 2000 [3]

Table 5.8. Technical Potential of Renewable Energy Sources

Geothermal energy is giving the largest share to the technical potential of renewables (Table 5.8). The technical potential is the yearly availability of the renewable resources. These estimates suggest that the technical potential of renewables is sufficiently large to meet future world energy requirements. The present annual consumption of primary energy in the world is about 407 EJ (Table 5.1). It is therefore expected that geothermal energy will be of large importance for the development of energy utilization in the future.

5.2.5 Cost of Renewable Energy

The range of energy cost is reported in WEA 2000 [3]. Table 5.9 shows the cost of electricity generation from renewable energy sources.

	Installed Cost USD/kW	**Energy Cost US cent/kWh**
Biomass	900 – 3,000	5 – 15
Solar photovoltaic	5,000 – 10,000	25 - 125
Solar thermal	3,000 – 4,000	12 – 18
Hydro	1,000 – 3,500	2 – 10
Geothermal	800 – 3,000	2 – 10
Wind	1,100 – 1,700	5 – 13
Tidal	1,700 – 2,500	8 – 15

Source: WEA 2000 [3]

Table 5.9. Current Installed Cost and the Cost of Electricity Generation

The installed cost and the energy cost for the generation of heat are shown in Table 5.10.

Tables 5.9 and 5.10 show clearly that the price of geothermal energy is favorable as compared to other energy sources, both renewable and finite energy sources.

	Installed Cost USD/kW	**Energy Cost US cent/kWh**
Biomass	250 – 750	1.0 – 5.0
Solar heat	500 – 1,700	3.0 – 20.0
Geothermal	200 – 2,000	0.5 – 5.0

Source: WEA 2000 [3]

Table 10. Current Installed Cost and Energy Cost for Generation of Heat

5.3 Geothermal Energy in USA

Temperature increases with depth in the earth at an average of 25ºC/km. If the average surface temperature is 20ºC, the temperature at 3 km is of the order of 95ºC. Although direct-use applications of geothermal energy can utilize temperatures as low as about 35ºC, the minimum temperature suitable for electrical generation is about 120ºC.

Spatial variations of the thermal energy within the deep crust and mantle of the earth give rise to concentrations of thermal energy near the surface of the earth that can be used as an energy resource. Heat is transferred from the deeper portions of the earth by conduction through rocks, by movement of hot deep rock toward the surface, and by deep circulation of water.

In older areas of continents, such as much of North America east of the Rocky Mountains, heat flow is generally 40 to 60 mWm^{-2} (milliwatts per square meter). This heat flow coupled with the thermal conductivity of rock in the upper 4 km of the crust yields subsurface temperatures of 90 to 110ºC at 4-km depth in the Eastern United States. Heat flow within the Basin and Range (west of the Rockies) is generally 70-90 mWm^{-2}, and temperatures are generally greater than 110ºC at 4 km. There are large variations in the western United States, with areas of heat flow greater than 100 mWm^{-2} and mountain areas such as the Cascades and Sierra Nevada of generally lower heat flow. The large rainfall on the Cascades may suppress flow of heat to the surface in this relatively young volcanic area.

5.3.1 Tectonic Controls

The unifying geologic concept of plate tectonics provides a generalized view of geologic processes that move concentrations of heat from deep within the earth to drillable depths. The heat can be related to movement of magma within the crust, particularly when associated with recent volcanism, or deep circulation of water in active zones of faulting. Figure 5.2 shows the major plate boundaries, where much of the geothermal exploration occurring worldwide is focused, since most of the current volcanic activity of the earth is located near plate boundaries associated with spreading centers and subduction zones.

Solid, bold lines are extensional boundaries, hachured lines are zones of convergence with the hachures on the overriding plate, and dotted lines indicate translational or diffuse plate boundaries.

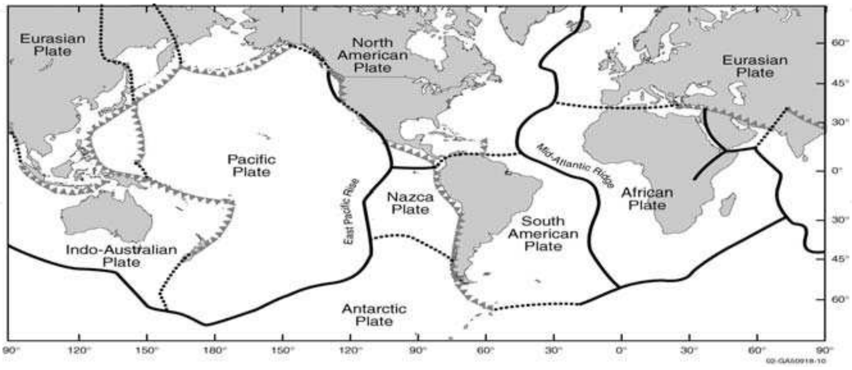


Fig. 5.2. Major Tectonic Plates of the World

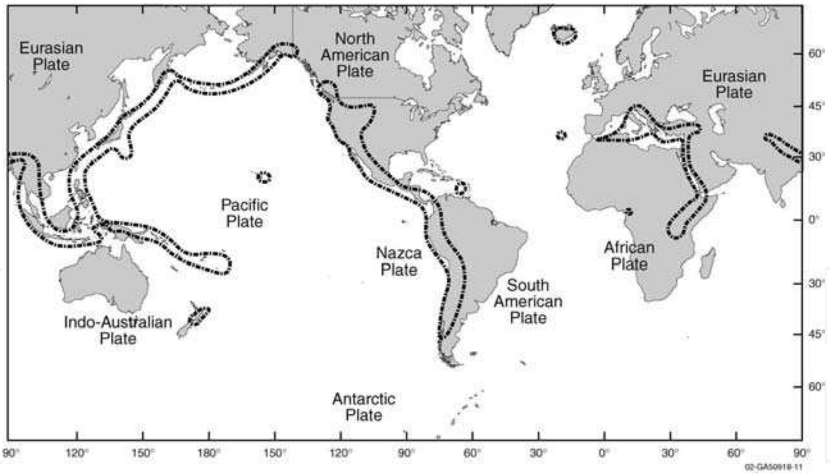


Fig. 5.3. Areas of the World with Potential for Producing Electricity using Geothermal Energy.

The brittle and moving plates of the lithosphere (crust and upper mantle) are driven by convection of plastic rocks beneath the lithosphere. Convection causes the crustal plates to break and move away in opposite directions from zones of up welling hot material. Magma moving upward into a zone of separation brings with it substantial amounts of thermal energy.

Rifting of the earth's crust can also occur in continental blocks. Two of the better-known examples are the East African Rift and the Rio Grand Rift in New Mexico. These rifts contain young volcanism and host several large geothermal systems.

Where continental plates converge, they crumple against each other. An example is the Himalayas, formed by the collision of the Indian and Asian plates.

Translational plate boundaries, which are locations where plates slide parallel to each other, may develop extensional troughs known as pull-apart basins, e.g., the Salton Trough of Southern California [7, p. 131]. Volcanism associated with the Salton Trough generated the heat in the Salton Sea, Cerro Prieto, and Imperial Valley geothermal fields. Tensional features further north on the San Andreas and related faults may be the cause of the volcanism thought to be the heat source for The Geysers geothermal field about 90 miles north of San Francisco.

A third source of elevated heat flow and volcanism are "hot spots." Several important geothermal systems are associated with recent volcanism caused by hot spots: Yellowstone, USA, the geothermal fields in Iceland, and those of the Azores.

Geothermal resources also have been developed in areas of anomalously high temperatures with no apparent active volcanism, such as the Basin and Range physiographic province in the western United States.

Areas of the world with geothermal potential are shown in Figure 5.3. Much of the world's potential for geothermal energy is associated with areas of volcanism caused by subduction and crustal spreading.

5.3.2 Types of Geothermal Systems

All commercial geothermal production is currently restricted to hydrothermal systems. Most hydrothermal resources contain water as liquid, but higher temperatures or lower pressures can create conditions where steam and water or only steam is the continuous phase in the reservoir. Successful, sustainable, geothermal energy usage depends on injection back into the reservoir of the maximum quantity of produced fluid to augment natural recharge of hydrothermal systems.

Other types of geothermal systems have been investigated for energy production:

- Geopressured-geothermal systems contain water with somewhat elevated temperatures (above normal gradient) and with pressures well above hydrostatic for their depth.
- Magmatic systems, with temperatures from 600 to 1400ºC are associated with magmatic bodies beneath the surface of the earth.
- Hot dry rock geothermal systems, with temperatures from 200 to 350ºC, are subsurface zones with low initial permeability and little water. These types of geothermal systems cannot be used economically for the production of energy.

5.3.3 US. Geothermal Energy Potential

A US. Geological Survey (USGS) assesses geothermal potential of the United States and provides an explanation of the terminology used to define various categories of the resources [8]. Resource base is all of the thermal energy contained in the earth. Accessible resource base is that part of the resource base shallow enough to be reached by production drilling. Resources are those portions of the accessible base that can be used at some reasonable future time. Reserves are that portion of the resource that has been identified and that can be used under current economic conditions. Reserves and resources are divided into categories of identified and undiscovered, based on knowledge of certainty of their existence.

The USGS published assessments of the moderate (90–150ºC) and high-temperature (>150ºC) geothermal resources of USA in 1975 [9] and 1979 [8] and published an estimate of low-temperature (<90ºC) resources in 1983 [11].

The USGS assessment of low-temperature resources [10] estimated the beneficial heat in discovered and undiscovered hydrothermal systems less than 90ºC to be about 41 and 30 GW_t for 3 years. The USGS [8] estimated that the identified high-temperature hydrothermal resource would operate power plants with an aggregate capacity of 23,000 MWe (megawatt electrical) for 30 years. The total U.S. hydrothermal resource, inferred from knowledge of earth science, was estimated to be 95,000 to 150,000 MWe for 30 years. Recent advances in the technology for converting geothermal energy into electricity have lowered the temperature needed for economic electrical production. As a result, lower-temperature resources will be included in the next USGS estimate of geothermal energy suitable for electrical production. The USGS initiated a new assessment of U.S. geothermal resources in 2003, beginning with those in the Great Basin.

5.3.4 Geothermal Energy Use in USA

Worldwide capacity for electrical generation using geothermal energy is 9,000 MWe (2008) of generating capacity on line in 21 countries [4,11]. Current net capacity in USA is 2,850 MWe. Electricity is produced in California (7 fields), Hawaii (1 field), Nevada (9 fields), New Mexico (1 field), and Utah (2 fields).

5.3.5 Operating Conditions for Electrical Generation

Most geothermal fields are liquid-dominated, i.e., water at high temperature and under high pressure but still in liquid form, is the pressure-controlling medium filling the fractured and porous rocks of the reservoir. In liquid-dominated geothermal systems used for electrical power production, water comes into the wells from the reservoir, and the pressure decreases as the water moves toward the surface, allowing part of the water to boil. As the wells produce a mixture of steam and water, a separator is installed between the wells and the power plant to separate the steam and water. The flashed steam goes into the turbine to drive the generator, and the water is injected back into the reservoir.

In several geothermal fields, the wells produce only steam. The separators and the system for handling the separated water are not needed. These systems are more economical, but are rare. Only two of the currently operating fields in the world, Larderello, Italy, and The Geysers, USA, are vapor-dominated.

Many water-dominated reservoirs below 175°C used for electricity generation are pumped to prevent the water from boiling as it is circulated through heat exchangers to heat a secondary liquid that then drives a turbine to produce electricity. Binary geothermal plants have no emissions because all of the produced geothermal water is injected back into the underground reservoir. The number of identified lower-temperature geothermal systems is many times greater than the reserves of high-temperature fluids. This provides an economic incentive to develop more efficient binary power plants.

5.3.6 Direct Use

Geothermal resources provide energy for agricultural uses, heating, industrial uses, and bathing. Fifty-five countries had 16,209 MWt (megawatt thermal) of total capacity for direct use in 1999 [5,12]. The total energy used is estimated at 162,000 TJ/y (terajoules per year). The US. capacity for direct use is about 3,766 MWt, and approximately 5,640 GWh per year are used [5,12].

The use of geothermal energy for direct uses is dominantly in the western states of Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, Washington, and Wyoming. However, warm waters are also used for pools and spas and some space heating in Alabama, Arkansas, Georgia, Louisiana, Mississippi, New York, South Dakota, Texas, Virginia, and West Virginia.

Warm water, at temperatures above 20°C can be used directly for a host of processes requiring thermal energy. Thermal energy for swimming pools, space heating, and domestic hot water are the most widespread uses, but industrial processes and agricultural drying are growing applications of geothermal use (see Table 5.11). The cities of Boise, Idaho; Elko, Nevada; Klamath Falls, Oregon; and San Bernardino and Susanville, California; have geothermal district-heating systems where a number of commercial and residential buildings are connected to distribution pipelines circulating water at 54 to 93°C from the production wells [13].

The use of geothermal energy through ground-coupled heat-pump technology has almost no impact on the environment and has a beneficial effect in reducing the demand for electricity. Geothermal heat pumps use the reservoir of constant temperature, shallow groundwater, and moist soil as the heat source during winter heating and as the heat sink during summer cooling. The energy efficiency of geothermal heat pumps is about 30 percent better than that of air-coupled heat pumps and 50 percent better than electric-resistance heating. Depending on climate, advanced geothermal heat pump use in USA reduces energy consumption, and correspondingly, power-plant emissions by 23 to 44 percent compared to advanced air-coupled heat pumps, and by 63 to 72 percent compared to electric-resistance heating and standard air conditioners [15].

	Capacity (MW [t])	**Use (TJ/y)**
District heating	268	4,232
Space heating	107	2,497
Agriculture	99	624
Balneology	92	947
Heat pumps	4,800	12,000
Total U.S.	**5,366**	**20,302**

Table 5.11. Direct use USA (Modified from [14])

5.3.7 Environmental Constraints

All known geothermal systems contain aqueous carbon dioxide species in solution. When a steam phase separates from boiling water, CO_2 is the dominant (over 90 percent by weight) non-condensable gas. In most geothermal systems, non-condensable gases make up less than five percent by weight of the steam phase. For each megawatt-hour of geothermal electricity produced in USA, the average emission of CO_2 is about 18% of that emitted when natural gas is burned to produce electricity.

A comparison of fossil and geothermal CO_2 emissions in kg CO_2 per kWh is: geothermal 0.082, coal 0.968, petroleum 0.709, natural gas 0.468 (data from [16]). Binary plants have no emissions, since all of the produced fluid is injected back into the reservoir.

Hydrogen sulfide can reach moderate concentrations of up to two percent by weight in the separated steam phase from some geothermal fields. This gas presents a pollution problem because it is easily detected by humans at concentrations of less than 1 part per million in air. H_2S concentrations are only high enough to require control at The Geysers, California, Coso, California, and Steamboat Springs, Nevada geothermal plants.

The incineration process burns the gas removed from the steam to convert H_2S to SO_2, the gases are absorbed in water to form SO_3 and SO_4 in solution, and iron chelate is used to form S_2O_3 [17]. The major product from the incineration process is a soluble thiosulfate, which is injected into the reservoir with the condensed water used for the reservoir pressure-maintenance program. Sulphur emissions for each megawatt-hour of electricity produced in 1991, as SO_2 by plant type in USA was 9.23 kg from coal, 4.95 kg from petroleum, and 0.03 kg from geothermal flashed-steam (from data of [18]). For each megawatt-hour of electricity produced in 1991, the average emission of nitrogen oxides by plant type in USA was 3.66 kg from coal, 1.75 kg from petroleum, 1.93 kg from natural gas, and zero from geothermal (from data of [18]).

In summary, geothermal energy provides a major economic source of base-load electrical energy for western USA as well as a clean source of energy for direct use over a broad area of USA. Geothermal energy produces about 2% of the electricity in Utah, 6% of the electricity in California, and 10% of the electricity in Northern Nevada. Further information concerning geothermal energy is available on many Web sites. Among the more informative are [19-23].

5.4 Geothermal Technologies Program: US. Department of Energy (DOE)

Geothermal energy is being used to generate electrical power; for direct use applications such as district heating, greenhouse heating, and aquaculture; among others.

The long-term sustainability of geothermal production has been demonstrated by continuous electrical power generation at the Lardarello field in Italy since 1913, at the Wairakei field in New Zealand since 1958, and at The Geysers field in USA since 1960. No geothermal field has been abandoned because of resource decline.

Today, geothermal energy amounts to more than 9,000 MW of installed electric power capacity worldwide. However, the ultimate promise of the geothermal energy is many times larger. With enhanced geothermal systems (EGS), using advanced techniques to engineer improved geothermal reservoirs; there is the potential to meet energy needs of approximately 17 percent of the world's population (see Sections 5.9~5.11).

P. Michael Wright of the Idaho National Engineering and Environmental Laboratory, Marshall Reed of DOE, and Karl Gawell of the Geothermal Energy Association have determined that with the advancement in technologies, geothermal energy has the capacity to produce 65GW to 138GW of electricity. World geothermal resources are estimated to be 15,000 times the world's oil reserves.

5.4.1 Comprehensive Research Program

The "next generation" technology currently under development will allow a greater portion of the geothermal resource base to be developed economically.
The Program adopted the following goals:

(i) Double the number of states with geothermal power facilities to eight
(ii) Reduce the levelized cost of generating geothermal power to 3~5 cents/kWh by 2010
(iii) Supply the electrical power or heat energy needs of 7 million homes and businesses in USA by 2015

Three business lines were formed to pursue those goals:

Geoscience and Supporting Technologies (Geoscience) – Geoscience research and development addresses characterization and management of the geothermal resource via improved understanding and enhancement of underground fracture systems, understanding the flow of hot fluids through reservoirs, and resource management through re-injection of spent geothermal fluid.

Exploration and Drilling Research – Exploration research seeks to improve the various geologic, geophysical, and geochemical methods used to find and define geothermal resources.

Energy Systems Research and Testing (ESR&T) – This business line concentrates on the means of converting geothermal heat into useful energy. Advanced cycles are developed to increase conversion efficiency (see Section 5.8). Improvements in equipment, such as condensers and heat exchangers, are made to reduce costs and improve performance. Operating problems are addressed to increase plant reliability.

5.5 Direct Use Geothermal Energy

Historically, direct use of geothermal resources has been on a small scale and on an individual basis, recent projects have focused more on the developments of major district heating systems, greenhouses or aquaculture complexes, or major industrial uses. Heat pumps utilizing very low-temperature geothermal fluids (120°) have extended geothermal developments into traditionally non-geothermal countries such as Denmark, Sweden, Switzerland, and large areas of the mid-western and eastern US. (Lund, 2002 [24]).

Worldwide (Lund and Freeston, 2000 [12]) the installed capacity of direct geothermal utilization in 2000 was 16,200 MWe and the energy use was approximately 162,000 TJ/year distributed among 60 countries. This amounted to a savings of an equivalent of 11.4 million metric tons of fuel oil per year. The worldwide distribution of direct use of geothermal energy is 14.33% Heat Pumps, 36.85% Space Heating, 11.75% Greenhouses, 6.50% Industrial, 6.64% Aquaculture, 22.15% Bathing, and 1.78% others. (Chandrasekharam and Bundschuh (Eds), 2002 [25]).

Internationally the largest uses of geothermal energy are for space heating (37%), 75 percent of which is in district heating systems and for swimming, bathing and balneology (22%) [26].

5.5.1 Direct Uses

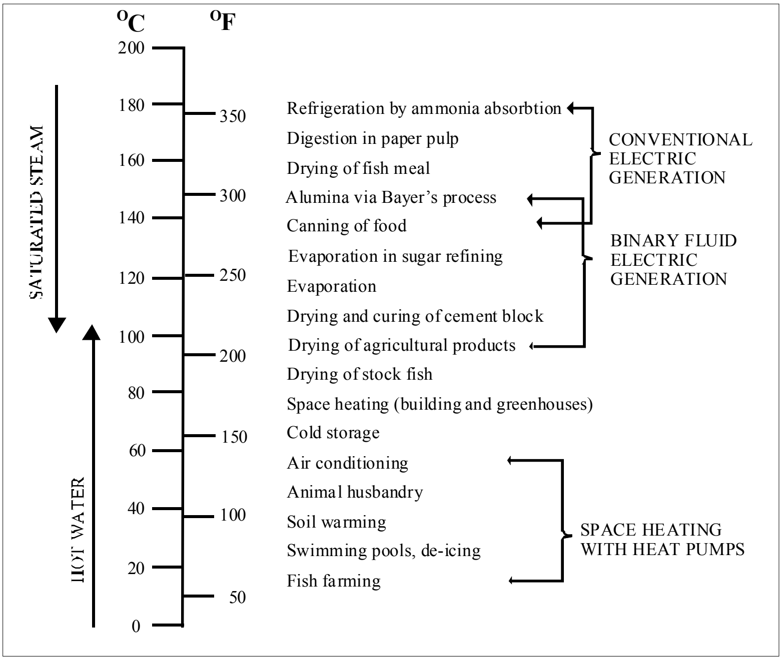
The Lindal diagram (Figure 5.5) indicates the temperature ranges suitable for various direct uses of geothermal energy. Typically, agriculture and aquaculture use the lowest temperature resources. Space heating generally requires temperatures above 50°C, although temperatures as low as 40°C may be adequate in certain cases. Geothermal heat pumps can allow the use of temperatures as low as 4-6°C to provide space heating. Cooling, industrial processes and dehydration normally require temperatures above 100°C. Refrigeration based on ammonia absorption is possible at approximately 180°C. At temperatures over 110-120°C binary fluid electrical generation also becomes economically viable, and above 140°C conventional electric generation is viable. There is increased interest in coupling geothermal electrical generation and direct uses. Electrical generation may be either topping or bottoming cycle depending upon the requirements of the direct use application.

5.5.2 District Heating

Geothermal district heating systems are in operation in at least 12 countries including Iceland, France, Poland, Hungary, Turkey, Japan, China, Romania, Italy, the United States, Sweden and Denmark.

The first known geothermal district heating system was built in Chaudes-Aigues Cantal, France in the 14th century (Bloomquist, 1988 [27]) and is still in operation today. The first system in USA was the Artisan Hot and Cold Water Company built in Boise, Idaho in 1892.

The most famous geothermal district heating system in the world is the system supplying nearly 98% of the residents of Reykjavik, Iceland. The installed capacity is 830 MWe and is designed to meet the heating load down to -10°C. Increased load during colder periods is met by large storage tanks and an oil-fired peaking plant (Ragnarsson, 2000 [28]).



Source: Lund 2002 [24]

Fig. 5.5. Lindal Diagram Indicating Temperature Range for Direct Use of Geothermal Energy

5.5.3 Agriculture and Aquaculture Applications

Agriculture, including greenhouses and soil warming, and aquaculture uses of geothermal energy are increasing rapidly. They are particularly widespread since they require heating at the lower end of the temperature range where there is an abundance of geothermal resources (Chandrasekharam and Bundschuh (eds), 2002 [25]).

5.5.4 Future Developments

The potential for substantially increased use seems very promising. Future developments will depend upon:

- Increased resource information
- Increased knowledge of potential uses
- Prices of competing fuels, e.g. oil and gas
- The establishment of clear legal, institutional and regulatory framework conducive to geothermal development on a country by country basis
- Availability of capital, especially in the developing countries.

5.6 Improving Geothermal Power Plant

Large plants produce electricity at about 5 cents/kWh and small plants at about 7 cents/kWh. Geothermal appears poised for expansion. Some of the aspects of needs and research to significantly improve geothermal power plant for the generation of electricity are now presented.

Geothermal power plants are suitable for deployment in all types of terrain and environment. If the resource is typically above about 150 °C, a direct flash steam plant is used. For lower resource temperatures, a binary plant is used. They are typical Rankine plants, with either steam (flash plant) or hydrocarbon (binary plant) working fluids.

5.6.1 Goal and Objectives

The goal is to work with industry to make geothermal energy fully cost-competitive with fossil-fuelled alternatives. The objectives are to reduce investment, enhance operability, and to promote geothermal energy. Reducing plant investment requires better components, such as air-cooled condensers; lower cost materials and inexpensive coatings; and better cycles.
Reducing operations and maintenance (O&M) costs can be achieved through actions to control brine chemistry; better instruments for tighter controls; and improved emissions control.

Efficiency can be enhanced by improved off-design operation; reduced parasitic losses; and improved cycles.

Plant revenue can be enhanced by co-production of a valuable by-product; and direct use of cascaded brine, first to produce electricity then as a thermal source.

The potential impacts of power plant Research and Development are shown in Table 5.12.
Aggregated, these improvements have a potential for 18 to 25% reduction in the cost of electricity, or about 1¢/kWh reduction.

. Technical Area	Percent Reduction in Cost of Electricity
Heat Exchangers	8 to 10%
Cycle Efficiency	5 to 7%
Enhancement of Off-design Operation	3 to 5%
Reduced O&M	2 to 3%

Table 5.12. Potential Impacts of Power Plant Research and Development

5.7 Geothermal Drilling R&D Overview

Drilling is a critical element of the entire life cycle of geothermal development: exploration, production, injection, and well maintenance. The cost of drilling, logging, and completing geothermal wells is high compared to that of oil and gas because the rock is typically very hard, formations are highly fractured, and the temperatures encountered are very high. As these costs often account for more than half of the total capital required for a geothermal power project, reductions in the cost of drilling and completing wells have a very large impact on a project's overall commercial viability. Some of the techniques for reducing these costs include drilling faster, experiencing less idle time, increasing bit or tool life, achieving higher overall success rates, and producing more per well via the use of multi-laterals. The mission of geothermal drilling programs is to develop cost-cutting technologies for accessing geothermal resources.

The development of high-temperature instrumentation, lost circulation technology, hard-rock drill bit technology, and advanced drilling systems are all directed toward achieving this goal. Technologies developed include improved PDC bits, "Dewarless" high temperature instrumentation, slim hole drilling, polyurethane grout for lost circulation, acid-resistant cement, acoustic telemetry, and diagnosis-while-drilling (DWD) [29].

Geothermal drilling uses the same basic elements as land-based oil and gas drilling – rotary drill rigs, blow-out preventers, drill strings and drill bits – but geothermal resources are found in formations that are much more difficult to drill than those typical of the hydrocarbon industry. Geothermal rocks are typically very hard, fractured, and abrasive; formations are under-pressured and often contain corrosive fluids; hole diameters are large compared to oil and gas; and the drilling environment is often extremely hot and corrosive.

Drilling actually tracks the price of crude oil very closely because as energy prices rise, it becomes viable to drill deeper, more expensive wells. A way of normalizing this cost while accounting for inflation is to compare the cost of drilling a geothermal well with a similar (depth and location) oil well. Over the twenty-year period 1980-2000, technology improvements have lowered the cost of geothermal wells from approximately 1.75 times to 1.4 times that of an oil well. Some of the science and technology related breakthroughs associated with this program include PDC bits, rolling float meter (RFM), polyurethane foam, acoustic telemetry, HT electronics, slim-hole drilling demonstrations, insulated drill pipe, and improved cement.

The single most important barrier to commercialization and deployment is the small size of the geothermal industry. The number of geothermal wells drilled each year is less than 0.1% of the number of oil and gas wells, so it is clear that manufacturers and service companies can quickly identify their market. There are three factors that may mitigate this problem: (1) because geothermal problems are often more difficult than oil and gas problems, hardware developed and tested for geothermal use is sometimes considered “premium” grade, and therefore more reliable, for other drilling, (2) rising energy prices may expand the geothermal market – there is already some evidence of this in California and Nevada, and (3) deep gas drilling now regularly encounters hard rock and temperatures above 225^0C, so this may be a new market for what were previously considered “geothermal” tools.

5.8 Advanced Power Cycles for Enhancing Geothermal Sustainability

Until the early 1980s geothermal plants used steam turbines exclusively, operating on dry steam or separated steam. In the mid 1980s, advanced power cycles were introduced, initially to enable exploitation of lower enthalpy resources, then to recover heat from the separated water, and thereafter to handle high gas content resources as well as high enthalpy resources using combined steam/organic cycles [30]. Most of these plants are air-cooled, assuring 100% re-injection of geothermal fluids and thus enhancing sustainability as well as reducing environmental impact.

Of the 9,000 MW of geothermal plants installed worldwide, most use steam turbines operating on dry steam or steam produced by single or double flash. About 1,000 MW use Organic Rankine Cycle (ORC) or steam/ORC-combined cycles [31]. Examples of commercial plants range in capacity from 200 kW to 130 MW.

Operational experience has confirmed the advantages of the ORC plants, not only for the low enthalpy water-dominated resources, but also at high enthalpy for aggressive brine or brine with high non-condensable gas content. Air-cooled ORC plants are particularly well adapted to Engineered Geothermal Systems (EGS). The somewhat higher installed cost of these systems is often justified by environmental and long-term resource management considerations [32,33].

5.8.1 Optimization in Design of the Power Cycle

Optimization of the whole geothermal power plant system is accomplished by matching the working cycle and fluid properties with the characteristics of the resource, considering not only the resulting efficiency and cost, but also impact on the environment, long-term pressure support, requirements for make-up wells, and costs of operation and maintenance (O & M).

5.8.1.1 Heat Cycle Considerations

When the source is a liquid phase only (sensible heat) the ideal cycle would have a varying source temperature, being a succession of infinitesimal Carnot cycles. In a sub-critical Rankine cycle, the constant temperature of evaporation leads to a loss of energy. However, because of the lower latent heat of vaporization, this drawback is lower than in a steam cycle.

The super-critical binary cycle, the different total flow regenerative cycle, the cascaded binary cycle and the Kalina cycle are aimed at achieving the objective of getting closer to the ideal cycle. When dry steam is available, the most effective way is to use the conventional condensing steam cycle.

When the source is a mixture of steam and brine and/or has a high content of non-condensable gases, the most effective utilization of the resource is achieved through a combined cycle by expanding the steam first in a back pressure steam turbine and then the heat of condensation together with heat of the separated brine is used to drive a bottoming ORC.

It is necessary to consider the output net of the parasites, such as cycle pumps, production pumps, injection pumps, cooling systems and non-condensable gas extraction power consumption [34].

5.8.1.2 Resource Considerations

Sustainability is defined as ability to economically maintain the installed capacity over the life of a plant [35]. In case of geothermal power plants this is controlled by two factors: heat recharge and water recharge.

The decline of production in the Larderello, Geysers and Wairakei fields has focused attention on the necessity for long-term pressure support by re-injection as much of the geothermal fluid as possible.

Use of secondary loops and of down-hole and booster pumps, as employed in air cooled ORC plants, assures complete water recharge and reduces both fouling of the heat exchangers and scaling of the injection wells.

5.8.1.3 Enhanced Geothermal Systems

The value of the air-cooled ORC is particularly important in the case of Engineered Geothermal Systems, which are very much dependent on the water recovery ratio.

5.8.1.4 Environmental Considerations

Use of air-cooled ORC reduces impact on the environment by re-injection of:

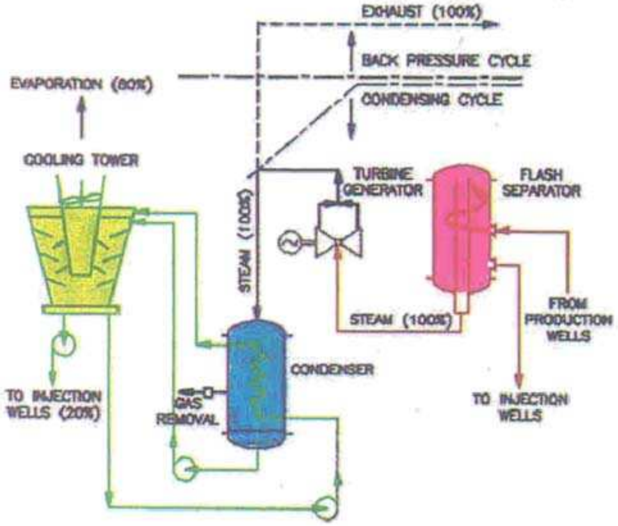
- Non condensable gases (mainly H_2S released by the steam)
- Discharged fluids such as the separated brine (carrying off heavy metals) and blow-down from the cooling towers (chemicals).

5.8.2 Conventional Steam Turbine Geothermal Power Plants

Geothermal power plants operating from dry steam or from steam flashed from high temperature water employ either:

- Back pressure turbines which exhaust the spent steam to the atmosphere, or
- Condensing steam turbines that condense the steam in water-cooled condensers under vacuum, with the condensate used as make-up water, in the cooling tower (Figure 5.6).

Backpressure turbines have the lowest capital cost at the expense of lowest efficiency; condensing steam turbines are more expensive but operate at a higher efficiency than backpressure turbines.



Source: Ormat Technologies, Inc., USA

Fig. 5.6. Conventional geothermal power plant – Backpressure or condensing

5.8.3 Geothermal Power Plants using Organic Rankine Cycle

The basic Organic Rankine Cycle (ORC) as used in an air-cooled binary geothermal plant is characterized by:

- 100 percent re-injection of the geothermal fluid
- Air-cooling for nearly zero environmental impact; and
- No surface discharge of fluids.

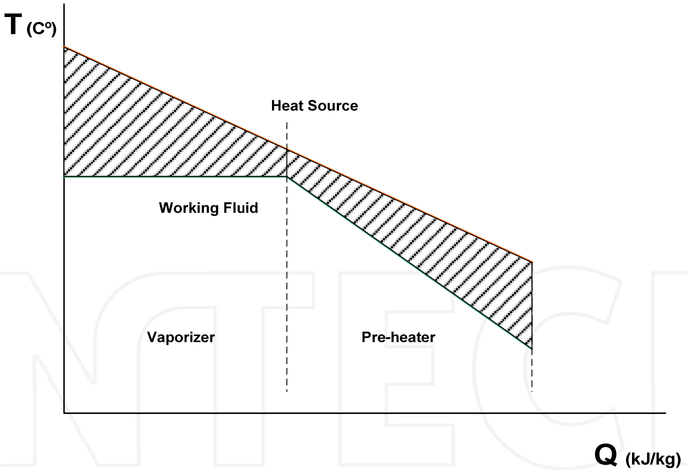
Different plant configurations have been developed to optimize use of the geothermal resource. A number of examples are given in 5.6.3.1—5.6.3.6.

5.8.3.1 Single Phase (Hot Water) Geothermal Power Plants

The irreversibility of a binary process on the hot side, namely the temperature difference between the heating fluid and the working fluid, is shown on the temperature (T) vs. heat withdrawn (Q) (from the liquid) diagram (Figure 5.7).

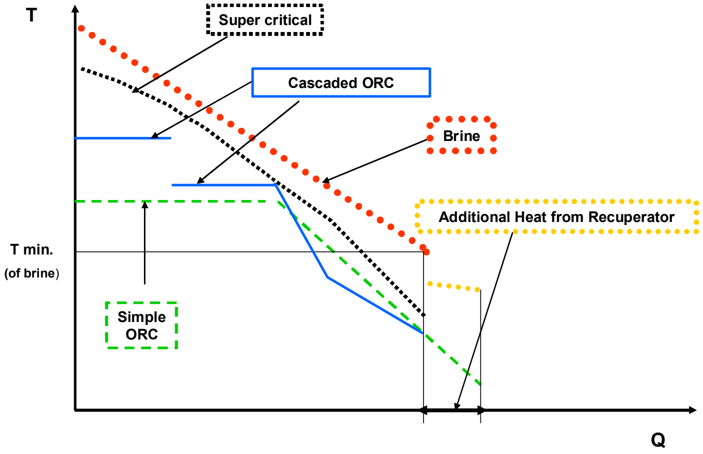
The marked parts between the two curves represent the irreversibility (losses) of the conversion process. Figure 5.7 shows that the similarity in shape of the two curves and the proximity between them are good indications of the process efficiency [36].

This loss can be reduced, as shown in Figure 5.8, by using a supercritical cycle as indicated earlier, by using a cascading approach [36] and/or by recovering some of the heat of the superheated exhaust vapor to preheat the motive fluid.



Source: Ormat Technologies, Inc., USA

Fig. 5.7. Typical T/Q diagram



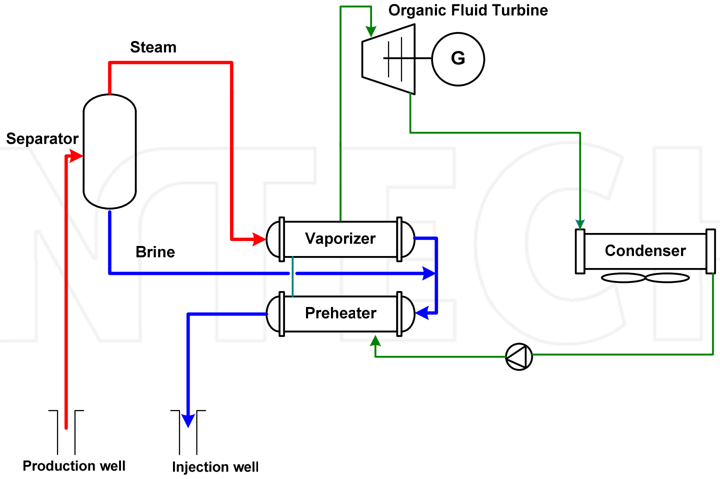
Source: Ormat Technologies, Inc., USA

Fig. 5.8. T/Q diagram: Reducing the irreversibility loss

5.8.3.2 Two-Phase Geothermal Power Plant

In the majority of geothermal fields worldwide, the geothermal fluid is separated in an aboveground separator into a stream of steam and a stream of brine.

In a low to moderate enthalpy resource the steam quality is 10-30 percent a function of the fluid enthalpy and the separation pressure. The two streams can very efficiently be utilized in a two-phase geothermal plant (Figure 5.9). Separated steam (usually with some percentage of Non-Condensable Gases (NCG)) is introduced in the vaporizer to vaporize the organic fluid.



Source: Ormat Technologies, Inc., USA

Fig. 5.9. Two-phase power plant

The geothermal condensate is mixed with the separated brine to provide the preheating medium of the organic fluid. In the ideal case, the latent heat would be equal to the heat of vaporisation of the organic fluid, and the sensible heat of the brine plus condensate would be equal to the heat required to preheat the organic fluid.

5.8.3.3 Recuperated Organic Rankine Cycle

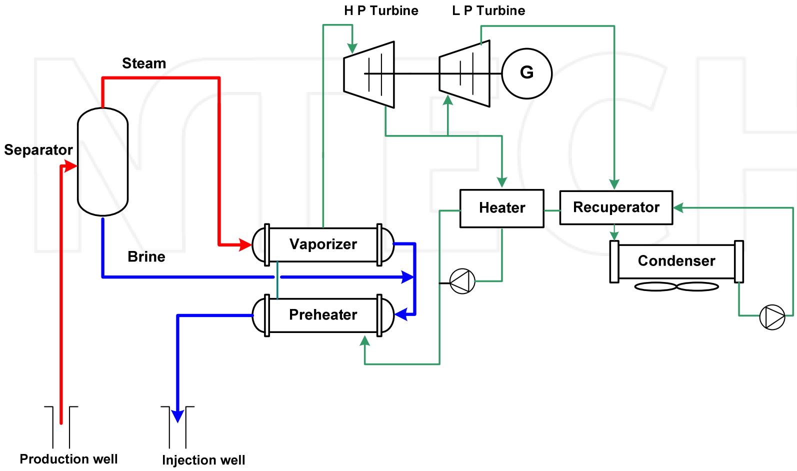
In most actual cases, the perfect match as above is not feasible, mainly because of limitation in the cooling temperature of the brine and condensate mixture. The limiting factor in most cases is silica-scaling risk, which is increased as the brine temperature drops. A method to partially overcome the cooling temperature limit is to add a recuperator that provides some of the preheating heat from the vapour exiting the turbine.

The recuperator is applicable when the organic fluid is of the "*dry expansion*" type, namely a fluid where the expansion in the turbine is done in the dry superheated zone and the expanded vapour contains heat that has to be extracted prior to the condensing stage. The recuperated Organic Rankine Cycle is typically 10-15 percent more efficient than the simple Organic Rankine Cycle [37]. This applies also to two-phase geothermal power plant.

5.8.3.4 Higher Enthalpy Two-Phase Geothermal Power Plant

When the resource enthalpy is higher and as a result the proportion of steam in the total fluid increases, the "*perfect match*" between the heat source and working fluid is not maintained. Thus, some of the available heat or the available energy is lost for power generation.

To utilize the two-phase heat source in a more efficient manner, a secondary organic loop, which uses the extra available steam, can be used. The cycle is shown in Figure 5.10. It is feasible when vapour extraction is possible within the expansion phase of the organic cycle. The simplest way to perform the extraction is with two turbines in series. In this case, some vapour is extracted between the high pressure and the low-pressure turbines and is condensed at an intermediate pressure (and temperature).



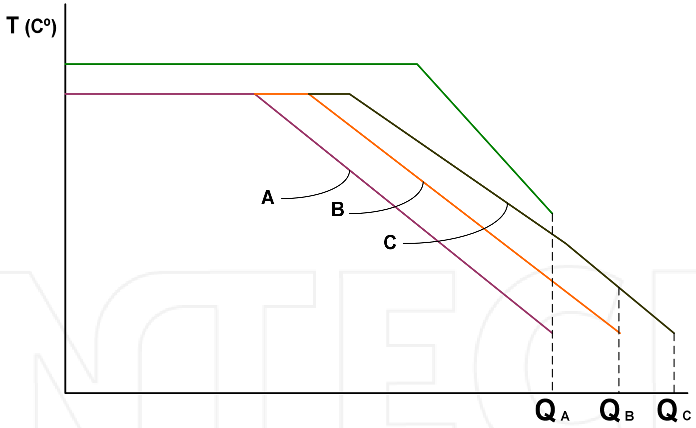
Source: Ormat Technologies, Inc., USA

Fig. 5.10. Secondary organic loop cycle

The condensed vapour preheats the main organic fluid stream as it exits the recuperator. The extracted organic fluid forms a secondary cycle that generates an additional 5 to 8 percent electrical power. When there is extra steam compared to brine (higher enthalpy) the above cycle is effective and the cooling temperature of the brine plus condensate is limited.

Figure 5.11 is a flow temperature diagram of the higher enthalpy cases. Line A is the simple two-phase cycle preheating phase. The significant irreversibility is represented by the large space between the steam and brine lines and line A. Line B shows the preheating phase in a recuperated two-phase cycle; the irreversibility is reduced and the cycle efficiency is increased accordingly.

The third line C demonstrates the additional gain in efficiency by using the two-phase/extraction cycle. The line moves further to the right, thus decreasing the gap between the heating line and the working fluid line. Another indication of the increase in efficiency from cycle A to B and to C, is the increasing heat quantity for heating the working fluid, as presented by points QA, QB, and QC.



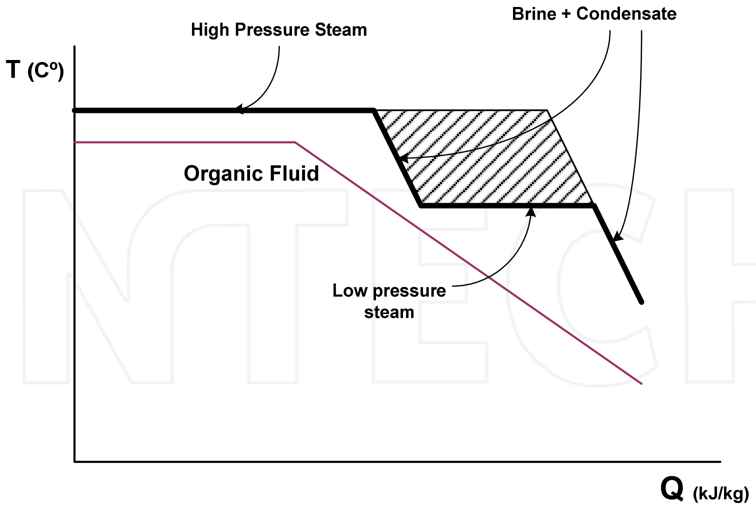
Source: Ormat Technologies, Inc., USA

Fig. 5.11. Higher enthalpy

5.8.3.5 Use of a Back Pressure Steam Turbine

Another approach for the higher enthalpy two-phase heat source is use of a back pressure steam turbine which generates extra power from excess steam not required for the vaporizer of the ORC.

Part of the preheating of the organic fluid is now done with low-pressure steam exiting the backpressure steam turbine (Figure. 5.12).



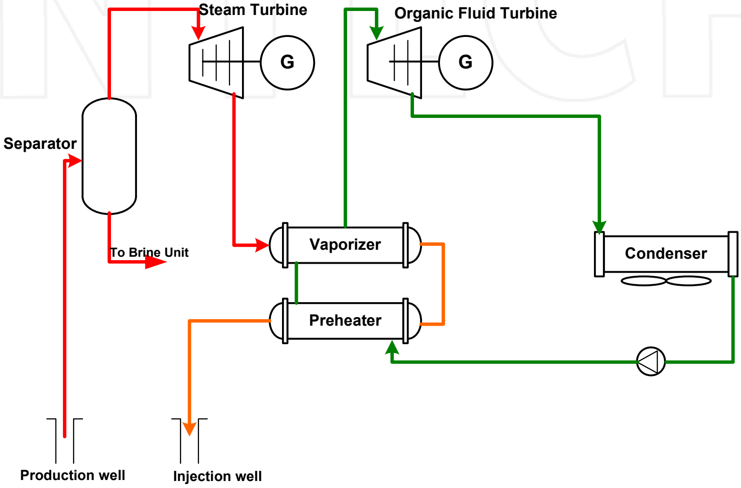
Source: Ormat Technologies, Inc., USA

Fig. 5.12. Pre-heating using exhaust in a backpressure steam turbine

The gap between the steam and the preheating line of the organic fluid could be filled even more efficiently by a multi-stage (two or more) backpressure steam turbine, with extraction of steam between the stages. But the decision on the number of stages is based on consideration of trade-off in process optimization between higher efficiency and complication (and cost) of the system.

5.8.3.6 Geothermal Combined Cycle [38]

For high enthalpy fluids with very high steam content a solution is the geothermal combined cycle configuration where the steam flows through the back pressure turbine to the vaporizer, while the separated brine is used for preheating or in a separated ORC (Figure 5.13) [38].



Source: Ormat Technologies, Inc., USA

Fig. 5.13. Geothermal combined cycle

5.8.4 Deployment

As of 2007, the capacity of geothermal plants using advanced power cycles worldwide is close to 1,000 MW, approximately 10% of the total geothermal capacity installed in the last 50 years.

A breakdown of the 1,000 MW of plants in commercial operation is as follows: 60 MW of ORC plants designed or built by Ben Holt, Turboden and Barber-Nichols; one 2 MW of Kalina cycle plant and more than 900 MW of ORC and combined cycle plants.

5.8.5 Enhancing Sustainability and Cost Effectiveness

Geothermal resources are complex geological structures that provide conduits for natural heat of the earth to heat underground waters that may then be utilised to convey heat to the surface. Technology to assess the heat content of geothermal resources is available, along with drilling technologies to access this heat and mature proven power technologies to convert this heat to commercial electricity.

The key to sustainability of this power generation lies in not depleting the waters that convey this energy to the surface.

The use of the field-proven air-cooled Organic Rankine Cycle based geothermal power plant enables these objectives to be achieved by extending the lifespan of the wells and reducing emissions.

Hence cost-effective power is generated with enhanced sustainability, mitigating depletion of geothermal resources. This element is particularly important in proposed Engineering Geothermal Systems.

5.9 Iceland Deep Drilling Project, Exploration of Deep Unconventional Geothermal Resources

The Iceland Deep Drilling Project (IDDP) is a long-term research and development program aimed to improve the efficiency and economics of geothermal power generation by harnessing deep natural supercritical hydrous fluids obtained at drillable depths. Producing supercritical fluids will require drilling wells and sampling fluids and rocks to depths of 3.5 to 5 km, and at temperatures of 450-600°C. The current plan is to drill and test a series of such deep boreholes in Iceland at the Krafla, the Hengill, and the Reykjanes high temperature geothermal fields. Investigations have indicated that the hydrothermal system extends beyond the three already developed target zones, to depths where temperatures should exceed 550-650°C. A deep well producing $0.67 m^3/sec$ steam ($\sim 2400 m^3/h$) from a reservoir with a temperature significantly above 450°C could yield enough high-enthalpy steam to generate 40-50 MW_{el} of electric power. This exceeds by an order of magnitude the power typically obtained from conventional geothermal wells.

The Project was initiated in 2000 by an Icelandic energy consortium, consisting of Hitaveita Sudurnesja Ltd. (HS), Landsvirkjun (LV), Orkuveita Reykjavikur (OR) and the Icelandic National Energy Authority Orkustofnun (OS). In 2007, Alcoa Inc. joined the IDDP consortium. The principal aim of the IDDP is to enhance the economics of high temperature geothermal resources by producing from deep reservoirs at supercritical conditions.

5.9.1 Supercritical Geothermal Fluids

Large changes in physical properties of fluids occur near the critical point in dilute systems. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces occur that can lead to extremely high rates of mass and energy transport. Because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena can play a major role in high temperature water/rock reaction and the transport of dissolved metals.

At temperatures and pressures above the critical point, which for pure water is at 221 bars and 374°C, only a single-phase supercritical fluid exists. Figure 5.14 shows the pressure-enthalpy diagram for pure water, showing selected isotherms. Steam turbines in geothermal plants generate electricity by condensing the steam separated from the two phase field (liquid and steam field in Figure 5.14) which, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20-30% of the total mass flow. The concept behind the Deep Drilling program is to bring supercritical fluid to the surface in such a way that it transitions directly to superheated steam along a path like F-G in Figure 5.14, resulting in a much greater power output than from a typical geothermal well.

The conditions under which steam and water coexist is shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show different possible cooling paths (from Fournier[1], 1999).

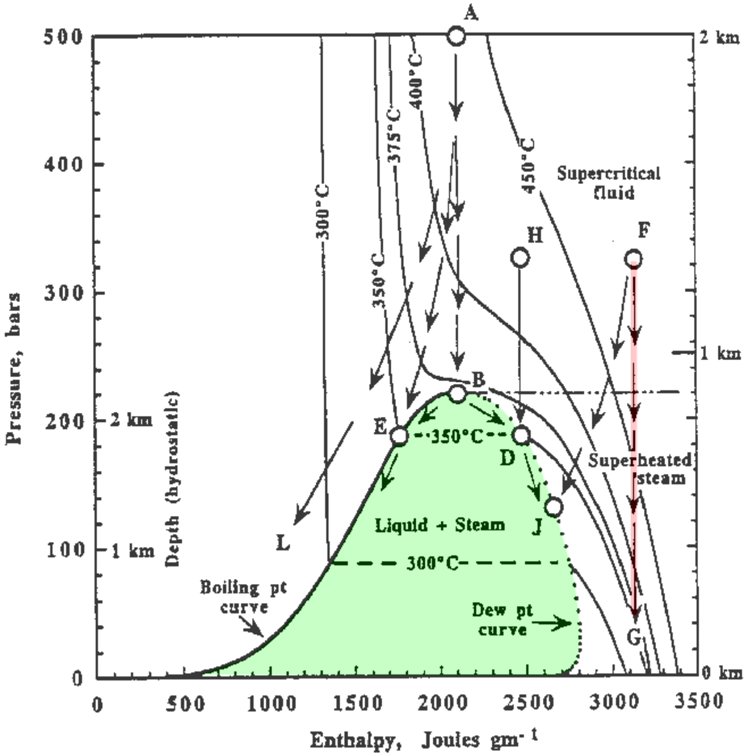


Fig. 5.14. Pressure enthalpy diagram for pure H_2O with selected isotherms

Supercritical conditions have been encountered during drilling in a small number of geothermal fields, like in Larderello in Italy, Kakkonda in Japan, and at Nesjavellir in Iceland, where they have presented problems for commercial exploitation and were sealed off from the conventional part of the systems. Apart from the high P-T conditions where underground blowout was involved, like at Nesjavellir [39] (Steingrimsson et al., 1990), the problems include low permeability, hole instability due to thermal creep, and the presence of acid volcanic gases. However, the drilling technology used in these cases was not designed to handle the conditions encountered when supercritical hydrous fluids were unexpectedly penetrated.

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[1] Fournier, R. *Hydrothermal Processes Related to Moment of Fluid Flow from Plastic into Brittle Rock in the Magmatic-Epithermal Environment*, Economic Geology, Vol. 94, (8), 1999, pp. 1193-1211.

The IDDP intends to meet the hostile conditions expected in supercritical geothermal reservoirs by a conservative well design and by adopting the necessary safety measures. The safety casing will be cemented down to 2.4 km before drilling down to 3.5 km depth or deeper to reach the critical point. Once beyond that, the production casing will be cemented in order to produce only the supercritical fluid. By releasing the pressure, the supercritical fluid will expand and move upwards to the surface through the well bore as a superheated dry steam, following a path like F-G in Figure 5.14. The deep casings will prevent the fluid from mixing with the two-phase zone and as the pressure decreases, condensation is less likely to occur. A pilot study for harnessing the fluid will need to be undertaken, especially with respect to the fluid chemistry that will only be known after drilling.

5.9.2 Drilling in IDDP Wells

5.9.2.1 Design

Conventional geothermal drilling techniques will be used in drilling the IDDP wells. The first well was designed as a dual-purpose hole. To meet the engineering goals of the power companies, it is designed as an exploration/production well, and to meet the scientific goals of understanding the supercritical environment, some spot cores will be taken in the lowest part of the drill hole, which hopefully will be the supercritical zone.

5.9.2.2 Potential Drill Sites

Geothermal reservoirs at supercritical conditions are potentially to be found worldwide in any active volcanic complex. However, the depth to such reservoirs may vary greatly from shallow to deep, and the simplest approach would be to seek supercritical reservoirs in active high-temperature geothermal fields, closest to the earth’s surface, in both sub aerial and submarine settings. Each high temperature hydrothermal system requires site-specific attention to target drill sites for reaching deep unconventional geothermal resource (DUGR) reservoirs with supercritical conditions and permeable rocks at drillable depths.

All active volcanic complexes are potential targets for finding deep geothermal systems at supercritical conditions. These volcanic complexes are of different ages and at different stages in their evolution; some are at infancy, others are mature and some are close to extinction.

The three Icelandic fields deemed to be prime targets for DUGR exploration, the Reykjanes, Hengill and Krafla geothermal systems, demonstrate different stages in the evolution of their magma-hydrothermal evolution, the first being at infancy, the second being “middle aged” and the third being mature. Deep drilling at all three will permit studying different stages in the development of supercritical conditions at depth. Additionally, they exhibit different fluid compositions, the first involving modified seawater, but the other two dilute fluids of meteoric origin. Extensive production in all three-drill fields has led to the hottest parts of the hydrothermal up-flow zones. However, the nature of their heat sources is poorly known except in the mature case of the Krafla system where a magna chamber has been identified at only 3-4 km depth [40].

5.9.3 Potential Benefits

5.9.3.1 Power Generation

The high-temperature fluids expected from the IDDP wells offer two advantages over fluids from conventional wells for generation of electric power, (i) higher enthalpy, which promises high power output per unit mass, and (ii) higher pressure which keeps the fluid density high and thus contributes to a high mass-flow rate.

The electric power output that can be expected from an IDDP well compared with that from a conventional has been estimated by Albertsson et. Al. [41,42].

The choice of technology to be applied for the power generation cannot be decided until the physical and chemical properties of the fluid are determined. Nonetheless, it appears likely that the fluid will be used indirectly, in a heat exchange circuit of some kind. In such a process the fluid from the well would be cooled and condensed in a heat exchanger and then injected back into the field. This heat exchanger would act as an evaporator in a conventional closed power-generating cycle.

5.9.3.2 Scientific Studies

In addition to investigations and sampling of fluids at supercritical conditions the IDDP will permit scientific studies of a broad range of important geological issues, such as investigation of the development of a large igneous province, and the nature of magma-hydrothermal fluid circulation on the landward extension of the Mid-Atlantic Ridge in Iceland. In addition, the IDDP will require use of techniques for high-temperature drilling, well completion, logging, and sampling, techniques that will have a potential for widespread applications in drilling into oceanic and continental high-temperature hydrothermal systems.

5.9.3.3 Economic Benefits

The potential economic benefits of the IDDP project may be listed as follows:

1) Increased power output per well, perhaps by an order of magnitude, and production of higher-value, high-pressure, high-temperature steam.
2) Development of an environmentally benign, high-enthalpy energy source beneath currently producing geothermal fields.
3) Extended lifetime of the exploited geothermal reservoirs and power generation facilities.
4) Re-evaluation of the geothermal resource base.
5) Industrial, educational, and economic spin-off.
6) Knowledge of permeability within drill fields deeper than 2-3 km depth.
7) Knowledge of heat transfer from magma to water.
8) Heat sweeping by injection of water into hot, deep wells.
9) Possible extraction of valuable chemical products.
10) Advances in research on ocean floor hydrothermal systems (the Reykjanes field).

Amongst approaches to improve the economics of the geothermal industry, three of the most significant are: (i) to reduce the cost of drilling and completing geothermal production wells as far as possible, (ii) to cascade the usage of thermal energy by using the effluent water for domestic heating and for industrial processes, and (iii) to reduce the number of wells needed by increasing the power output of each well, by producing supercritical fluids. Accordingly, the completion of the IDDP project is of considerable importance for the geothermal industry at large.

5.9.3.4 Environmental Issues

Developing environmentally benign high-enthalpy energy sources below the depth of currently producing geothermal fields is not only of economic value in relation to the already installed infrastructures, but it is also of environmental value by diminishing environmental impact of geothermal utilization. Producing more power without increasing the *footprint* of the exploited drill field is a significant benefit.

5.9.4 Potential Impacts

5.9.4.1 Global Impacts

Potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. If producing supercritical fluids became widespread it would lead to a major enlargement of the accessible geothermal resource base.

It is conceivable that, in the more distant future, utilization of ocean floor geothermal systems might become viable. Submarine geothermal systems are abundant along the world's mid-ocean ridge systems and some of them (the black smokers) expel ~400°C hot seawater direct into the deep oceans, and precipitate chimneys of sulphide-ore deposits. The pressure of 2.5-3 km deep seawater results in supercritical hydrostatic pressures, and allows almost supercritical fluids to be expelled directly into the oceans. Tapping energy through shallow drill holes on the mid-ocean ridges using techniques initially developed by the international IDDP program is an exciting prospect.

5.9.4.2 Potential Impact on Greenhouse Gases

In the Stern Review to the British Government 2006 [43] (www.sternreview.org.uk) it is reported that since industrialization, greenhouse gas (GHG) levels have risen from 280 ppm CO_2 equivalent (CO_2e) to 430 ppm CO_2e today, and they increase by 2 ppm each year. The risks of the worst impacts of climate change can be substantially reduced, according to the review, if the GHG levels can be stabilized between 450 and 550 ppm CO_2e. Stabilization in this range would require emissions to be at least 25% below current levels by 2050, and perhaps much more. According to the Review, three measures need be taken, (1) taxation on GHG emission, (2) new techniques, and (3) removal of hindrances against economic energy usage. According to the Stern Report the main sources of the polluting greenhouse gases are 24% in the Power Sector, 14% in the Industry sector, another 14% in the Transport sector, and 5% in other energy related activities, altogether some 57%. Attempting to decrease CO_2e emission in any of these sectors would be a logical step to respond to the Stern Review.

The World Energy Council (WEC) has presented several scenarios for meeting future energy requirements with varying emphasis on economic growth rates, technological progress, environmental protection and international equity [44] (Nakicenovic et al., 1998). In all WEC´s scenarios, the peak of the fossil fuel era has already passed (Nakicenovic et al., 1998). Oil and gas are expected to continue to be important sources of energy in all cases, but the role of renewable energy sources and nuclear energy vary highly in the scenarios and the level to which these energy sources replace coal. In all the scenarios, the renewables are expected to become very significant contributors to the world primary energy consumption, providing 20-40% of the primary energy in 2050 (UK 80%) and 30-80% in 2100. They are expected to cover a large part of the increase in energy consumption and to replace coal.

Evidently, a large opportunity to cut GHG emission exists with the geothermal energy sector. However this estimate did not include innovations such as IDDP.

In summary, the long-term program to improve efficiency and economics of geothermal energy by harnessing deep unconventional geothermal resources is an ambitious project to produce electricity from natural supercritical hydrous fluids from drillable depths. Producing higher-temperature fluids for generation of electric power offers two advantages over using the fluids from conventional wells: (i) higher enthalpy, which promises high power output and higher efficiency per unit mass, and (ii) higher pressure, which keeps the fluid density high and thus contributes to higher mass-flow rates. The choice of technology to be applied for power generation from these high-temperature fluids will be decided after determining the physical and chemical properties of the fluids that are produced.

There are three approaches to improve the economics of the geothermal industry worldwide: (i) cascading the usage of geothermal energy by using the effluent water from electricity production for industrial processes and for domestic heating, (ii) reducing the cost of drilling and completing geothermal production wells, and (iii) reducing the number of wells needed by increasing the power output of each. The best way to achieve the latter is to produce supercritical fluids. Successful completion of the IDDP project is of considerable importance for the geothermal industry at large. A successful outcome would be a major step forward for the geothermal industry on a global scale, which in turn, could help counterbalance the threat of global warming by increased use of sustainable, non-polluting energy resources.

5.10 Geothermal Power Plants in Iceland in the Hengill Area

Geothermal plants in Iceland are now discussed. The Hengill area in SW-Iceland is one of the most extensive geothermal areas in Iceland. It is located 25 km east of Reykjavik. It has an area of approximately 110 km² and is estimated to sustain 700 MW_{el} power production in several power plants [45]. Two power plants operate in the area. Environmental impact assessment for two new power plants is being worked on. Power plants in the Hengill area will produce at least 600 MW_{el} and 433 MW_{th} by end of 2011. Research projects connected with the power plant project: (i) the Carb-Fix project, and (ii) the IDDP project, is being worked on.

Research drilling started at Nesjavellir in the north of the Hengill area in 1965. Hot water production for district heating in Reykjavík started at the Nesajvellir plant in 1990. Power production started there in 1998. Today, the Nesjavellir power plant produces 120 MW_{el} and 300 MW_{th}. The Nesjavelir plant was built in several stages.

To meet increasing demand for electricity and hot water for space heating in the industrial and domestic sectors, Orkuveita Reykjavíkur (OR) is currently building a CHP geothermal power plant at Hellisheiði. The approach for the Hellisheiði plant is the same as for Nesjavellir, i.e., it will be built in several stages. The first stage, which came on line in 2006, consist of two 45 MW_{el} units. The second stage of the Hellisheiði power plant, which consists of a 33 MW_{el} Low Pressure unit, started operating in November 2007. Construction of the third stage of the plant is in progress, that is the erection of a two additional high-pressure units, 45 MW_{el} each. Erection of the thermal plant, the fourth stage, started at the beginning of 2008.

At least two new geothermal power plants are planned for the Hengill area, at Hverahlíð and Bitra.

An environmental impact assessment (EIA) for the power plants at Hverahlíð and Bitra was published towards end 2007.

The capacity of the Hellisheiði power plant will be 300 MW_{el} electric and 400 MW_{th} thermal. Estimated capacity of the power plants in Hverahlíð and Bitra will be 90 MW_{el} and 135 MW_{el}, respectively.

With more knowledge of the Hengill geothermal area accumulated through running the Nesjavellir and Hellisheiði power plants and research drilling, new opportunities arise which can be utilized both in future power plants in the area and in other projects.

5.10.1 The Hengill Area

The Hengill area is a rural mountainous area in the middle of the western volcanic zone of Iceland that runs from Reykjanes in a northerly direction to Langjökull (Figure. 5.14). The Hengill region is one of the most extensive geothermal areas in Iceland. Surface measurements and the heat distribution estimate that the region will sustain 690 MW_{el} power production in several power plants [45]. The high temperature geothermal area at Hengill covers three central volcanoes and their surroundings. The youngest one is the most active, whereas the oldest one is eroded but still geothermal active.

5.10.2 Nesjavellir Power Plant

The first geothermal power plant in the Hengill area is the Nesjavellir power plant. Construction of the power plant began in early 1987, with the first stage being completed in May 1990. Four holes, generating about 100 MW_{th}, were then connected to the processing cycle, The next stage of power harnessing was brought online in 1995 when the fifth hole was connected; heat exchangers and a deaerator were added; and the production capacity was increased to 150 MW_{th} of geothermal power [46].

In fall 1998, the first steam turbine was commissioned and the second at the end of the year, producing total of 60 MW_{el}. Five additional holes were put online, increasing the total processing power of the power station to 200 MW_{th}, In June 2001 the third turbine was put into operation. The turbines are 30 MW_{el} each, making the total production of electricity 90 MW_{el} [19].

Early 2008, Nesjavellir power plant generates 300 MW_{th} and 120 MW_{el}. The Nesjavellir area is being researched to see if it is possible to add one more turbine to the power plant.

5.10.3 Hellisheiði Power Plant

The first research drilling for the Hellisheiði power plant was in 1985 and then again in 1994. These boreholes indicated that the geothermal fields could sustain power production but more drilling was needed before decisions could be made. In 2001 and 2002 five boreholes were drilled. Based on the results from these boreholes it was decided to start preparations for a power plant with total capacity of 120 MW_{el} and 400 MW_{th} with the objective to meet increasing demand for electricity and hot water for space heating in the industrial and the domestic sectors.

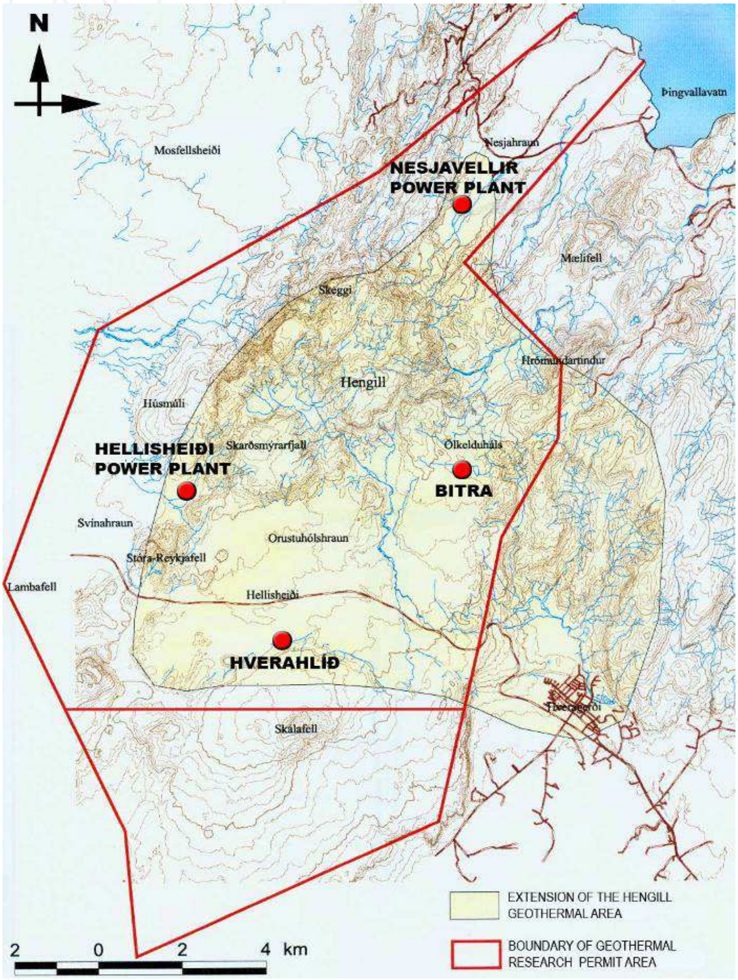

Fig. 5.14. Detailed map of the Hengill area.

Drilling continued and by end of 2005 18 new boreholes had been drilled. In light of the results of these drillings it was decided to enlarge the development area further north towards the main volcano. With this new area, estimated capacity of the geothermal area was increased by 120 MW_{el}. The first stage from this new area is 90MW_{el} to be ready in 2008. With this enlarged potential more geothermal water was available than initially estimated and more than is needed for the thermal plant. It was decided to add one low-pressure unit to increase utilization of the geothermal energy. Its size ended as 33 MW_{el}.

The first stage started operating in 2006 and comprises two 45 MW_{el} units. The second stage, a 33 MW_{el} Low Pressure unit, started operating in November 2007. The construction of the third stage, the erection of two additional high-pressure units rated at 45 MW_{el} each, is in progress. Erection of the thermal plant started at beginning 2008.

5.10.3.1 Construction Plan

The Hellisheiði power plant is being constructed similar to the Nesjavellir power plant. It is a cogeneration plant and will be comprised of modular units. The power plant capacity can expand as market demand increases, and can utilize greater knowledge of the geothermal capacity of the area that is being provided by drilling.

Commis-sioning	2006 MW_{el}	2007 MW_{el}	2008 MW_{el}	2009 MW_{th}	2910 MW_{el}	>2011 MW_{el}
Electricity						
High Pressure	1st. 90		3rd. 90		5th 90.	
Low Pressure		2nd. 33				
Thermal unit				4th 133		267

Table 5.13. Main Construction Stages for Hellisheiði Power Plant

The power production capacity of each electric unit will be 45 MW_{el} and 33 MW_{el} for the Low Pressure unit. For each thermal unit the capacity will be 133 MW_{th}. Table 5.13 shows the main construction stages for the Hellisheiði power plant and when each stage is scheduled to start operating.

5.10.3.2 Technical Description

The total development area of the Hellisheiði power plant is 820 ha. The development consists of geothermal utilization, access roads, service roads, production wells, the water supply system, steam transmission pipes, steam separator stations, power house, cooling towers, steam exhaust stacks, a fresh groundwater supply system, water tanks, hot-water transmission pipes, quarrying, discharge system, injection areas, and connection to the power grid.

5.10.3.3 Production Wells and Directional Drilling

Production wells are drilled both vertically and directionally, up to five wells per drilling site. With directional drilling it is possible to reach under valleys and in the direction of the mountain Hengill, without disrupting the valleys. Production wells can be up to 3.000 m and with directional drilling it is possible to drill 1,200 m from the center.

Production wells are grouped on drilling sites, up to five wells on predefined areas. The mean number of production wells per drill site is four with an area of about 12,000 m^2. The location of drill sites depends on geothermal and geophysics researches. Visual appearance of drill sites on the landscape has impact on where the drill sites are positioned. Minimum distance between production wells on a drill site is around 10m.

5.10.4 Hverahlíð and Bitra

Because of a growing demand for electricity in the industrial sectors, for example aluminum smelters, planning for two new power plants at the Hengill area has started, the Bitra power plant and the Hverahlíð power plant.

5.10.4.1 Environmental Policy

Construction of new geothermal power plants are subject to Environmental Impact Assessment (EIA) according to Article 5 and item 2 of Annex 1 of the Icelandic EIA Act No. 106/2000. Preliminary EIA proposals for the project at Bitra and Hverahlíð were presented in August 2006, and work on the EIA has been in progress since then. It was expected that the Planning Agency would issue their conclusion regarding the EIA early 2008.

5.10.4.2 Power Plant at Bitra

The development area is located about 8 km northeast of the Hellisheiði power plant. The development area of the plant was reduced from its original size on account of environmental reasons. Because of reduction of the development area and environmental policy, the effect of the Bitra power plant on its surroundings has been minimized [47].

Three research boreholes have been drilled in the area. The size of the power plant was estimated from information gathered from those boreholes and from results from a model of the geothermal area [48]. Estimated capacity of power plant at Bitra is 135 MW_{el}.

5.10.4.3 Power Plant at Hverahlíð

The development is located about 3 km southeast of the Hellisheiði power plant. The development area of the power plant was also reduced from its original size because of environmental reason. Like at Bitra, reduction of the development area and environmental policy will result in a minimal effect of the Hverahlíð plant on its surroundings [49].

Three research boreholes have been drilled in the area. The size of the power plant was estimated from information gathered from those boreholes and the results from a model of the geothermal area [48]. Estimated capacity of the power plant in that area is 90 MW_{el}.

5.10.5 Research Projects in the Hengill Area

5.10.5.1 New research Areas in the Hengill Area

Research boreholes have been drilled south of the Hellisheiði power plant. It was thought that these should be on the edge of the defined geothermal area. Results from the research drilling showed that the geothermal area extends further south. Because of this, it was decided to research the areas that are called Gráuhnúkar and Meitill. If research drilling gives positive results, it will be possible to extend the operation area of the Hellisheiði power plant to those sites or construct new smaller power plants in those areas. Ether way an EIA will be necessary.

5.10.5.2 Carb-Fix--Nature Imitated in Permanent CO_2 Storage Project

In fall 2007 a project was launched with the aim at storing CO_2 in Iceland's lavas by injecting greenhouse gases into basaltic bedrock where it literally turns to stone. CO_2 turning into calcite is a well-known natural process in volcanic areas. Now scientists of the University of Iceland, Columbia University N.Y. and the CNRS in Toulouse, France are developing methods to imitate and speed up this transformation of $CO_{2\ \text{into}}$ calcite that is a prevalent contributor to global warming.

Injecting CO_2 at carefully selected geological sites with large potential storage capacity can be a long lasting and environmentally benign storage solution. To date, CO_2 is stored as gas in association with major gas production facilities. The uniqueness of the Icelandic project is that whereas other projects store CO_2 mainly in gas form, where it could potentially leak back into the atmosphere, the current project seeks to store CO_2 by creating calcite in the subsurface. Calcite, a major component of limestone, is a common and stable mineral in the Earth that is known to persist for tens of millions of years.

In the project at the Hengill area, a mixture of water and steam is harnessed from 2000 m deep wells at the Hellisheidi power plant. The steam contains geothermal gases, i.e. CO_2. It is planned to dissolve the CO_2 from the plant in water at elevated pressure and then inject it through wells down to 400-800 m just outside the boundary of the geothermal system

It is estimated that the project will take three to five years. It was scheduled to start a full-scale CO_2 injecting end 2008 or beginning 2009.

At least 600 MW_{el} and 433 MW_{th} are planned at power plants in the Hengill area by end of 2011.

5.11 A Perspective on the Future of Geothermal Energy in USA

Geothermal production began in USA at The Geysers field about 140 km north of San Francisco, California at what is now the world's largest geothermal field. USA continues to be the world leader in online capacity of geothermal energy and generation of electric power from geothermal energy. According to US Energy Information Agency, geothermal energy in 2005 generated approximately 16,010 GWh of electricity or about 0.36% of US annual electricity generation. Generation capacity is about 2850 MW.

Numerous exploration and development projects are underway which, if successful, would double this capacity. Beyond this growth there is still untapped potential for development of additional hydrothermal resources. The US Geological Survey (USGS) [50] estimated about 23,000 MWe capacity for 30 years of identified hydrothermal resources suitable for generation of electricity in USA and suggested that another 100,000 MWe of resources may be present but not yet identified. A more recent estimate prepared by a panel of experts hosted by the US. Department of Energy National Renewable Energy Laboratory [51] estimated that the identified accessible hydrothermal resource suitable for electrical generation is 30,000 MWe for 30 years with an additional 120,000 MWe unidentified. In addition, the US coastal region of Texas and Louisiana contains a significant amount of hot water nearly saturated with methane and with high wellhead pressures. A recent study by the Massachusetts Institute of Technology [52] reported that the thermal energy and energy in the methane may represent as much as 1,000 MWe capacity for 100 years.

5.11.1 Future Resources

Although these numbers are significant, they represent only a small fraction of the thermal energy underlying the USA. Current geothermal development is limited to geothermal systems driven by the convective flow of hot water associated with active volcanoes or with deep circulation of fluids. However, the majority of the earth's thermal energy is contained in areas where heat is transferred by conduction. It is this energy that is truly the future of geothermal energy in USA.

Researchers throughout the world have looked since the 1970s for ways to tap the conductive heat in the earth. The conceptual model, termed enhanced geothermal systems (EGS), is to drill wells and create or enhance subsurface fractures by use of reservoir stimulation practices pioneered by the petroleum industry. Such technology offers the promise of tapping the enormous amount of heat contained within the earth.

The US Department of Energy (USDOE) is working with private developers to investigate stimulation technology in poorly productive areas of commercial geothermal fields. They commissioned a study of the potential for enhanced geothermal systems in USA. The Massachusetts Institute of Technology lead team published their findings in December 2006 [52]. Report is available at http://geothermal.inl.gov or
http://www1.eere.energy.gov/geothermal/future_geothermal.html .The study found that EGS represents a large, indigenous resource that could provide 100 GWe of electrical generation in the next 50 years with a reasonable investment in R&D. The report estimates that the EGS resource base is more than 13 million exajoules of which about 200,000 exajoules may be extractable. That represents 2,000 times the annual consumption of primary energy in the United States.

The USDOE is evaluating the findings of the report and comments from the geothermal and petroleum industries.

5.12 Acknowledgements

This Chapter has been prepared and coordinated by T. J. Hammons, Chair of International Practices for Energy Development and Power Generation IEEE; University of Glasgow, UK.

Contributors included Valgardur Stefansson (Orkustofnun, National Energy Authority of Iceland, Iceland); Arni Gunnarsson (Landsvirkjun, National Power Company, Iceland); Jay Nathwani (Department of Energy, Idaho Operations Office, USA); R. Gordon Bloomquist (Washington State University Cooperative Extension Energy Program, Washington, USA); Luciem Y. Bronicki and Daniel N. Schochet (ORMAT Technologies, Inc., USA); R. Gerald Nix (National Renewable Energy Laboratory, USA); Ed Hoover (Sandia National Laboratory, USA); Karl Urbank (Calpine Corporation, USA); Kenneth H. Williamson (UNOCAL Corporation, CA, USA); William E. Lewis (Power Engineers, USA), Björn Stefánsson and Bjarni Pálsson (Landsvirkjun, Iceland), Guðmundur Ómar Friðleifsson (Hitaveita Suournesja, Iceland); Ingólfur Hrólfsson and Sigurgeir Bjorn Geirsson (Orkuveita Reykjavikur, Iceland); and Allan Jelacic and Joel L. Renner (Idaho National Laboratory, US Department of Energy, USA). The Chapter is primarily based on an up-date of the invited panel session summary papers presented at the Panel Session on Harnessing Untapped Geothermal Power; and on Developments in Geothermal and Hydro Power in Iceland, Europe and Worldwide at the IEEE-PES 2008 General Meeting (GM2008) organized and chaired by T. J. Hammons and A. Gunnarsson [53].

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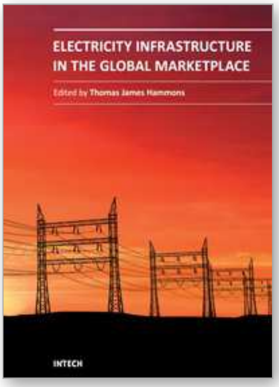

Electricity Infrastructures in the Global Marketplace
Edited by

ISBN 978-953-307-155-8
Hard cover, 802 pages
Publisher InTech

Published in print edition June, 2011

This book discusses trends in the energy industries of emerging economies in all continents. It provides the forum for dissemination and exchange of scientific and engineering information on the theoretical generic and applied areas of scientific and engineering knowledge relating to electrical power infrastructure in the global marketplace. It is a timely reference to modern deregulated energy infrastructure: challenges of restructuring electricity markets in emerging economies. The topics deal with nuclear and hydropower worldwide; biomass; energy potential of the oceans; geothermal energy; reliability; wind power; integrating renewable and dispersed electricity into the grid; electricity markets in Africa, Asia, China, Europe, India, Russia, and in South America. In addition the merits of GHG programs and markets on the electrical power industry, market mechanisms and supply adequacy in hydro-dominated countries in Latin America, energy issues under deregulated environments (including insurance issues) and the African Union and new partnerships for Africa's development is considered.

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How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

T. J. Hammons (2011). Geothermal Power Generation: Global Perspectives, Technology, Direct Uses, Plants, Drilling and Sustainability Worldwide, Electricity Infrastructures in the Global Marketplace, (Ed.), ISBN: 978-953-307-155-8, InTech, Available from: http://www.intechopen.com/books/electricity-infrastructures-in-the-global-marketplace/geothermal-power-generation-global-perspectives-technology-direct-uses-plants-drilling-and-sustainab

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