Fridleifsson, I.B., R. Bertani, E. Huenges, J. W. Lund, A. Ragnarsson, and L. Rybach 2008. The possible role and contribution of geothermal energy to the mitigation of climate change. In: O. Hohmeyer and T. Trittin (Eds.) IPCC Scoping Meeting on Renewable Energy Sources, Proceedings, Luebeck, Germany, 20-25 January 2008, 59-80.

The possible role and contribution of geothermal energy to the mitigation of climate change

IPCC Geothermal 11 February 2008

Ingvar B. Fridleifsson (United Nations University Geothermal Training Programme, Iceland), Ruggero Bertani (Enel S.p.A., Italy), Ernst Huenges (GFZ Potsdam, Germany), John W. Lund (Oregon Institute of Technology, USA), Arni Ragnarsson (ISOR, Iceland), and Ladislaus Rybach (Geowatt AG, Switzerland).

Abstract

Electricity is produced by geothermal in 24 countries, five of which obtain 15-22% of their national electricity production from geothermal energy. Direct application of geothermal energy (for heating, bathing etc.) has been reported by 72 countries. By the end of 2004, the worldwide use of geothermal energy was 57 TWh/yr of electricity and 76 TWh/yr for direct use. Ten developing countries are among the top fifteen countries in geothermal electricity production. Six developing countries are among the top fifteen countries reporting direct use. China is at the top of the latter list. It is considered possible to increase the installed world geothermal electricity capacity from the current 10 GW to 70 GW with present technology, and to 140 GW with enhanced technology. Enhanced Geothermal Systems, which are still at the experimental level, have enormous potential for primary energy recovery using new heat-exploitation technology to extract and utilise the Earth's stored thermal energy. Present investment cost in geothermal power stations is 2-4.5 million euro/MWe, and the generation cost 40-100 euro/MWh. Direct use of geothermal energy for heating is also commercially competitive with conventional energy sources. Scenarios for future development show only a moderate increase in traditional direct use applications of geothermal resources, but an exponential increase is foreseen in the heat pump sector, as geothermal heat pumps can be used for heating and/or cooling in most parts of the world. CO_2 emission from geothermal power plants in high-temperature fields is about 120 g/kWh (weighted average of 85% of the world power plant capacity). Geothermal heat pumps driven by fossil fuelled electricity reduce the CO_2 emission by at least 50% compared with fossil fuel fired boilers. If the electricity that drives the geothermal heat pump is produced from a renewable energy source like hydropower or geothermal energy the emission savings are up to 100%. The total CO_2 emission reduction potential of geothermal heat pumps has been estimated to be 1.2 billion tonnes per year or about 6% of the global emission. The CO_2 emission from low-temperature geothermal water is negligible or in the order of 0-1 g CO_2/kWh depending on the carbonate content of the water. Geothermal energy is available day and night every day of the year and can thus serve as a supplement to energy sources which are only available intermittently. Renewable energy sources can contribute significantly more to the mitigation of climate change by cooperating than by competing. Likely case scenarios are presented in the paper for electricity production and direct use of geothermal energy, as well as the mitigation potential of geothermal resources 2005-2050. These forecasts need to be elaborated on further during the preparation of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.

Introduction

Although geothermal energy is categorised in international energy tables amongst the "new renewables", it is not a new energy source at all. People have used hot springs for bathing and washing clothes since the dawn of civilisation in many parts of the world. An excellent book has been published with historical records and stories of geothermal utilisation from all over the world (Cataldi et al., 1999).

Electricity has been generated commercially by geothermal steam since 1913, and geothermal energy has been used on the scale of hundreds of MW for five decades both for electricity generation and direct use. The utilisation has increased rapidly during the last three decades. Geothermal resources have been identified in some 90 countries and there are quantified records of geothermal utilisation in 72 countries. Summarised information on geothermal use in the individual countries for electricity production and direct use (heating) is available in Bertani (2005) and Lund et al. (2005), respectively. Electricity is produced by geothermal energy in 24 countries. Five of these countries obtain 15-22% of their national electricity production from geothermal (Costa Rica, El Salvador, Iceland, Kenya and the Philippines). In 2004, the worldwide use of geothermal energy was about 57 TWh/yr of electricity (Bertani, 2005), and 76 TWh/yr for direct use (Lund et al., 2005). The installed electric capacity in 2004 was 8,933 MWe (Bertani, 2005). The installed capacity for direct applications in 2004 was 28,268 MWth (Lund et al., 2005). Figure 1 shows the installed capacity and the geothermal energy in the different continents in 2004. Figure 2 shows the installed capacity for electricity production in 2007 in different countries.

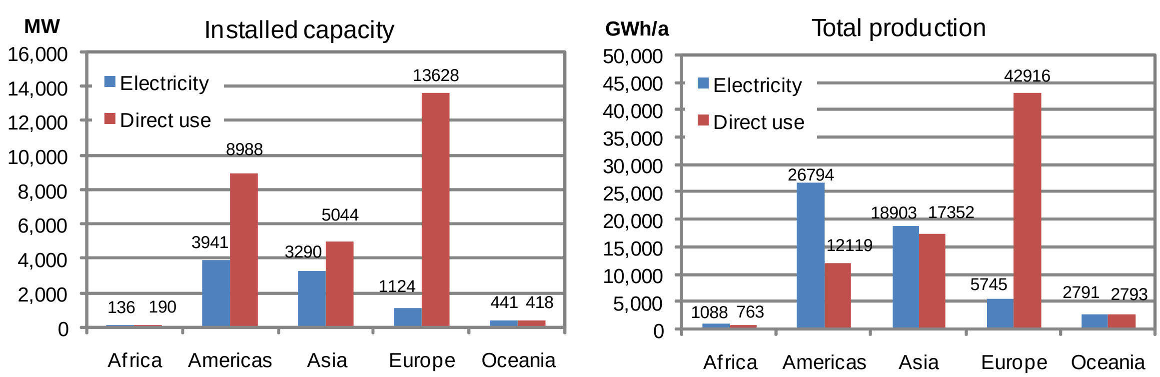

Figure 1. Installed capacity (left) and energy production (right) for geothermal electricity generation and direct use (heating) in the different continents (from Fridleifsson and Ragnarsson 2007, based on data from Bertani, 2005 and Lund et al., 2005). The Americas include North, Central and South America.

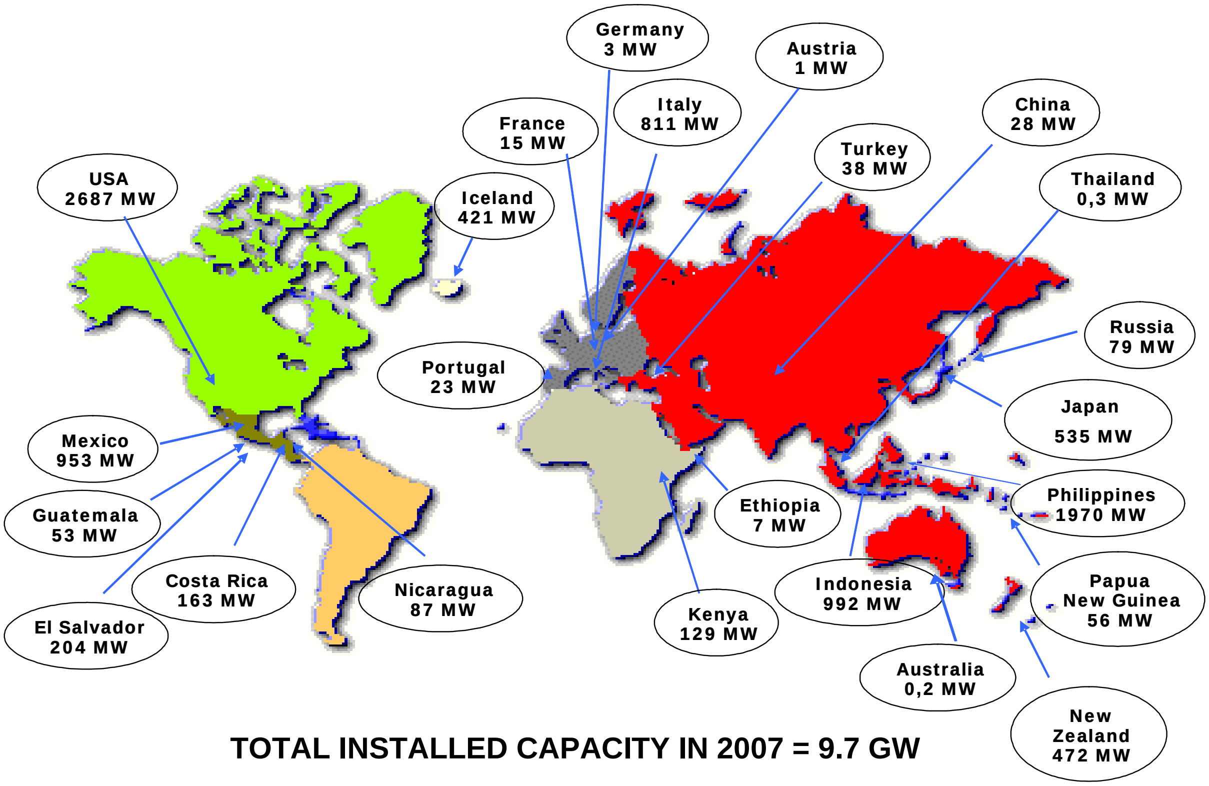

Figure 2. Installed capacity for electricity production in 2007 in different countries (Bertani, 2007).

The world geothermal electricity production increased by 16% from 1999 to 2004 (annual growth rate of 3%). Direct use increased by 43% from 1999 to 2004 (annual growth rate of 7.5%). Only a small fraction of the geothermal potential has been developed so far, and there is ample opportunity for an increased use of geothermal energy both for direct applications and electricity production.

The installed electrical capacity achieved an increase of about 800 MWe in the three year term 2005-2007, following the rough standard linear trend of approximately 200/250 MWe per year (Figure 3, from Bertani, 2007).

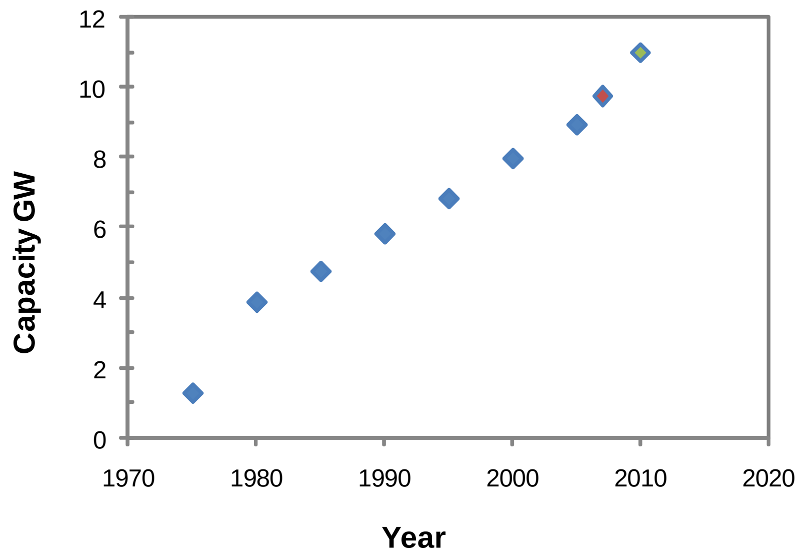

Figure 3. Installed capacity for electricity production from 1975 up to end of 2007 (red) and forecast to 2010 (green) (Bertani, 2007).

Of the total electricity production from renewables of 2968 TWh in 2001 (WEA 2004), 91% came from hydropower, 5.7% from biomass, 1.8% from geothermal sources and 1.4% from wind. Solar electricity contributed 0.06% and tidal 0.02%. A comparison of the renewable energy sources at that time (data from the UN World Energy Assessment Report update (WEA 2004)) showed the electrical energy cost to be 2-10 UScents/kWh for geothermal energy and hydro, 4-8 UScents/kWh for wind, 3-12 UScents/kWh for biomass, 25-160 UScents/kWh for solar photovoltaic and 12-34 UScents/kWh for solar thermal electricity. Heat from renewables is also commercially competitive with conventional energy sources. The UN World Energy Assessment Report update (WEA 2004) showed the cost of direct heat from biomass to be 1-6 UScents/kWh, geothermal energy 0.5-5 UScents/kWh, and solar heating 2-25 UScents/kWh (WEA 2004). It is recommended that a table similar to Table 7 of the 2004 update of the World Energy Assessment Report (WEA, 2004) be prepared for the IPCC Special Report on Renewable Energy and Climate Change Mitigation.

Table 1 shows the installed capacity and electricity production in 2005 for renewable energy sources, namely hydro, biomass, wind, geothermal, and solar energy. The data for the table is compiled from “Tables” in the 2007 Survey of Energy Resources (WEC, 2007). It should be noted that the installed capacity for biomass is not given in the “Tables”, but reported as “In excess of 40 GW” in the text. The capacity factor for biomass is thus uncertain. No figures are given for the installed capacity and electricity production of tidal energy in the 2007 Survey of Energy Resources (WEC, 2007). Tidal energy is therefore absent from Table 1.

The table clearly reflects the variable capacity factors of the power stations using the renewable sources. The capacity factor of 73% for geothermal is by far the highest. Geothermal energy is independent of weather conditions contrary to solar, wind, or hydro applications. It has an inherent storage capability and can be used both for base load and peak power plants. However, in most cases, it is more economical to run the geothermal plants as base load suppliers. The relatively high share of geothermal energy in electricity production compared to the installed capacity (1.8% of the electricity with only 1% of the installed capacity) reflects the reliability of geothermal plants which can be (and are in a few countries) operated at capacity factors in excess of 90%.

Table 1. Electricity from renewable energy resources in 2005.
Compiled from Tables in 2007 Survey of Energy Resources (WEC, 2007)

	Installed capacity		**Production per year**		**Capacity factor** (%)
	GWe	**%**	**TWh/yr**	**%**	
Hydro	778	87.5	2,837	89	42
Biomass	40*	4.5	183	5.7	52*
Wind	59	6.6	106	3.3	21
Geothermal	8.9	1.0	57	1.8	73
Solar	4	0.4	5	0.2	14
Total	890	100	3,188	100	41**

*The installed capacity for Biomass is not given in the WEC 2007 Survey of Energy Resources, but said "In excess of 40 GW" in the text. The capacity factor is thus uncertain.
**Weighted average.

It should be stressed that Table 1 is not published here in order to diminish the importance of wind or solar energy. On the contrary, the table shows that geothermal energy is available day and night every day of the year and can thus serve as a supplement to energy sources which are only available intermittently. It is most economical for geothermal power stations to serve as a base load throughout the year, but they can also, at a cost, be operated to meet seasonal variations and as peak power. This applies both to electricity production (Table 1) and direct utilisation for heating/cooling.

Geothermal energy has until recently had a considerable economic potential only in areas where thermal water or steam is found concentrated at depths less than 3 km in restricted volumes, analogous to oil in commercial oil reservoirs. This has changed in the last two decades with the development of power plants that can economically utilise lower temperature resources (around 100°C) and the emergence of ground source heat pumps using the earth as a heat source for heating or as a heat sink for cooling, depending on the season. This has made it possible for all countries to use the heat of the earth for heating and/or cooling, as appropriate. It should be stressed that heat pumps can be used basically everywhere.

Geothermal Resources

Geothermal energy, in the broadest sense, is the natural heat of the Earth. Immense amounts of thermal energy are generated and stored in the Earth's core, mantle and crust. At the base of the continental crust, temperatures are believed to range from 200 to 1,000°C, and at the centre of the earth the temperatures may be in the range of 3,500 to 4,500°C. The heat is transferred from the interior towards the surface mostly by conduction, and this conductive heat flow makes temperature rise with increasing depth in the crust on average 25-30°C/km. Geothermal production wells are commonly more than 2 km deep, but rarely much more than 3 km at present. With an average thermal gradient of 25-30°C/km, a 1 km well in dry rock formations would have a bottom temperature near 40°C in many parts of the world (assuming a mean annual air temperature of 15°C) and a 3 km well 90-100°C.

The total heat content of the Earth is of the order of 12.6 x 10^{24} MJ, and that of the crust the order of 5.4 x 10^{21} MJ (Dickson and Fanelli, 2004). This huge number should be compared to the world electricity generation in 2005, 6.6 x 10^{13} MJ. The thermal energy of the Earth is therefore immense, but only a fraction can be utilised. So far our utilisation of this energy has been limited to areas in which geological conditions permit a carrier (water in the liquid or vapour phases) to "transfer" the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources.

It is difficult to estimate the overall worldwide potential, due to the presence of too many uncertainties. Nevertheless, it is possible to identify a range of estimations, taking also into consideration the possibility of new technologies, such as permeability enhancements, drilling improvements, special Enhanced Geothermal Systems (EGS) technology, low temperature electricity production, and the use of supercritical fluids.

Bertani (2003) presents a compilation of data on geothermal potential published by different authors. The data is strongly scattered, but according to a method that seems to be realistic the expected geothermal electricity potential is estimated to be between a minimum of 35-70 GW and a maximum of 140 GW (Figure 4). The potential may be estimated orders of magnitude higher based on enhanced geothermal systems (EGS)-technology. The MIT-study (Tester et al., 2006) indicates a potential of more than 100 GW for USA alone or 35 GW for Germany alone (Paschen et al., 2003). Stefansson (2005) concluded that the most likely value for the technical potential of geothermal resources suitable for electricity generation is 240 GWe. Theoretical considerations, based on the conditions in Iceland and the USA, reveal that the magnitude of hidden resources is expected to be 5-10 times larger than the estimate of identified resources. If this is the case for other parts of the world, the upper limit for electricity generation from geothermal resources is in the range of 1-2 TWe. Furthermore, the frequency distribution of the temperature of geothermal resources in Iceland and the USA indicates that the magnitude of low-temperature geothermal resources in the world is about 140 EJ/yr of heat. For comparison, the world energy consumption is now about 420 EJ/yr.

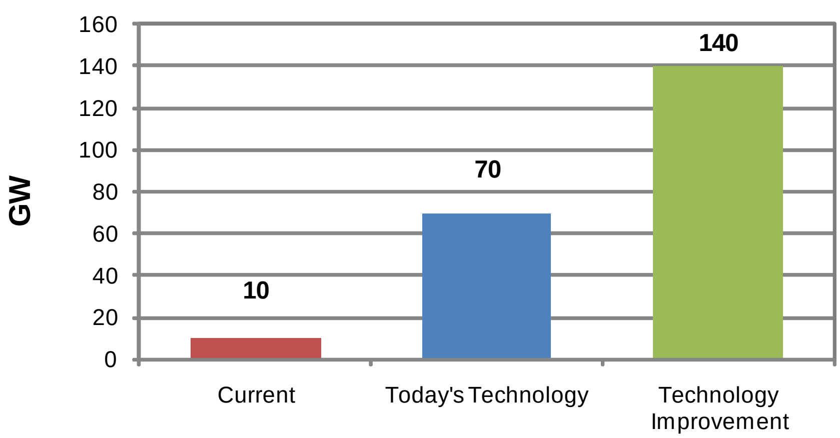

Figure 4. Estimated World geothermal electricity potential with present technology (blue) and with technology improvement (green). The current installed capacity is also shown (red).

It is considered possible to produce up to 8.3% of the total world electricity with geothermal resources, serving 17% of the world population. Thirty nine countries (located mostly in Africa, Central/South America, and the Pacific) can potentially obtain 100% of their electricity from geothermal resources (Dauncey, 2001).

Exploitable geothermal systems occur in a number of geological environments. They can be divided broadly into two groups depending on whether they are related to young volcanoes and magmatic activity or not. High-temperature fields used for conventional power production (with temperatures above 180°C) are mostly confined to the former group, but geothermal fields utilised for direct application of the thermal energy can be found in both groups. The temperature of the geothermal reservoirs varies from place to place depending on the geological conditions.

High-temperature fields (> 180 °C)

Volcanic activity takes place mainly along so called plate boundaries (Figure 5). According to the plate tectonics theory, the Earth's crust is divided into a few large and rigid plates which float on the mantle and move relative to each other at average rates counted in centimetres per year (the actual movements are highly erratic). The plate boundaries are characterised by intense faulting and seismic activity and in many cases volcanic activity. Geothermal fields are very common on plate boundaries, as the crust is highly fractured and thus permeable to water, and sources of heat are readily available. In such areas magmatic intrusions, sometimes with partly molten rock at temperatures above 1000°C, situated at a few km depth under the surface, heat up the groundwater. The hot water has lower density than the surrounding cold groundwater and therefore flows up towards the surface along fractures and other permeable structures.

Figure 5. World map showing the lithospheric plate boundaries (red dots = active volcanoes).

Most of the plate boundaries are below sea level, but in cases where the volcanic activity has been intensive enough to build islands or where active plate boundaries transect continents, high temperature geothermal fields are commonly scattered along the boundaries. A spectacular example of this is the "ring of fire" that circumscribes the Pacific Ocean (the Pacific Plate) with intense volcanism and geothermal activity in New Zealand, Indonesia, the Philippines, Japan, Kamchatka, Aleutian Islands, Alaska, California, Mexico, Central America, and the Andes mountain range. Other examples are Iceland, which is the largest island on the Mid-Atlantic Ridge plate boundary, the East African Rift Valley with impressive volcanoes and geothermal resources in e.g. Djibouti, Ethiopia, and Kenya, and “hot spots” such as Hawaii and Yellowstone.

Low-temperature fields (< 180 °C)

Geothermal resources unrelated to volcanoes can be divided into four types: a) Resources related to deep circulation of meteoric water along faults and fractures; b) Resources in deep high permeability rocks at hydrostatic pressure; c) Resources in high porosity rocks at pressures greatly in excess of hydrostatic (i.e. "geopressured"); and d) Resources in hot but dry (low porosity) rock formations. These four types are in fact end members, with most natural systems displaying some intermediate characteristics. All these, with the exception of type c), can also be associated with volcanic activity. Types c) and d) are not commercially exploited as yet. A comprehensive description of the nature of geothermal systems is given (with diagrams) on the homepage of the International Geothermal Association (http://iga.igg.cnr.it).

Type a) is probably the most common type for warm springs in the world. These can occur in most rock types of all ages, but are most obvious in mountainous regions where warm springs appear along faults in valleys. Warm springs of this type are of course more numerous in areas with a high regional conductive heat flow (with or without volcanic activity), but are also found in areas of normal and low heat flow. The important factor here is a path for the meteoric water to circulate deep into the ground and up again. Areas of young tectonic activity, such as Turkey and the Balkan Peninsula, Iceland, Japan, The Western USA, SE-China etc. are commonly rich in this type of geothermal springs.

Type b) is probably the most important type of geothermal resources that is not associated with young volcanic activity. Many regions throughout the world are characterized by deep basins filled with sedimentary rocks of high porosity and permeability. If these are properly isolated from surface ground water by impermeable strata, the water in the sediments is heated by the regional heat flow. The age of the sediments makes no difference, so long as they are permeable. The geothermal reservoirs in the sedimentary basins can be very extensive, as the basins themselves are commonly hundreds of km in diameter. The temperature of the thermal water depends on the depth of the individual aquifers and the geothermal gradient in the area concerned, but is commonly in the range 50 to 100°C (in wells less than 3 km deep) in areas that have been exploited (such as the Paris basin in France, the Pannonian basin in Hungary, the Williston Basin in Montana, North Dakota, USA and several areas in China). Geothermal resources of this type are rarely seen on the surface, but are commonly detected during deep exploration drilling for oil and gas. The widespread low-temperature geothermal resources of China are divided between types a) and b).

Geothermal Utilisation

Geothermal utilisation is commonly divided into two categories, i.e. electricity production and direct application. Conventional electric power production is commonly limited to fluid temperatures above 180°C, but considerably lower temperatures can be used with the application of binary fluids (outlet temperatures commonly about 70°C). The ideal inlet temperatures into buildings for space heating is about 80°C, but by application of larger radiators in houses/or the application of heat pumps or auxiliary boilers, thermal water with temperatures only a few degrees above the ambient temperature can be used beneficially.

As mentioned in the Introduction, geothermal resources have been identified in some 90 countries and there are quantified records of geothermal utilisation in 72 countries. Electricity is produced from geothermal energy in 24 countries. The top fifteen countries producing geothermal electricity and using geothermal energy directly in the world in 2005 (in GWh/yr) are listed in Table 2. It is of great interest to note that among the top fifteen countries producing geothermal electricity, there are ten developing countries. Among the top fifteen countries employing direct use of geothermal energy, there are six developing and transitional countries. China is on top of the list of countries on direct use (Table 2). Some 55% of the annual energy use of geothermal energy in China is for bathing and swimming, 14% for conventional district heating, and 14% for geothermal heat pumps used for space heating (Zheng et al., 2005).

Table 2. Top fifteen countries utilising geothermal energy in 2005.
Data on electricity from Bertani (2005) and on direct use from Lund et al. (2005).

Geothermal electricity production		**Geothermal direct use**	
	GWh/yr		**GWh/yr**
USA	17,917	China	12,605
Philippines	9,253	Sweden	10,000
Mexico	6,282	USA	8,678
Indonesia	6,085	Turkey	6,900
Italy	5,340	Iceland	6,806
Japan	3,467	Japan	2,862
New Zealand	2,774	Hungary	2,206
Iceland	1,483	Italy	2,098
Costa Rica	1,145	New Zealand	1,968
Kenya	1,088	Brazil	1,840
El Salvador	967	Georgia	1,752
Nicaragua	271	Russia	1,707
Guatemala	212	France	1,443
Turkey	105	Denmark	1,222
Guadeloupe (France)	102	Switzerland	1,175

Electricity generation

Figure 6 shows the top fourteen countries with the highest % share of geothermal energy in their national electricity production. Special attention is drawn to the fact that El Salvador, Costa Rica and Nicaragua are among the six top countries, and Guatemala is in eleventh place. Central America is one of the world´s richest regions in geothermal resources. Geothermal power stations provide about 12% of the total electricity generation of Costa Rica, El Salvador, Guatemala and Nicaragua, according to data provided by the countries for the World Geothermal Congress in 2005 (Bertani, 2005). The geothermal potential for electricity generation in Central America has been estimated to be some 4,000 MWe (Lippmann 2002). Only a small portion of the geothermal resources in the region has been harnessed so far (under 500 MWe). The electricity generated in the geothermal fields is in all cases replacing electricity generated by imported oil.

This clearly demonstrates how significant geothermal energy can be in the electricity production of countries and regions rich in high-temperature fields which are associated with volcanic activity. Kenya is the first country in Africa to utilise its rich geothermal resources and can in the foreseeable future produce most of its electricity with hydropower and geothermal energy. Several other countries in the East African Rift Valley may follow suit. Indonesia is probably the world´s richest country in geothermal resources and can in the future replace a considerable part of its fossil fuelled electricity by geothermal energy.

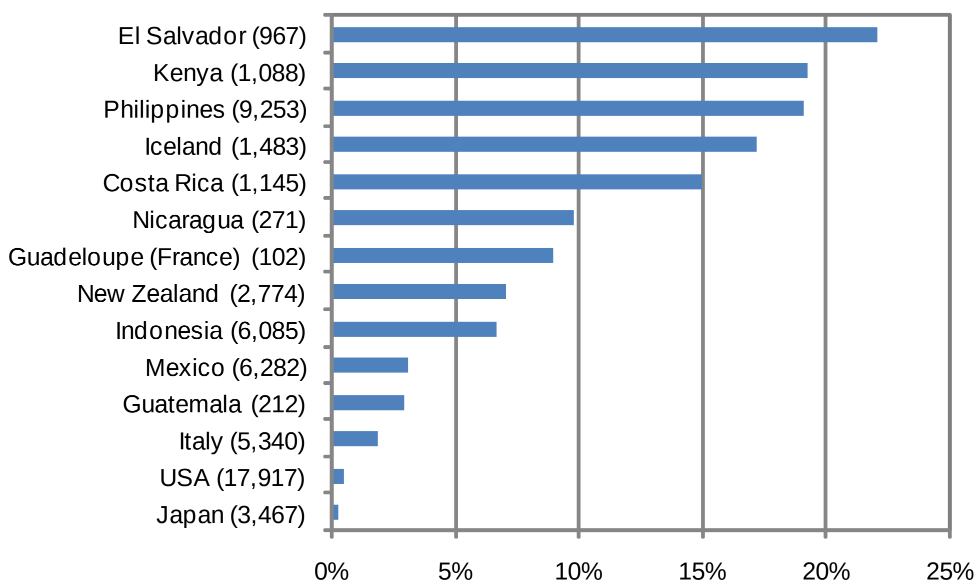

Figure 6. The fourteen countries with the highest % share of geothermal energy in their national electricity production (Fridleifsson, 2007). Numbers in parenthesis give the annual geothermal electricity production in GWh in 2004 (Bertani, 2005).

Most commonly electricity generation takes place in conventional steam turbines (see Figure 7). The steam, typically at a temperature above 150°C, is piped directly from dry steam wells or after separation from wet wells through a turbine which drives the electric generator (Dickson and Fanelli, 2003). After that it is lead to a condenser where vacuum conditions are maintained by cooling water. The unit sizes are commonly 20-110 MWe, but both larger and smaller turbines are produced.

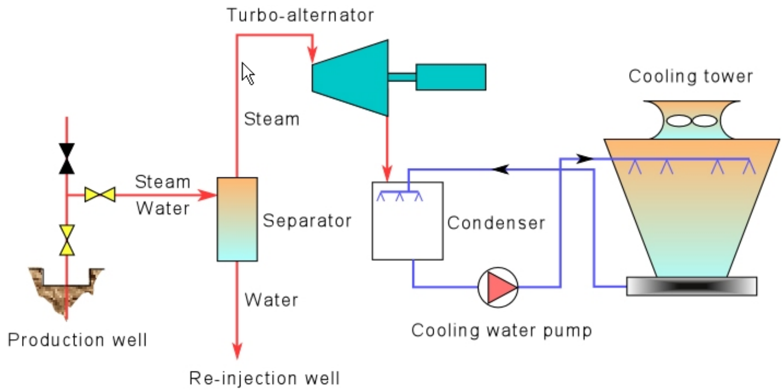

Figure 7. A schematic diagram of a geothermal condensing power plant.

Binary plants (organic Rankine cycle) have been gaining popularity in recent years. They utilise geothermal fluids at lower temperatures than conventional plants or in the range 74-170°C. They use a secondary working fluid, usually an organic fluid that has a low boiling point and high vapour pressure at low temperatures, compared with steam. The fluid passes through a turbine in a similar way as steam in conventional cycles. Binary plants are usually constructed in small modular units of up to a few MWe capacity which are linked together. Kalina is a relatively new binary fluid cycle which utilises a water-ammonia mixture as working fluid to allow more efficient power production. This makes it an interesting option for combined heat and power generation. A 2-MWe Kalina pilot plant has been in operation in Husavik, North Iceland, since 2000. An idealised diagram of the Husavik plant including cascaded uses of the geothermal resource is shown in Figure 7.

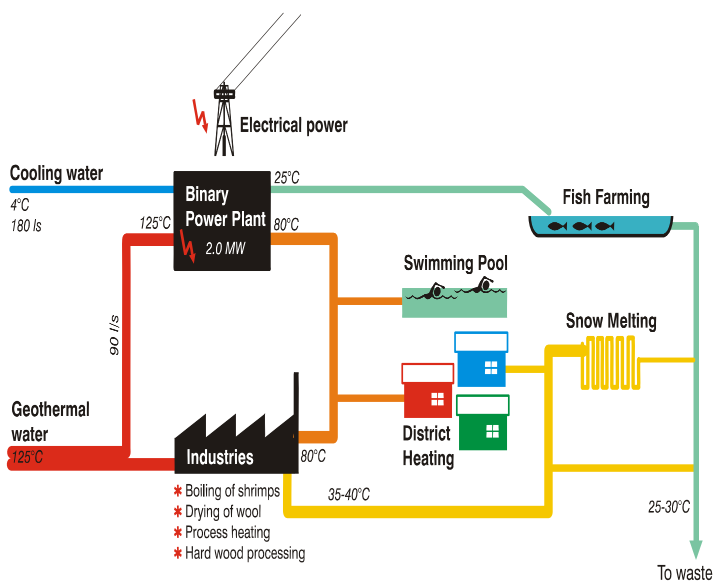

Figure 8. An idealized diagram showing cascaded uses of geothermal energy.

The efficiency of geothermal utilisation is enhanced considerably by cogeneration plants (combined heat and power plants), compared with conventional geothermal plants. A cogeneration plant produces both electricity and hot water which can be used for district heating as well as other direct uses. A necessary condition for the operation of a cogeneration power plant is that a relatively large market for hot water exists at a distance not too far from the plant. Iceland, where three geothermal cogeneration plants are in operation, is an example of this. There the distance of the plants to the towns is 12-25 km. The longest geothermal water pipeline in the world is in Iceland, 63 km.

Direct utilisation

The main types of direct applications of geothermal energy are space heating 52% (thereof 32% using heat pumps), bathing and swimming (including balneology) 30%, horticulture (greenhouses and soil heating) 8%, industry 4%, and aquaculture (mainly fish farming) 4% (Lund et al., 2005). Figure 9 shows the direct applications of geothermal energy worldwide by percentage of total energy use. The main growth in the direct use sector has during the last decade been the use of geothermal (ground-source) heat pumps. This is due, in part, to the ability of geothermal heat pumps to utilise groundwater or ground-coupled temperatures anywhere in the world.

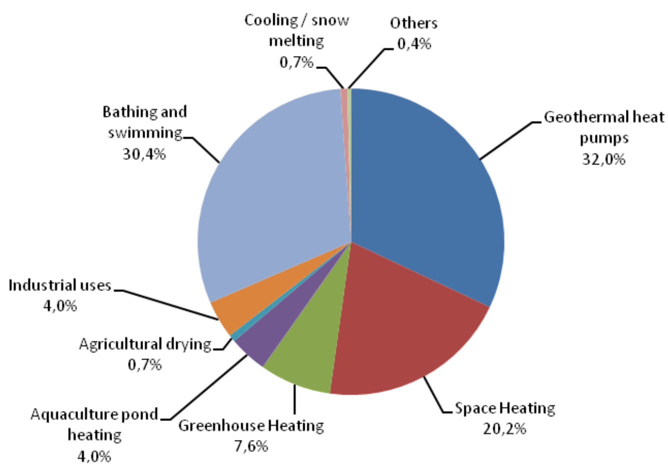

Figure 9. Direct applications of geothermal worldwide in 2004 by percentage of total energy use (data from Lund et al. 2005).

Space heating, of which more than 80% are district heating, is among the most important direct uses of geothermal energy. Preferred water delivery temperature for space heating is in the range 60-90°C and commonly the return water temperature is 25-40°C. Conventional radiators or floor heating systems are typically used, but air heating systems are also possible. If the temperature of the resource is too low for direct application, geothermal heat pumps can be used, as will be discussed below. Space cooling can also be provided by geothermal systems; geothermal heat pumps can heat and cool with the same equipment.

Open loop (single pipe) distribution systems are used for both private users and district heating systems. In that case geothermal water is used directly for heating and the spent water from radiators is discharged at the surface to waste. This type of system is only possible where the water quality is good and recharge into the geothermal system adequate. More commonly closed loop (double pipe) systems are used. Then heat exchangers are used to transfer heat from the geothermal water to a closed loop that circulates heated freshwater through the radiators. This is often needed because of the chemical composition of the geothermal water. The spent water is disposed of into wells which are called reinjection wells. Closed loop systems are more flexible than open loop systems and they allow substitution of the geothermal energy with other energy sources. Both of these two main types of district heating systems are shown schematically in Figure 10.

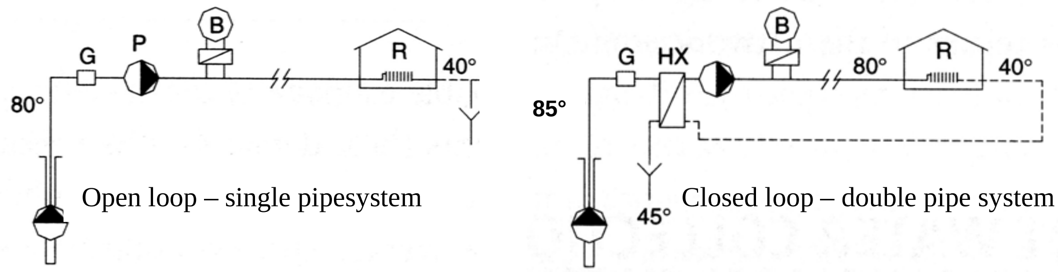

Figure 10. Two main types of district heating systems. G=gas separator, P=pump, B=boiler, R=radiation heating, HX=heat exchanger (Dickson and Fanelli, 2003).

In Iceland, the geothermal water is commonly piped 10-20 km from the geothermal fields to the towns. Transmission pipelines are mostly of steel insulated by rock wool (surface pipes) or polyurethane (subsurface). However, several small villages and farming communities have successfully used plastic pipes (polybutylene) with polyurethane insulation as transmission pipes. The temperature drop is insignificant in large diameter pipes with a high flow rate, exemplified by a 1°C drop in a 27 km steel pipeline with 800 mm diameter and a flow of 1500 l/s and (Gunnlaugsson, personal communication 2008), and 3.5 °C in a 10 km steel pipeline with 200 mm diameter and a flow of 45 l/s (Baldursson, personal communication 2008).

Heat pump applications

Geothermal heat pumps (GHPs) are one of the fastest growing applications of renewable energy in the world today (Rybach, 2005). They represent a rather new but already well-established technology, utilising the immense amounts of energy stored in the earth´s interior. This form for direct use of geothermal energy is based on the relatively constant ground or groundwater temperature in the range of 4°C to 30°C available anywhere in the world, to provide space heating, cooling and domestic hot water for homes, schools, factories, public buildings and commercial buildings.

There exist mainly two types of geothermal heat pumps (Figure 11). In ground-coupled systems a closed loop of plastic pipe is placed in the ground, either horizontally at 1-2 m depth or vertically in a borehole down to 50-250 m depth. A water-antifreeze solution is circulated through the pipe. Thus heat is collected from the ground in the winter and optionally heat is rejected to the ground in the summer. An open loop system uses groundwater or lake water directly as a heat source in a heat exchanger and then discharges it into another well, a stream or lake or even on the ground. In essence heat pumps are nothing more than refrigeration units that can be reversed. In the heating mode the efficiency is described by the coefficient of performance (COP) which is the heat output divided by the electrical energy input. Typically this value lies between three and four (Rybach, 2005).

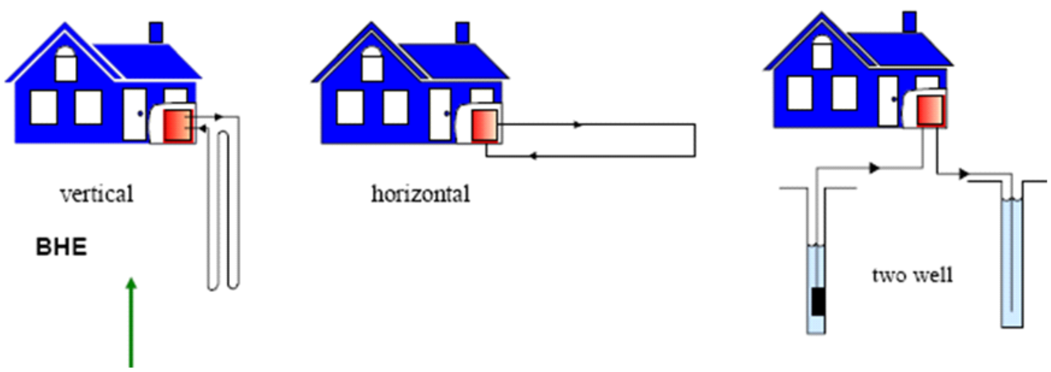

Figure 11. Closed loop and open loop heat pump systems. The green arrow indicates the most common system, with borehole heat exchangers (BHE). The heat pump is shown in red. (Modified from Geo-Heat Center, 2008).

Due to the rapidly growing GHP development, statistical data can provide only snapshots of the current situation. Table 3 shows the number of GHPs and the installed capacity in EU countries in 2005 and 2006. Table 4 shows the estimated number of installed GHP units per year in EU countries and Switzerland in 2007. In the USA, over 800,000 units have been installed at a rate of 50,000 GHP units annually with a capacity of over 9,600 MWth (Lund - personal communication, 2007). The growth is illustrated in Figure 12, where the increase of new GHP installations in some European countries is shown for year 2006. (Note that the references for Figure 12 and Table 4 are different, and the numbers not exactly the same).

Table 3. Estimated number of GHP units and total installed capacity in EU countries (Geothermal Energy Barometer, 2007)

Countries	**2005**		**2006**	
	Number	**Capacity (in MW_{th})**	**Number**	**Capacity (in MW_{th})**
Sweden	230094	2070.8	270111	2431.0
Germany	61912	681.0	90517	995.7
France	63830	702.1	83856	922.4
Denmark	43252	821.2	43252	821.2
Finland	29106	624.3	33612	721.9
Austria	32916	570.2	40151	664.5
Netherlands	1600	253.5	1600	253.5
Italy	6000	120.0	7500	150.0
Poland	8100	104.6	8300	106.6
Czech Republic	3727	61.0	5173	83.0
Belgium	6000	64.5	7000	69.0
Estonia	3500	34.0	5000	49.0
Ireland	1500	19.6	1500	19.6
Hungary	230	6.5	350	15.0
United Kingdom	550	10.2	550	10.2
Greece	400	5.0	400	5.0
Slovenia	300	3.4	420	4.6
Lithuania	200	4.3	200	4.3
Slovakia	8	1.4	8	1.4
Latvia	10	0.2	10	0.2
Portugal	1	0.2	1	0.2
Total EU 25	**493236**	**6158.0**	**599511**	**7328.3**

Source: EurObserv'ER 2007

Table 4. Estimated number of installed GHP units per year in EU countries and Switzerland (Geothermal Energy Barometer, 2007)

Country	**2003**	**2004**	**2005**	**2006**
Sweden	31564	39359	34584	40017
Germany	7349	9593	13250	28605
France	9000	11700	13880	20026
Austria	3633	4282	5205	7235
Finland	2200	2905	3506	4506
Estonia	n.a.	1155	1310	1500
Czech Republic	n.a.	600	1027	1446
Belgium	n.a.	n.a.	1000	1000
Poland	n.a.	n.a.	100	200
Slovenia	n.a.	35	97	120
Hungary	n.a.	n.a.	80	120
Total	**53746**	**69629**	**74039**	**104775**
Switzerland	3558	4380	5128	7130

Source: EurObserv'ER 2007

It is evident that GHP development is increasing significantly, albeit with quite different intensity from country to country.

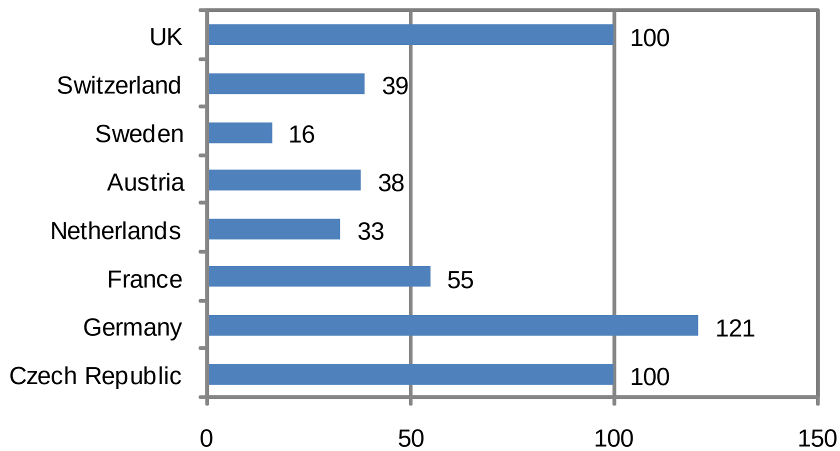

Figure 12. Increase of the number of GHP installations (in %) in European countries in 2006. (Source: European Heat Pump Association, EHPA).

Worldwide data on geothermal heat pump applications were presented at the World Geothermal Congress held in Antalya, Turkey, in 2005 (WGC-2005). According to that data GHP's account for 54.4% of the worldwide geothermal direct use capacity and 32% of the energy use. The installed capacity is 15,384 MWth and the annual energy use is 87,503 TJ/yr, with a capacity factor of 0.18 in the heating mode. Based on the size of a typical heat pump unit of 12 kW and the total installed capacity the total number of installations were estimated to be 1.3 million in 2005, which is over double the number of units reported in 2000 (Curtis et al., 2005). Figure 13 shows the rapid growth in the worldwide use of geothermal heat pumps as well as the leading countries as reported at and after WGC-2005.

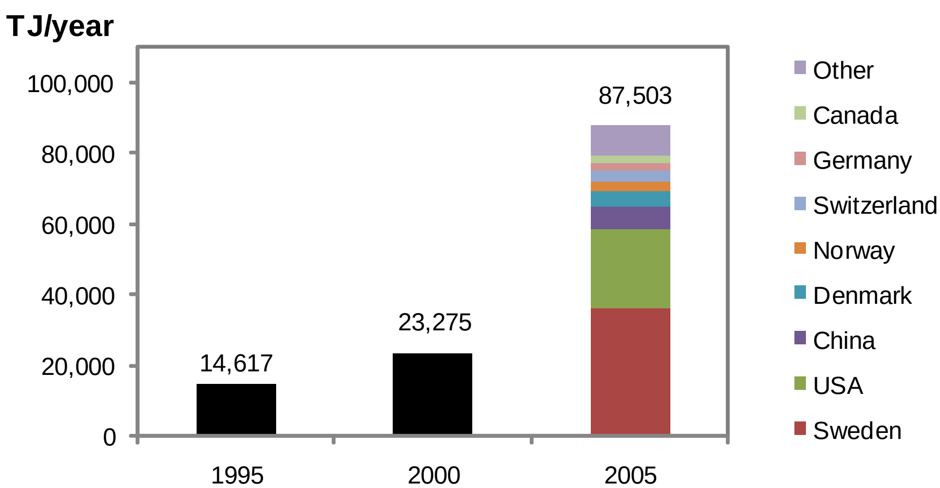

Figure 13. Worldwide growth of ground source heat pump applications and the leading GHP countries. Data from Lund et al. (2005).

Until recently, almost all of the installations of the ground source heat pumps have been in North America and Europe, increasing from 26 countries in 2000 to 33 countries in 2005 (Lund et al., 2005). China is, however, the most significant newcomer in the application of heat pumps for space heating. According to data from the Geothermal China Energy Society in February 2007, space heating with ground source heat pumps expanded from 8 million m^2 in 2004 to 20 million m^2 in 2006, and to 30 million m^2 in 2007 (Keyan Zheng, personal communication 2008). Conventional geothermal space heating in the country had grown from 13 million m^2 in 2004 to 17 million m^2 in 2006. The numbers reflect the policy of the Chinese government to replace fossil fuels where possible with clean, renewable energy. The “Law of Renewable Energy of China” came into implementation in 2006.

Enhanced Geothermal Systems (EGS)

The principle of Enhanced Geothermal Systems (EGS) is simple: in the deep subsurface where temperatures are high enough for power generation (150-200 °C) an extended fracture network is created and/or enlarged to act as new pathways. Water from the deep wells and/or cold water from the surface is transported through this deep reservoir using injection and production wells, and recovered as steam/hot water. Injection and production wells as well as further surface installations complete the circulation system. The extracted heat can be used for district heating and/or for power generation.

While conventional geothermal resources cover a wide range of uses for power production and direct uses in profitable conditions, a large scientific and industrial community has been involved for more than 20 years in promoting Enhanced Geothermal Systems, the so-called EGS concept (Ledru et al., 2007). The enhancement challenge is based on several conventional methods for exploring, developing and exploiting geothermal resources that are not economically viable yet. This general definition embraces different tracks for enlarging access to heat at depth:

- stimulating reservoirs in Low Permeability Systems and enlarging the extent of productive geothermal fields by enhancing/stimulating permeability in the vicinity of naturally permeable rocks
- improving thermodynamic cycles in order to ensure power production from water resources at medium temperature (from 80°C)
- improving exploration methods for deep geothermal resources
- improving drilling and reservoir assessment technology
- defining new targets and new tools for reaching supercritical fluid systems, especially high-temperature down-hole tools and instruments

A recent publication, “The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21th Century“, determined a large potential for the USA: recoverable resources > 200,000 EJ, corresponding to 2,000 times the annual primary energy demand (Tester et al., 2006). An EGS power generation capacity of >100,000 MWe could be established by the year 2050 with an investment volume of 0.8 - 1 billion USD. The report presents marketable electricity prices, based on economic models that need to be substantiated by EGS realisations.

The original idea calls for general applicability, since the temperature increases with depth everywhere. But still a number of basic problems need to be solved for the realisation of EGS systems, mainly that the techniques need to be developed for creating, characterising, and operating the deep fracture system (by some means of remote sensing and control) that can be tailored to site-specific subsurface conditions. Some environmental issues like the chance of triggering seismicity also need detailed investigation.

There are several places where targeted EGS demonstration is underway: Australia can claim a large-scale activity, through several stock market-registered enterprises (e.g. Geodynamics, Petratherm, Green Rock Energy, Geothermal Resources, Torrens Energy, and Eden Energy). A real boom can be observed: with 19 companies active in 140 leases (a total of 67,000 km^2 in four states), with an investment volume of 650 million USD. The project developers plan to establish the first power plants (with a few MWe capacity) in the coming years (Beardsmore, 2007). The EU project "EGS Pilot Plant" in Soultz-sous-Forêts/France (started in 1987), has ordered a power plant (1.5 MWe) to utilise the enchanced fracture permeability at 200°C (low fracture permeability was enhanced). In Landau Germany, the first EGS-plant with 2.5 to 2.9 MWe went into operation in fall 2007 (Baumgärtner, 2007). Another approach is made for deep sediments in the in situ geothermal laboratory in Groß Schönebeck using two research wells (Huenges et al., 2007). One of the main future demonstration goals in EGS will be to see whether and how the power plant size could be upscaled to several tens of MWe. The U.S. plans to include an R&D component as part of a revived EGS program.

EGS plants, once operational, can be expected to have great environmental benefits (CO_2 emissions zero). The potential impact of EGS in the future, and also the environmental benefits like avoiding additional CO_2 emission, cannot yet be satisfactorily quantified.

To achieve high levels of CO_2 emissions reduction using renewables, it will be necessary to have large sources of carbon-free, base load electricity that are dispatchable on a wide scale in both developed and developing countries. Geothermal is a proven technology for providing highly reliable base load electricity with capacity factors above 90% for many of the hydrothermal plants in operation today. Widespread deployment of geothermal would have a very positive impact on our energy security, on our environment, and on global economic health. However, there is an inherent limitation on a global scale in that the world's high grade hydrothermal systems are too localized and relatively small in number. Through EGS approach, it could be possible for geothermal energy to achieve high levels of CO_2 reduction or offset by exploiting the massive resource characterized by high temperature but low permeability and lack of natural fluid circulation.

New developments - Drilling for higher temperatures

Production wells in high-temperature fields are commonly 1.5-2.5 km deep and the production temperature 250-340°C. The energy output from individual wells is highly variable depending on the flow rate and the enthalpy (heat content) of the fluid, but is commonly in the range 5-10 MWe and rarely over 15 MWe per well. It is well known from research on eroded high-temperature fields that much higher temperatures are found in the roots of the high-temperature systems. The international Iceland Deep Drilling Project (IDDP) is a long-term program to improve the efficiency and economics of geothermal energy by harnessing deep unconventional geothermal resources (Fridleifsson et al., 2007). Its aim is to produce electricity from natural supercritical hydrous fluids from 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 central science team participants are from Iceland, USA, Japan, New Zealand, Italy, Germany and France. Other scientists and geothermal experts involved are from Russia, Spain, Norway, UK, Luxembourg, Greece, Turkey and Portugal. Some 40-50 research proposals have been put forward and 100-150 scientists and their students are currently active in the project.

The current plan is to drill and test at least three 3.5-5 km deep boreholes in Iceland within the next few years (one in each of the Krafla, Hengill, and Reykjanes high-temperature geothermal systems). Beneath these three developed drill fields temperatures should exceed 550-650°C, and the occurrence of frequent seismic activity below 5 km, indicates that the rocks are brittle and therefore likely to be permeable. Modelling indicates that if the wellhead enthalpy is to exceed that of conventionally produced geothermal steam, the reservoir temperature must be higher than 450°C. A deep well producing 0.67 m^3/sec steam (~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 of electric power. This exceeds by an order of magnitude the power typically obtained from conventional geothermal wells (Fridleifsson et al., 2007). This would mean that much more energy could be obtained from presently exploited high-temperature geothermal fields from a smaller number of wells. Further information on the IDDP can be obtained on the webpage www.iddp.is.

Environmental issues

Geothermal fluids contain a variable quantity of gas, largely nitrogen and carbon dioxide with some hydrogen sulphide and smaller proportions of ammonia, mercury, radon and boron. The amounts depend on the geological conditions of different fields. Most of the chemicals are concentrated in the disposal water which is routinely reinjected into drillholes and thus not released into the environment. The concentration of the gases is usually not harmful and they can be vented to the atmosphere. Removal of hydrogen sulphide released from geothermal power plants is a requirement in the USA and Italy.

The range in CO_2 emissions from **high-temperature geothermal fields** used for electricity production in the world is variable, but much lower than that for fossil fuels. USA is the leading producer of electricity from geothermal fields in the world with a generation of 18,000 GWh/yr in 2005. Bloomfield et al. (2003) compared the average values for all geothermal capacity in the USA, including binary power plants. In Figure 14 the CO_2 emission from geothermal power plants is compared to that from fossil fuel plants. CO_2 emission values for coal, oil and natural gas plants are calculated using data from DOE´s Energy Information Administration. The CO_2 emission of the geothermal plants in the USA was reported as: CO_2 91 g/kWh by Bloomfield et al. (2003).

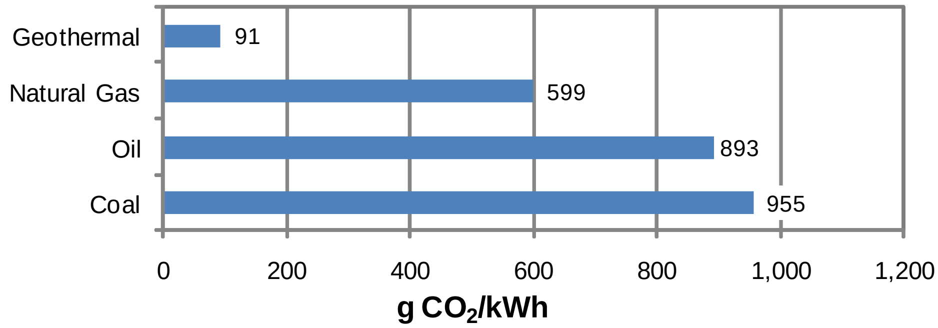

Figure 14. Comparison of CO_2 emission from electricity generation from different energy sources in the USA. Data from Bloomfield et al. (2003).

Bertani and Thain (2002) reported on CO_2 emission data obtained in 2001 from 85 geothermal power plants operating in 11 countries around the world. These plants had an operating capacity of 6,648 MWe which constituted 85% of the world geothermal power plant capacity at the time. In the survey, details were obtained of the MWe output of the respective power plants together with their steam flow rate per MWe and % weight of CO_2 contained in the geothermal steam. From this data, the MWe weighted CO_2 emission rate in g/kWh of generation was calculated. (In the case of the Larderello plants in Italy, the data was provided on a summated basis for a group of plants operating in this field). The collected data showed a wide spread in the overall CO_2 emission rates from the plants included in the survey. The actual range was from 4 g/kWh to 740 g/kWh with the weighted average being 122 g/kWh. This compares fairly well with the value of 91 g/kWh reported for the USA plants by Bloomfield et al. (2003). From the collected data, the average CO_2 content was 90.46% of the non condensable gases (Bertani and Thain, 2002). Where there is a high natural release of CO_2 from the geothermal fields prior to development, any measurable decrease in this natural emission resulting from the power development should be subtracted from the measured plant emission rate.

The gas emissions from **low-temperature geothermal resources** are normally only a fraction of the emissions from the high-temperature fields used for electricity production. The gas content of low-temperature water is in many cases minute, like in Reykjavik (Iceland), where the CO_2 content is lower than that of the cold groundwater. In sedimentary basins, such as the Paris basin, the gas content may cause scaling if it is released. In such cases the geothermal fluid is kept under pressure within a closed circuit (the geothermal doublet) and reinjected into the reservoir without any de-gassing taking place. Conventional geothermal schemes in sedimentary basins commonly produce brines which are generally reinjected into the reservoir and thus never released into the environment (zero CO_2 emission). No systematic collection has been made of CO_2 emission data from geothermal district heating systems in the world. The CO_2 emission from low-temperature geothermal water can be regarded negligible or in the range of 0-1 g CO_2 /kWh depending on the carbonate content of the water. As an example, for Reykjavik District Heating, the CO_2 emission from low-temperature areas is about 0.05 mg CO_2 /kWh (5 times 10^{-5} g CO_2/kWh). The data from geothermal district heating systems in China (Beijing, Tianjin and Xianyang) is limited, but is less than 1 g CO_2/kWh (Gunnlaugsson, personal communication 2007). The district heating system in Klamath Falls, Oregon, USA has zero emission as all the geothermal water is used and reinjected in a closed system.

Thanks to geothermal district heating, Reykjavik (Iceland) is one of the cleanest capitals in the world. There is no smoke from chimneys. Heating with polluting fossil fuels has been eliminated, and about 100 million tonnes of CO_2 emissions have been avoided by replacing coal and oil heating by geothermal (see Figure 15). Almost 90% of all houses in Iceland are currently heated by geothermal water, and the remainder is heated by electricity generated by hydropower (83%) and geothermal energy (17%). Geothermal utilisation has reduced CO_2 emissions in Iceland by some two million tonnes annually compared to the burning of fossil fuels. The total release of CO_2 in Iceland in 2004 was 2.8 million tonnes. The reduction has significantly improved Iceland's position globally in this respect. Many countries could reduce their emissions significantly through the use of geothermal energy.

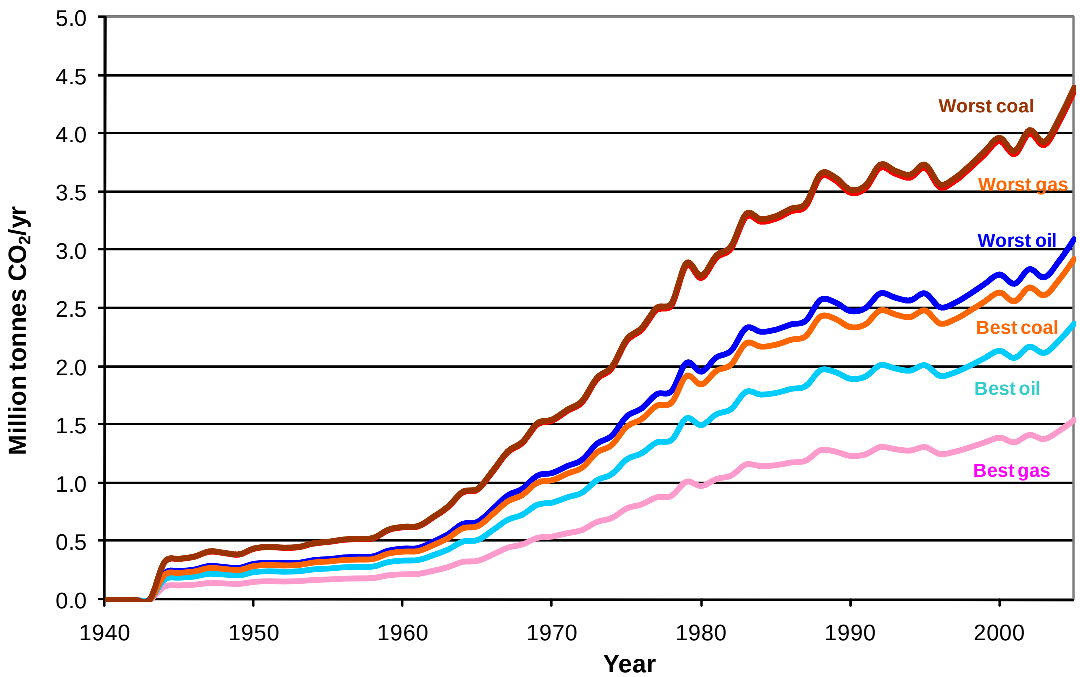

Figure 15. CO_2 savings using geothermal water in Reykjavik (Iceland) compared to other energy sources 1940-2006. Total avoidance 90 million to 110 million tonnes of CO_2 emissions depending on the type of fossil fuel(s) replaced by geothermal resources (Gunnlaugsson, personal communication 2008).

The home page of the Clinton Climate Initiative gives an interesting bird´s eye view on the best practices in 40 cities, including Reykjavik in the top ten examples of best practices in renewables http://www.c40cities.org/bestpractices/renewables/reykjavik_geothermal.jsp.

Another good example (although on a smaller scale) of replacing fossil fuels by geothermal water is in Galanta, Slovakia. A district heating system using natural gas with about 9,000 GJ/yr heat production was modified. The natural gas was replaced as a heat source by carbonate rich geothermal water. The replacement resulted in the reduction of CO_2 emission by about 5,000 tonnes annually (Galantaterm, 2007). Although this geothermal water is rich in carbonate, its CO_2 emission is negligible (about 0.3 g CO_2/kWh).

Similar geothermal water is common in many countries in Central and Eastern Europe, but is as yet only used on a very limited scale. The largest user there is Hungary in the Pannonian basin with very wide spread geothermal resources and a long tradition for geothermal utilisation (Lund et al., 2005; Arpasi, 2005). Another substantial user of geothermal resources in Europe is France, which started considerable geothermal development with geothermal district heating systems in Paris and several other localities in the vast Paris basin in the 1970s as a response to the first oil crises. During 1978-1987, over seventy geothermal district heating systems were constructed in France, providing space heating and hot water for around 200,000 housing units. There was very little new activity in France during the period of low energy prices in the 1990s. Several geothermal district heating systems were in fact converted to natural gas. Following the Kyoto Agreement (since 1998), France has resumed an active policy for energy management and the development of renewable energy sources, including geothermal (Laplaige et al., 2005).

Kaltschmitt (2000) published figures of 4-16 tons CO_2-equivalent /TJ based on life cycle analysis of low-temperature district heating systems. There is a very large potential for replacing fossil fuels by conventional geothermal resources in the space heating (and hot tap water) sector in many European countries. With the application of heat pumps, all European countries can obtain a significant proportion of their space heating (and hot tap water) sector from geothermal heat. The limiting factor may, however, be the way in which the electricity (providing 25-30% of the energy coming from the heat pumps) is produced. If the electricity is produced from low emission resources, then the road is clear.

CO_2 emission reduction by heat pumps

Geothermal heat pumps (GHP) are environmentally benign and represent a large potential for reduction of CO_2 emission. This can be demonstrated by comparing the CO_2 emission related to heating of buildings using different energy sources. The emission rates depend on the energy efficiency of the equipment as well as the fuel mix and the efficiency of electricity generation. The heat pump needs auxiliary power to accomplish the temperature rise needed in the system. In most cases, heat pumps are driven by electric power resulting in an amount of CO_2 emission that depends on the type of energy source used for electricity generation (zero emission if the electricity is generated from renewables). The average CO_2 emission associated with generation of electricity in Europe has been estimated to be 0.55 kg CO_2/kWh. With proper system design, seasonal performance coefficients in the heating mode of 4.0 (heating energy supplied by the GHP system/electricity input for heat pumps and circulation pumps) can be reached. The results show that the electrically driven heat pump reduces the CO_2 emission by 45% compared with an oil boiler and 33% compared with a gas fired boiler. Kaltschmitt (2000) published data for heat pumps driven systems of 50-56 tonnes CO_2-equivalent/TJ based on life cycle analysis. If the electricity that drives the heat pump is produced from a renewable energy source like hydropower or geothermal energy, the emission savings are even higher. The total CO_2 reduction potential of heat pumps has been estimated to be 1.2 billion tonnes per year or about 6% of the global emission (ISEO webpage: www.uniseo.org/heatpump.html).

The European Heat Pump Association (EHPA) has recently published a vision for the year 2020 (EPHA webpage: ehpa.fiz-karlsruhe.de). There it is pointed out that heating and cooling consume at least 40% of all primary energy consumed within the EU and that replacement of oil and gas boilers as well as electrical heating with heat pumps could contribute significantly to the renewable energy strategy of the EU. It is concluded that widespread installation of heat pumps would result in nearly 70 million installed heat pumps in 2020 and that they would contribute 20.5% of the EU‘s GHG reduction goal for 2012 and 21.5% to this goal for 2020. They conclude further that heat pumps would produce about 30% of the EU´s target for renewable energy in 2020.

Possible contribution of geothermal energy to the mitigation of climate change

One of the major concerns of mankind today is the ever increasing emission of greenhouse gases into the atmosphere and the threat of global warming. It is internationally accepted that a continuation of the present way of producing most of our energy by burning fossil fuels will bring on significant climate changes, global warming, rises in sea level, floods, droughts, deforestation, and extreme weather conditions. And the sad fact is that the poorest people in the world, who have done nothing to bring on the changes, will suffer most. One of the key solutions to these difficulties is to reduce the use of fossil fuels and increase the sustainable use of renewable energy sources. Geothermal energy can play an important role in this aspect in many parts of the world.

In the **geothermal direct use sector**, the potential is very large as space heating and water heating are significant parts of the energy budget in large parts of the world. In industrialised countries, 35 to 40% of the total primary energy consumption is used in buildings. In Europe, 30% of energy use is for space and water heating alone, representing 75% of total building energy use. The recent decision of the Commission of the European Union to reduce greenhouse gas emissions by 20% by 2020 compared to 1990 in the member countries implies a significant acceleration in the use of renewable energy resources. Most of the EU countries already have some geothermal installations. The same applies to the USA and Canada where the use of ground source heat pumps is widespread both for space heating and cooling. The largest potential is, however, in China. Due to the geological conditions, there are widespread low-temperature geothermal resources in most provinces of China which are already widely used for space heating, balneology, fish farming and greenhouses during the cold winter months and for tap water also in the summer.

To estimate the future development of the worldwide geothermal utilisation, three scenarios have been prepared. They include the installed capacity in heat pump applications and other direct use applications separately, as well as the annual energy production for the same. The scenario that is considered to be the most likely case is shown in Table 5 and Figures 16 and 17. They show that while only a moderate increase is expected in direct use applications, an exponential increase is foreseen in the heat pump sector. The reason is that geothermal heat pumps (GHPs) can be used for heating and/or cooling in most parts of the world. The most critical issue here is the source of electricity providing 25-30% of the energy supplied by the heat pumps. As previously mentioned, results show that an electrically driven heat pump reduces the CO_2 emission by 45% compared with an oil boiler and 33% compared with a gas fired boiler.

Table 5. Likely case scenario for direct use of geothermal from 2005 to 2050.

Year	Average annual growth rate from 2005		Direct Use other than GHP		Geothermal Heat Pumps (GHP)		Total	
	Direct Use (%)	GHP (%)	MW_{th}	TJ/yr	MW_{th}	TJ/yr	MW_{th}	TJ/yr
2005			12,855	185,869	15,384	87,503	28,239	273,372
2010	7	22	18,000	260,000	41,500	236,000	59,500	496,000
2020	6	16	30,900	446,000	143,000	811,000	173,000	1,260,000
2030	5	12.5	43,600	630,000	292,000	1,660,000	336,000	2,290,000
2040	4	10	50,800	734,000	476,000	2,710,000	527,000	3,444,000
2050	3.5	9	60,500	874,000	744,000	4,230,000	804,000	5,100,000

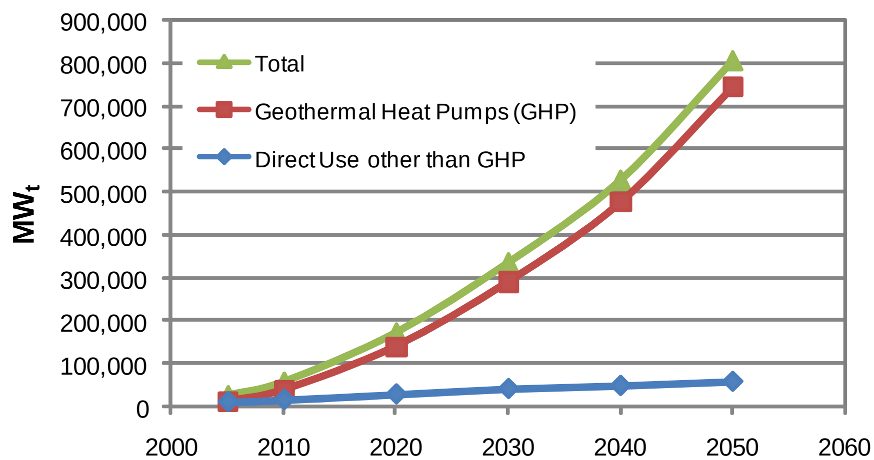

Figure 16. Likely case scenario for growth in direct use and GHP installed capacity.

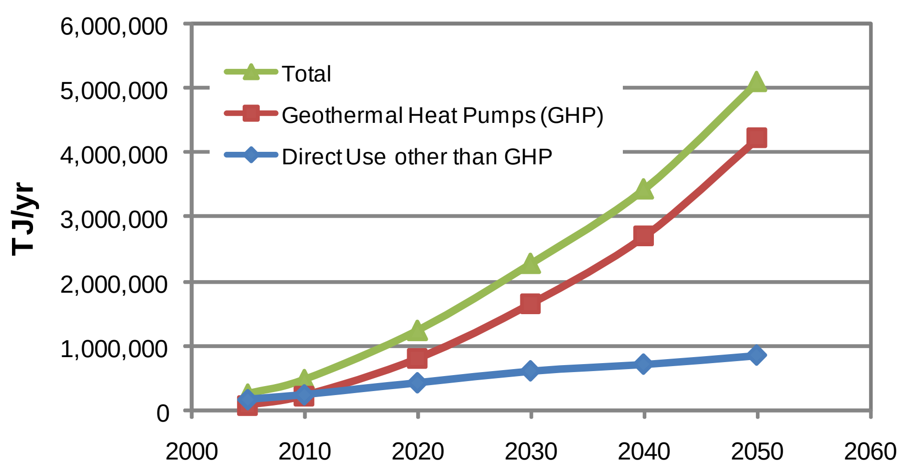

Figure 17. Likely case scenario for growth in direct use and GHP energy production.

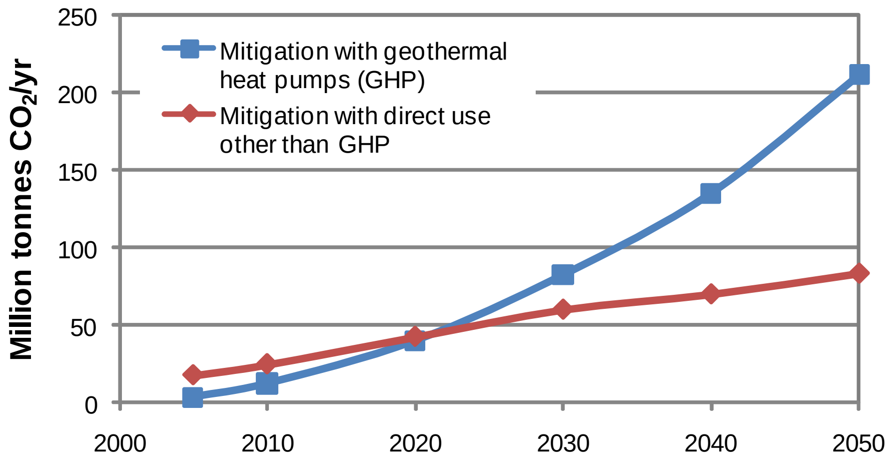

Figure 18. Mitigation potential of geothermal direct heating use in the world based on data in Table 5. The blue line shows the estimated mitigation from Geothermal Heat Pumps (GHP) assuming an emission of 50 tonnes CO_2-equivalent/TJ for GHP. The red line shows the estimated mitigation from direct heating use (other than GHP) assuming an emission of 4 tonnes CO_2-equivalent/TJ for direct use (without GHP). Both estimates are based on an emission of 100 tonnes CO_2-equivalent/TJ for fossil heat provision based on the life cycle analysis of Kaltschmitt (2000).

The mitigation potential of CO_2 for the heat provision is large for GHPs as long as GHPs substitute fossil energy. Nevertheless, in the case of fossil provided electricity to drive the heat pump a production of 200 Million tons CO_2/yr has to be taken into account to fulfil the 2050 goal of 4 Million TJ/yr GHP heat provision (see Figure 18). A scenario of a heat provision of nearly 1 Million TJ/yr by direct use of geothermal systems brings a mitigation potential of 100 Million tons CO_2/yr with very low self emissions of CO_2.

In the electricity sector, the geographical distribution of suitable high-temperature hydrothermal fields is more restricted and mainly confined to countries or regions on active plate boundaries or with active volcanoes. As mentioned earlier, geothermal power stations provide about 12% of the total electricity generation of the four countries Costa Rica, El Salvador, Guatemala and Nicaragua. Hydropower stations provide 48% of the electricity for the four countries, and wind energy 1%. With an interconnected grid, it would be easy to provide all the electricity for the four countries by renewable energy. The geothermal potential for electricity generation in Central America has been estimated at some 4,000 MWe (Lippmann 2002), and less than 500 MWe have been harnessed so far. With the large untapped geothermal resources and the significant experience in geothermal energy as well as hydropower development in the region, Central America may become an international example of how to reduce the overall emissions of greenhouse gases in a large region. Similar development can be foreseen in the East African Rift Valley, as well as in several other countries and regions rich in high-temperature geothermal resources.

As mentioned before, it is difficult to estimate the overall world-wide potential. With the present engineering solutions it is possible to increase from the extrapolated value of 11 GW for year 2010 up to a maximum of 70 GW. The gradual introduction of the aforesaid new developments may boost the growth rate with exponential increments after 10-20 years, thus reaching the global world target of 140 GW for year 2050 (Figure 4).

It should be pointed out that some of these "new technologies" are already proven and are currently spreading fast into the market, like the binary plant ("low temperature electricity production"), whereas the EGS are just entering the field demonstration phase to prove their viability.

The electricity production from geothermal sources is strongly related to the plant capacity factor. Since 1995, it has been continuously increasing from the initial value of 64% to the present one of 73%. Better technical solutions for the power plants improve their performances; the most advanced approaches for the resource development (reinjection, inhibitors against scaling/corrosion, better knowledge of the field performances and parameters using advanced geophysical surveys) will increase the capacity factor linearly to the limit of 90%, presently already reached by many geothermal fields in operation. The forecast for capacity, capacity factor and energy is presented in Table 6 and Figures 19 and 20.

Table 6. World installed capacity, electricity production and capacity factor of geothermal power plants 1995-2005 and forecasts for 2010-2050.

Year	**Installed Capacity (GW)**	**Electricity Production (GWh/yr)**	**Capacity Factor (%)**
1995	6.8	38,035	64
2000	8.0	49,261	71
2005	8.9	56,786	73
2010	11	74,669	77
2020	24	171,114	81
2030	46	343,685	85
2040	90	703,174	89
2050	140	1,103,760	90

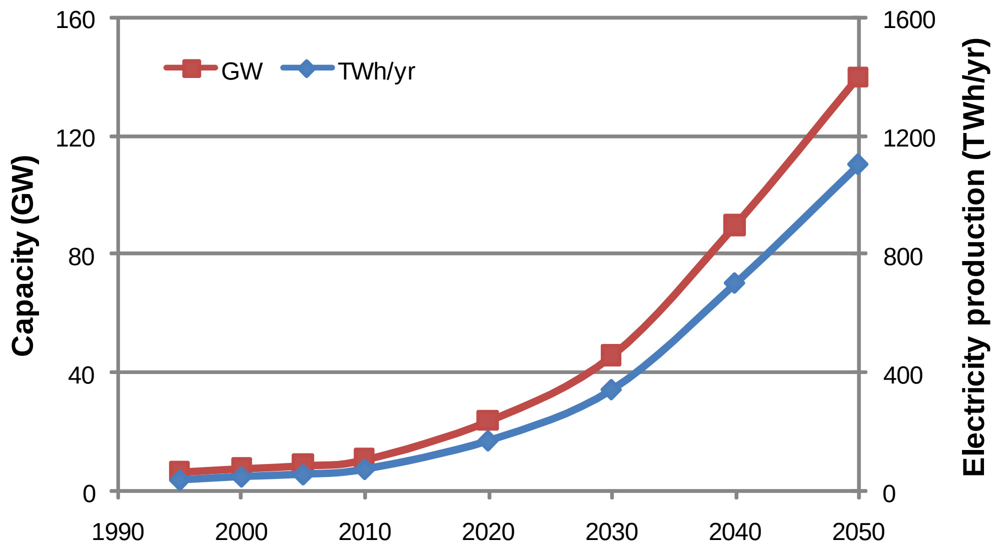

Figure 19. Installed Capacity and Electricity production 1995-2005 and forecasts for 2010-2050.

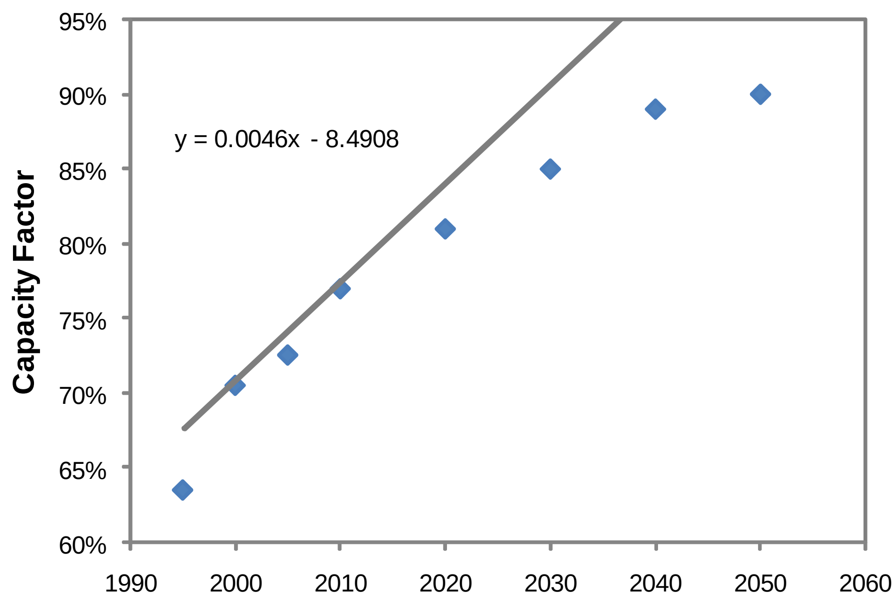

Figure 20. Capacity Factor of geothermal power plants in the world 1995-2005 and forecasts for 2010-2050

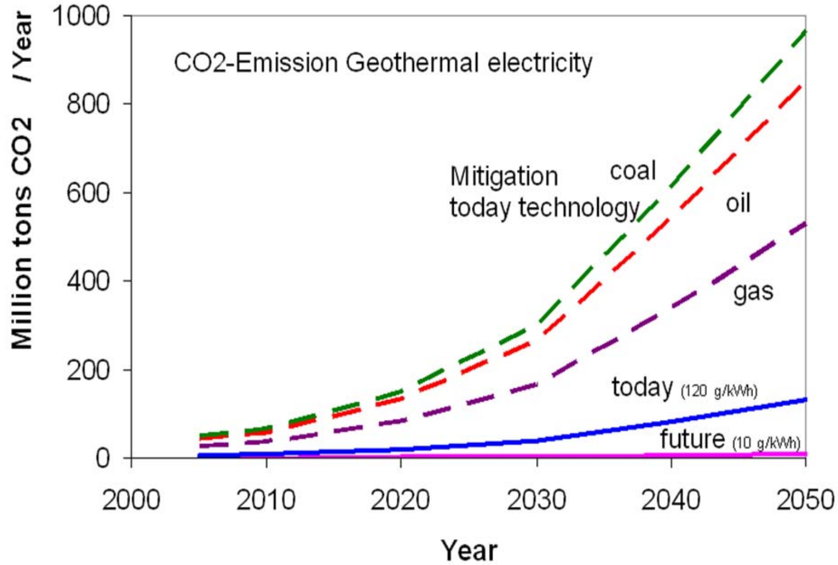

Figure 21. Mitigation potential of geothermal power plants in the world based on data of Table 6 and assumptions for emission of 120 g CO_2/ kWh for today and 10 g CO_2/ kWh for future technology.

Geothermal electricity production of about 100 TWh/yr in 2050 will mitigate (depending on what is substituted) hundreds of million tons CO_2/yr as given in Figure 21. Present technology with dominant open systems and release of emissions will produce some tens of million tons CO_2/yr, whereas future technology including reinjection will result in negligible emissions.

Geothermal sustainability

Geothermal energy is generally classified as a renewable resource, where "renewable" describes a characteristic of the resource: the energy removed from the resource is continuously replaced by more energy on time scales similar to those required for energy removal (Stefansson, 2000). Consequently, geothermal production is not a "mining" process. Geothermal energy can be used in a "sustainable" manner, which means that the production system applied is able to sustain the production level over long times. The longevity of production can be secured and sustainable production achieved by using moderate production rates, which take into account the local resource characteristics (field size, natural recharge rate, etc.).

It appears natural to define the term "sustainable production" as production which can be maintained for a very long time. In Iceland, a reference period of 100 – 300 years has been proposed (Axelsson et al., 2005), while in New Zealand production for a period longer than 100 years is considered sustainable (Bromley et al., 2006). Much longer time scales, such as time scales comparable to the lifetimes of geothermal resources, are considered unrealistic in view of the time scale of human endeavours.

The production of geothermal fluid/heat continuously creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn – after termination of production – generate fluid/heat inflow to re-establish the pre-production state. The regeneration of geothermal resources is a process, which occurs over various time scales, depending on the type and size of the production system, the rate of extraction, and on the attributes of the resource. This nature of recovery, or re-establishment, characterising geothermal resources contributes to their potential for sustainable use.

Time scales for re-establishing the pre-production state following the cessation of production have been determined using numerical model simulations for: 1) heat extraction by geothermal heat pumps, 2) the use of doublet systems on a hydrothermal aquifer for space heating, 3) the generation of electricity on a high enthalpy, two-phase reservoir, and 4) an enhanced geothermal system (for details see Rybach and Mongillo, 2006; Axelsson et al., 2005). The results show that after production stops, recovery driven by natural forces like pressure and temperature gradients begins. The recovery typically shows an asymptotic behaviour, being fast at the start and then slowing down subsequently, and theoretically taking an infinite amount of time to reach its original state. However, practical replenishment (e.g. 95%) will occur much earlier, generally on time scales of the same order as the lifetime of the geothermal production systems (Axelsson et al., 2005).

A good example of what appears to be (after 64 years of continuous production) a sustainable use of a low-temperature geothermal field is the Reykir field (Mosfellssveit), which has been used for district heating of Reykjavik, the capital of Iceland, since 1943 (Gunnlaugsson, 2003). Prior to drilling, the artesian flow of thermal springs was estimated about 120 l/s of 70-83 °C water. After drilling, about 200 l/s of 86 °C water was piped to Reykjavik for heating buildings (15 km). After 1970, the field was redeveloped with deep rotary drilling of large diameter wells and the installation of down-hole pumps. The yield from these wells then increased to 2000 l/s of 85-100 °C water. Figure 22 shows the production (in Gigaliters) and the water level in well MG-28 from 1983 to 2007. The water level was steadily decreasing until 1990, when it became possible to reduce pumping from the field as an additional geothermal field for Reykjavik started operation. Immediately after the reduction of production, the pressure built up and the water level rose again. Changes in the chemistry and temperature of the geothermal fluid have only been observed at the southeastern boundary of the field (Gunnlaugsson et al., 2000). This is the main production field for Reykjavik (see also Figure 15), which is the largest single geothermal district heating system in the world.

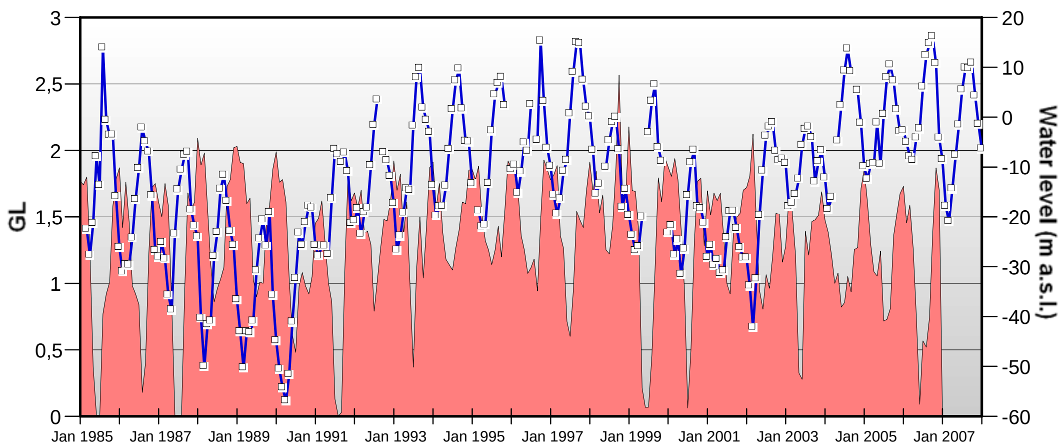

Figure 22. Production in Gigaliters (in red) from the Reykir low-temperature field and the water level (black line with data points) in well MG-28 (observation well) from 1985 to 2007 (Ivarsson, 2007).

There are similar examples of the sustainable use of hydrothermal systems in different geological environments in many countries (including large fields in sedimentary formations in China, where sustainability is only maintained by re-injection of the same amount of water as is being produced). Numerical model simulations have been carried out for the application of down-hole heat exchangers and heat pump applications.

Discussion of geothermal energy and other renewables

Renewable energy, which includes production from geothermal, wind, solar, biomass, hydroelectric and tide/wave/ocean sources, is gaining interest from politicians and developers due to global warming predictions and the high cost of oil. Putting geothermal energy in perspective with the other renewables, helps in the appraisal of its place in the market along with strengths and weaknesses of each renewable resource.

The overall consumption of different energy sources in the world is described by the Total Primary Energy Supply (TPES). It refers to the direct use at the source, or supply to users without transformation, that is energy that has not been subjected to any conversion or transformation process. The world TPES in 2005 was 11,435 Mtoe (million tonnes of oil equivalents, 1 Mtoe = 41,868 GJ), of which 12.7% came from renewable energy sources. The share of the different energy sources in the world renewable primary energy supply was as follows in 2004: Biomass 79.4%, hydropower 16.7%, geothermal energy 3.2%, wind energy 0.5% and solar/tide/ocean energy 0.3%. Since 1990, renewable energy sources have grown at an average annual rate of 1.9%, as compared to the world TPES of 1.8% per annum. Wind energy has had the highest growth rate of 24.4%; albeit, from a small base in 1990. The second highest growth rate was from non-solid biomass combustible renewables and waste, such as renewable municipal waste, biogas and liquid biomass, averaging 8.1% annually since 1990.

Looking at world electricity generation on its own the picture is quite different. This can be seen in Table 7, which shows the fuel shares in the world electricity generation 2004. That year the renewable energy share was 18.6% (mainly hydropower). This is a slightly lower share of the total electricity generation than in 1990. Since 1990 renewable electricity generation has grown on average 2.1% per annum worldwide which is lower than the total electricity generation growth rate of 2.8%. The growth of developing countries is expected to produce a doubling of the global electricity demand over the next 25 years, from 18,235 TWh in 2005.

The most important renewable energy source with respect to electricity generation is hydropower, which represents almost 89% of the total generation. This share is similar for all the continents except Europe, where wind energy plays a considerable role. Hydropower also has a significant share in the total electricity generation worldwide or 16.5%, with a growing rate of 2-5%. The largest markets are in the USA, Canada, Brazil, Norway and China.

Wind energy provides about 0.5% of world global electricity generation, with the most important countries being in Europe (Germany, Spain, and Denmark) and USA. A very aggressive growth rate of 15-20% is expected, mainly in the UK, China, India and Australia.

Geothermal Energy provides approximately 0.3% of the world global electricity generation, with a stable long-term growth rate of 5%. At present the largest markets are in the USA, Philippines, Mexico, Indonesia, Italy and Iceland. Future developments are limited to certain areas worldwide, particularly under current technologies.

Solar energy plays a very limited role in global electricity generation, but it has a very high growth rate of 25-30%, especially in the USA, Spain, China, Australia and India.

Table 7. Fuel shares in world electricity generation 2004 (International Energy Agency).

	GWh	**%**
Coal	6,944,328	39.61
Gas	3,418,676	19.50
Nuclear	2,738,012	15.62
Oil	1,170,152	6.67
Other sources	2,292	0.01
Non-renewables total	**14,273,460**	**81.42**
Hydro power	2,889,094	16.48
Biomass	149,811	0.85
Waste	77,471	0.44
Wind energy	82,259	0.47
Geothermal energy	55,896	0.32
Solar thermal energy	1,608	0.01
Solar PV energy	840	0.00
Tide, Wave, Oceanenergy	551	0.00
Renewables total	**3,257,530**	**18.58**
Total world generation	**17,530,990**	**100.00**

The present installed geothermal capacity of 10 GW is expected to increase up to 11 GW in 2010. Its investment costs are close to average, depending on the quality of the resource (temperature, fluid chemistry and thermodynamics phase, well productivity etc.), ranging from approximately 2 to 4.5 million euro/MWe, and its generation costs are very attractive, from 40 to 100 euro/MWh. It is a resource suitable for base load power. Geothermal electricity generation can be considered as broadly cost-competitive, despite its relatively high capital costs up front for development of the geothermal field (resource evaluation, mining risk, drilling and piping). Its availability is very high and the energy production stable. The next generation is expected to see the implementation of Enhanced Geothermal System (EGS) and an intensive increase in low-to-medium temperature applications through binary cycles and cascade utilisations. The potential of geothermal energy has barely been exploited, but its base-load capability is a very important factor for its success. The utilisation of binary plants and the possibility of production from enhanced geothermal systems (to be considered as possible future developments) can expand its availability on a worldwide basis

Among the other renewable energy resources, with hydro potential considered as already known utilised and without an important growth margin, only wind energy can be considered as a realistic competitor to geothermal energy. But they should not be considered as opponents, both resources can be developed where more convenient and where their presence has been assessed. Wind energy is more widely distributed, but it is not generally even throughout the day and its production is not easily predictable, especially considering the very fast climate changes worldwide.

Estimates for the future indicate a major growth in wind and solar electricity generation, and a slower growth in geothermal energy, hydroelectricity and biomass. Tide/ocean/wave energy is in its infancy with unknown growth. By 2010 the expected electrical generation capacity for wind energy is 74 GW, solar energy 20 GW and geothermal energy 11 GW. Hydroelectricity generation will primarily grow in non-OECD countries such as China, India, and in Latin America. Biomass growth will be strong, especially in OECD countries.

Each of the respective renewables has certain limitations; some are better suited for electric energy production and others for direct heating. Solar panels and wind mills can be easily installed and in a short period of time, whereas hydro power and geothermal energy tend to be more time consuming, especially large projects. Solar energy obviously depends on daytime sun light and night-time storage, wind can be intermittent and also depends on storage, hydropower is subject to drought and limited site, biomass depends on a supply of fuel and can contribute to greenhouses gases and particulate emission, tide and ocean energy is limited to areas where sufficient oscillations are available and where it does not interfere with navigation, and even though geothermal energy is base load for power and can supply the full load for heating, it is site specific. The development of the various renewable energy sources is not only dependent upon the technical aspects mentioned above, but are also influenced by the support (or lack of) from government policies and financial incentives. Thus, all renewables have limitations, but must be supported as they can complement each other. It is very important for the proponents of the various types of renewable energy to work together in order to find the optimal use of energy resources in the different regions of the world.

Conclusions

Geothermal energy is a renewable energy source that has been utilised economically in many parts of the world for decades. A great potential for an extensive increase in worldwide geothermal utilisation has been proven. This is a reliable energy source which serves both direct use applications and electricity generation. Geothermal energy is independent of weather conditions and has an inherent storage capability which makes it especially suitable for supplying base load power in an economical way, and can thus serve as a partner with energy sources which are only available intermittently. The renewable energy sources can contribute significantly to the mitigation of climate change and more so by working as partners rather than competing with each other.

Presently, the geothermal utilisation sector growing most rapidly is heat pump applications. This development is expected to continue in the future making heat pumps the major direct utilisation sector. The main reason for this is that geothermal heat pumps can be installed economically all over the world.

One of the strongest arguments for putting more emphasis on the development of geothermal resources worldwide is the limited environmental impact compared to most other energy sources. The CO_2 emission related to direct applications is negligible and very small in electricity generation compared to using fossil fuel.

The geothermal exploitation techniques are being rapidly developed and the understanding of the reservoirs has improved considerably over the past years. Combined heat and power plants are gaining increased popularity, improving the overall efficiency of the geothermal utilisation. Also, low-temperature power generation with binary plants has opened up the possibilities of producing electricity in countries which do not have high-temperature fields. Enhanced Geothermal Systems (EGS) technologies, where heat is extracted from deeper parts of the reservoir than conventional systems, are under development. If EGS can be proven economical at commercial scales, the development potential of geothermal energy will be limitless in many countries of the world.

A project for drilling down to 5 km into a reservoir with supercritical hydrous fluids at 450-600°C is under preparation (IDDP). If this project succeeds, the power obtained from conventional geothermal fields can be increased by an order of magnitude. This would mean that much more energy could be obtained from presently producing high-temperature geothermal fields from a smaller number of wells.

Likely case scenarios are presented in the paper for electricity production and direct use of geothermal energy, as well as the mitigation potential of geothermal resources 2005-2050. These forecasts need to be elaborated on further during the preparation of the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation.

Acknowledgements

The authors would like to thank Einar Gunnlaugsson, Toshihiro Uchida, Keyan Zheng, Dorthe H. Holm, Halldor Armannsson and Gudni Axelsson for valuable contributions to the paper.

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