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III

GEOTHERMAL ENERGY:
AN OVERVIEW ON RESOURCES AND POTENTIAL

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SUMMARY

This paper will highlight the present status of geothermal electricity in the world, the perspectives and the possibilities from the application of the new technologies to reach the expected potential target of 140 GW for year 2050.

INTRODUCTION

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%.

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.

The most important source of information for this contribution is a position paper of the International Geothermal Association (IGA) presented at the IPPC Meeting on Renewable Energy Sources (Fridleifsson et al., 2008). The cost analysis is based on a very detailed Geothermal Energy Association paper (GEA, 2005).

1. PRESENT STATUS

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

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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, and 76 TWh/yr for direct use. The installed electric capacity in 2004 was 8,933 MWe. The installed capacity for direct applications in 2004 was 28,268 MWth. 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.

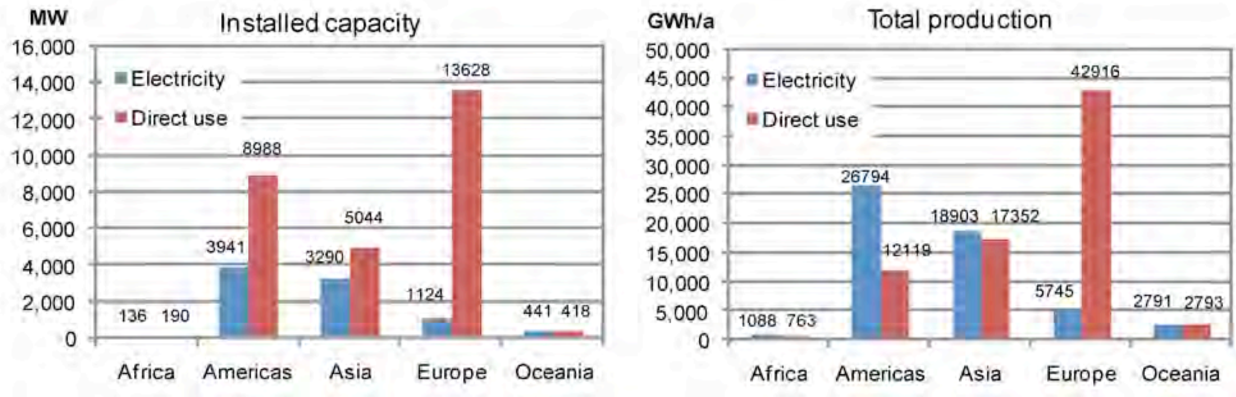

Figure 1. Installed capacity (left) and energy production (right) for geothermal electricity generation and direct use (heating) in the different continents; the Americas include North, Central and South America. (from Fridleifsson and Ragnarsson 2007).

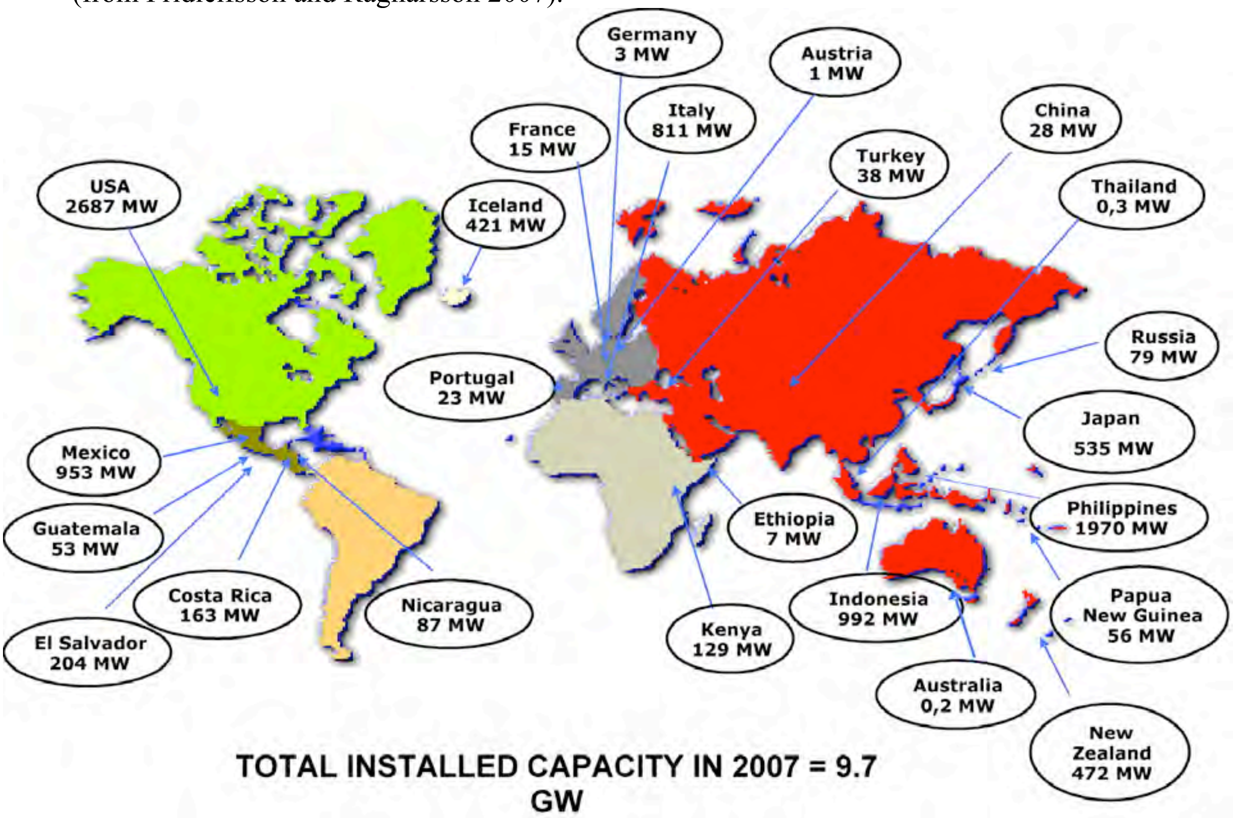

Figure 2. Installed capacity for electricity production in 2007 in different countries (Bertani, 2007).

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 (Gawell et al. 1999).

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).

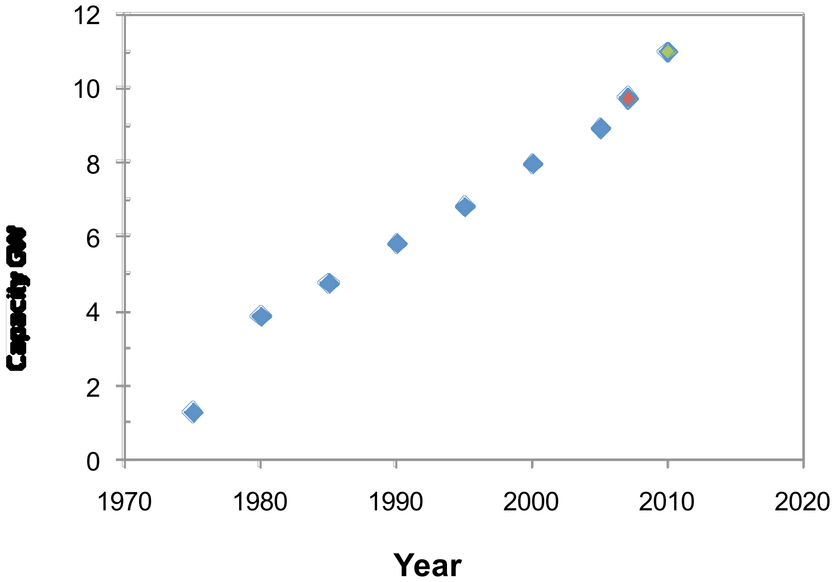

Figure 3. Installed capacity for electricity production from 1975 up to end of 2007 (red) and forecast to 2010 (green) (Bertani, 2007).

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 (Cataldi, 1999, Fridleifsson, 1999). 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 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.

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 1. 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 1). 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.

1.1. 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. 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.

Table 1. 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

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 (see figure 4).

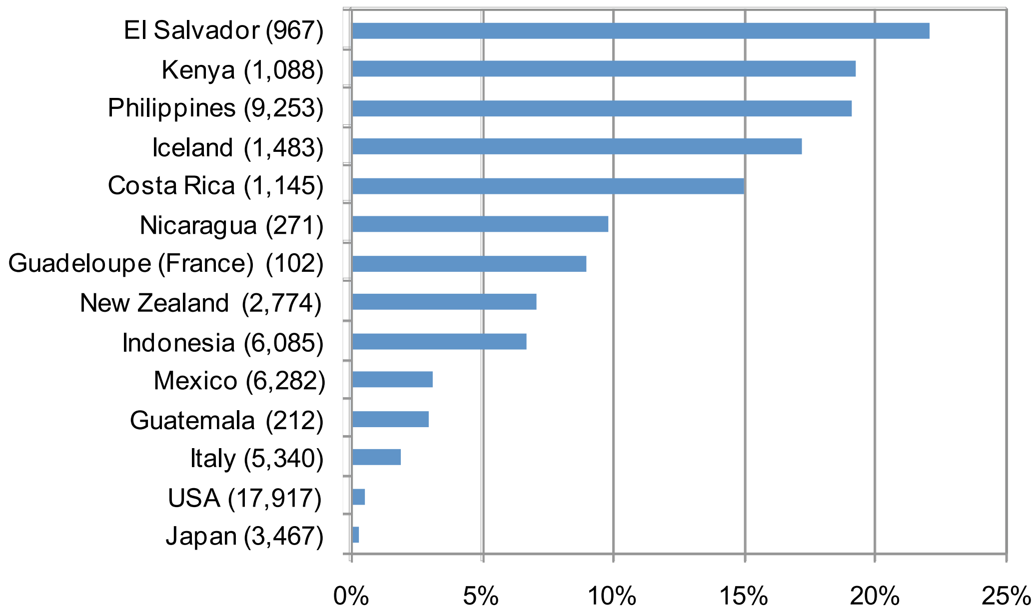

Figure 4. The fourteen countries with the highest % share of geothermal energy in their national electricity production (Fridleifsson, 2007). Numbers in parenthesis give the annual geothermal electricity production in GWh in 2004 (Bertani, 2005).

1.2. 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%. Figure 5 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.

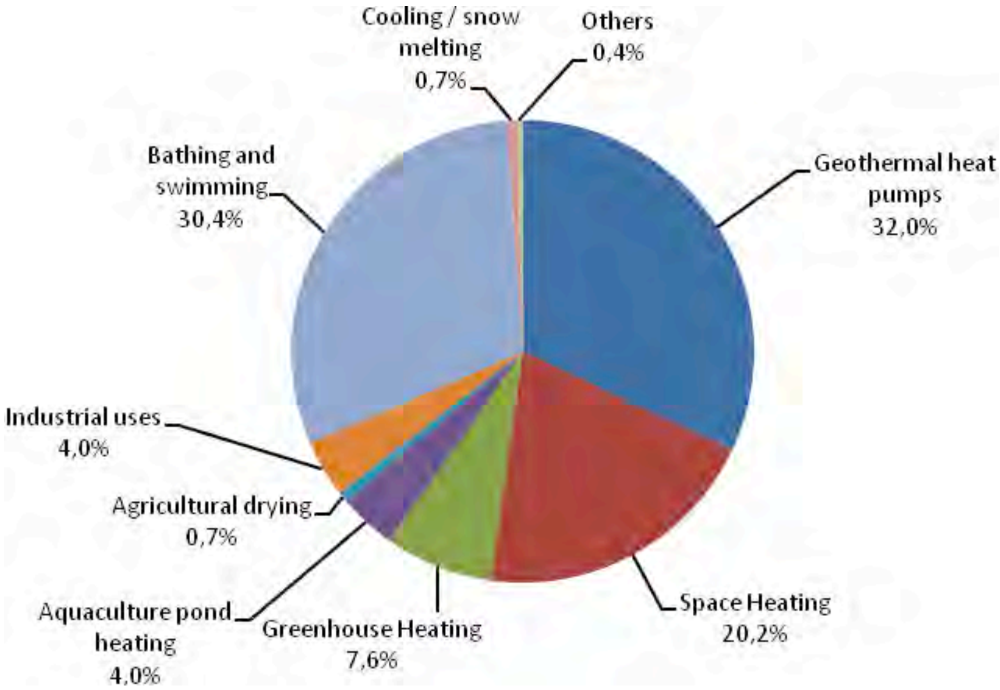

Figure 5. Direct applications of geothermal worldwide in 2004 by percentage of total energy use (Lund et al. 2005).

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.

1.3. 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.

Due to the rapidly growing GHP development, statistical data can provide only snapshots of the current situation. Table 2 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. 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 6 and Table 3 are different, and the numbers not exactly the same).

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

7 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.

Table 2. 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**

Table 3. 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

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

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. 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. 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.

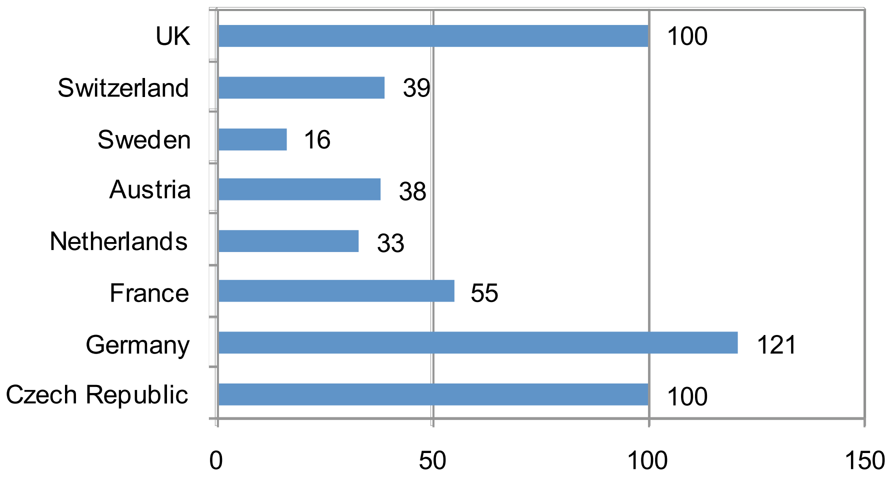

Figure 6. Increase of the number of GHP installations (in %) in European countries in 2006. (European Heat Pump Association, EHPA).

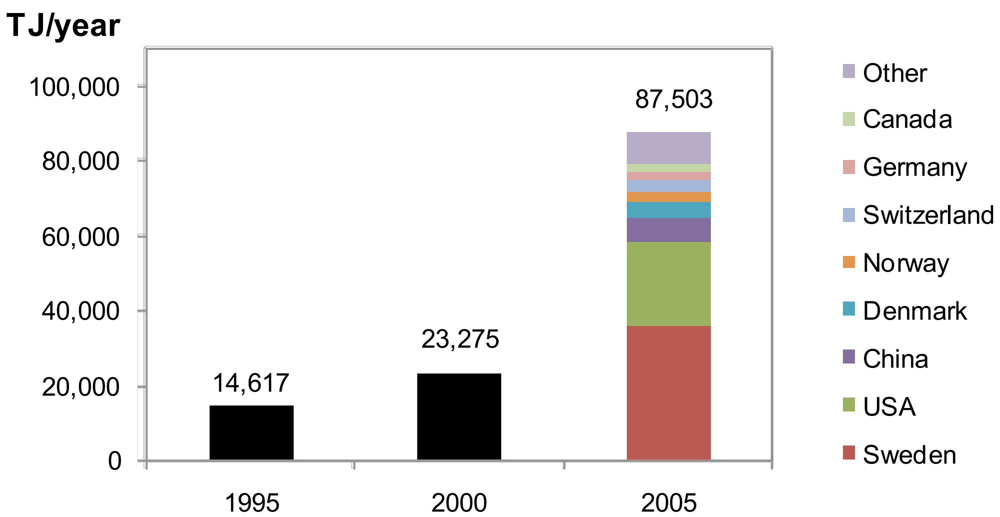

Figure 7. Worldwide growth of ground source heat pump applications and the leading GHP countries (Lund et al., 2005).

2. 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, 2003 and 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.

Geothermal energy have been considered exploitable, until recently, only in areas where the fluid is found at depths less than 4 km with temperature above 180°C. This has changed in the last two decades with the development of power plants that can economically utilise lower temperature resources (down to 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 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, Enhanced Geothermal Systems (EGS) technology, low temperature electricity production, and the use of supercritical fluids.

When we speak generically about geothermal resources, what we are usually referring to is what should more accurately be called the *accessible resource base*; that is, all of the thermal energy stored between the Earth's surface and a specified depth in the crust, beneath a specified area and measured from local mean annual temperature (Muffler and Cataldi, 1978). The accessible resource base includes the *useful accessible resource base* (= *Resource)*—that part of the accessible resource base that could be extracted economically and legally at some specified time in the future (less than a hundred years). This category includes the *identified economic resource* (= *Reserve)*—that part of the resources of a given area that can be extracted legally at a cost competitive with other commercial energy sources and that are known and characterized by drilling or by geochemical, geophysical and geological evidence. Figure 8 illustrates in graphic form these and other terms that may be used by geothermal specialists.

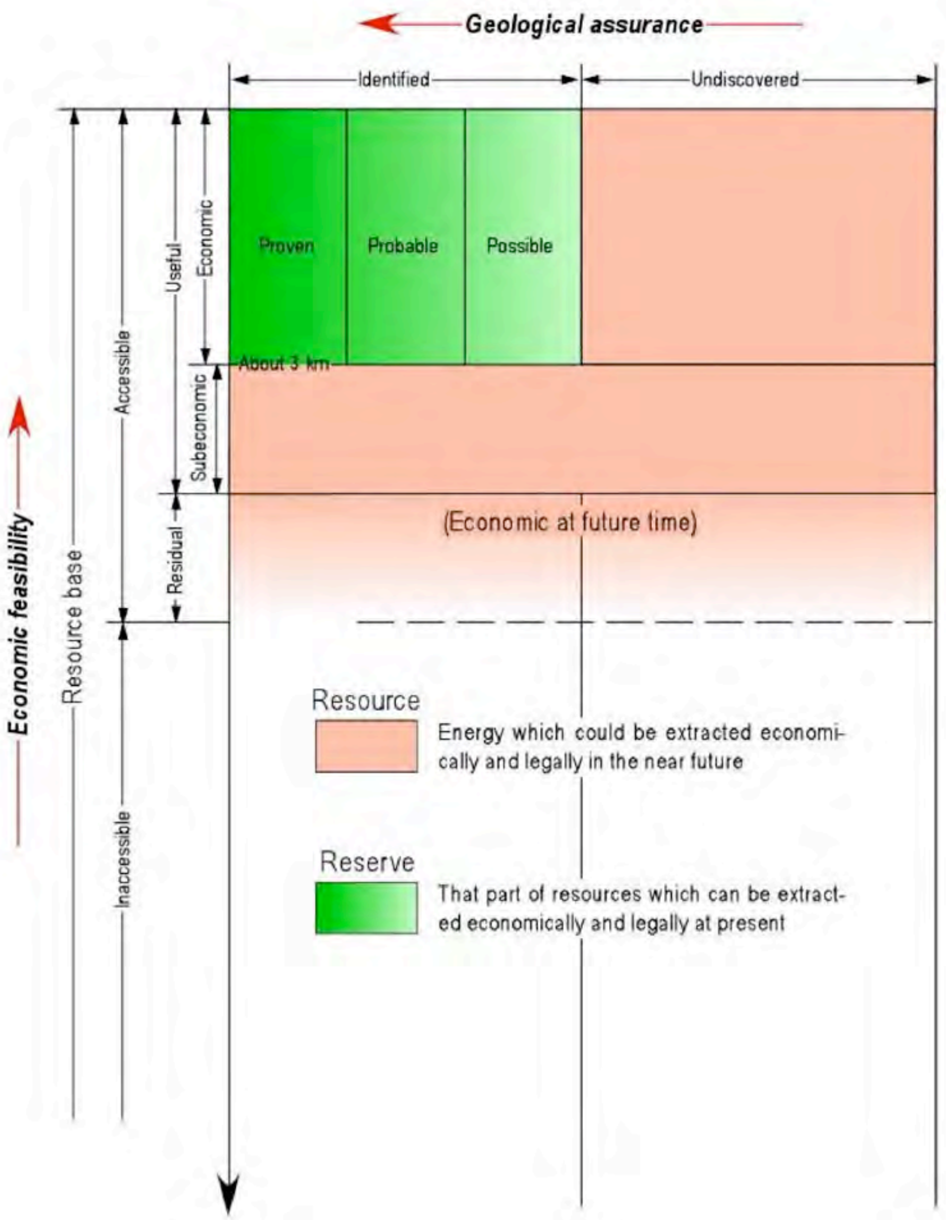

Figure 8: Diagram showing the different categories of geothermal resources. The vertical axis is the degree of economic feasibility; the horizontal axis is the degree of geological assurance, (Muffler and Cataldi, 1978).

Different authors have performed different estimation of the geothermal potential (named from [A] to [E]), both for electricity generation and the direct uses. In Bertani, 2003 the data has been revised and integrated, and are presented a the following table.

Table 4. Estimated geothermal potential (Bertani, 2003)

	Electricity			Direct uses		
	GW	TWh/y	EJ/y	GWth	TWh/y	EJ/y
WGC2005	8.930	55.18	0.20	15.145	74.30	0.27
Potential [A]	1,700	12,000	43	48,000,000	170,000,000	600,000
Potential [B]	140	1,000	3.5			
Potential [C]	3,100	22,000	79	160,000	>560,000	>2,000
Potential [D]	5,900	42,000	150	28,000	97,000	350
Potential [E]	46	330	1.2	190	670	2.4

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 70 GW and a maximum of 140 GW (Figure 9). 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. 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.

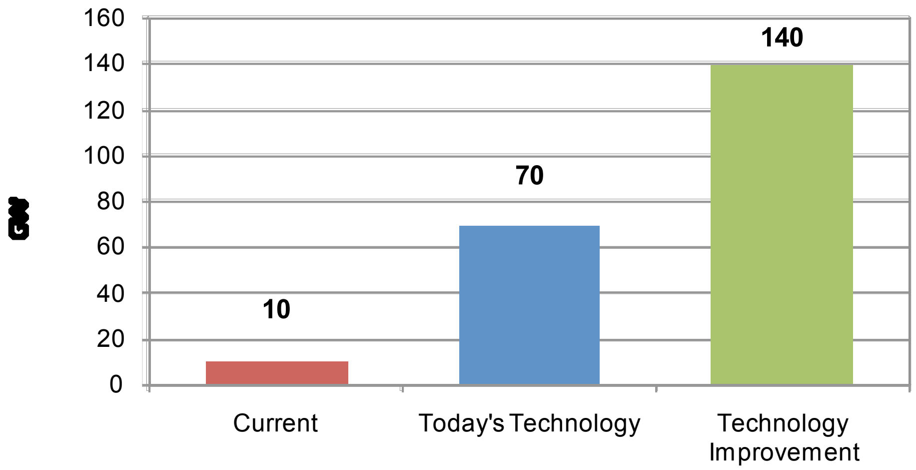

Figure 9. Estimated World geothermal electricity potential with present technology (blue) and with technology improvement (green). The current installed capacity is also shown (red), (Bertani, 2003).

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). 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 (Fridleifsson, 2001). 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 10).

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. A discussion on the new technologies will be presented later in this paper.

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. (see figures 11).

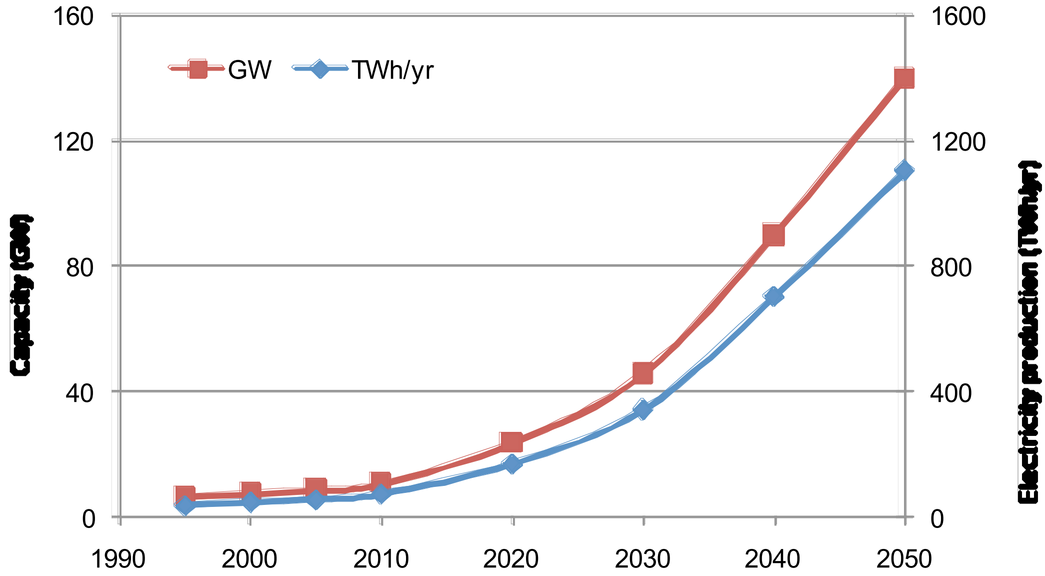

Figure 10. Installed Capacity and Electricity production 1995-2005 and forecasts for 2010-2050, (Fridleifsson et al., 2008).

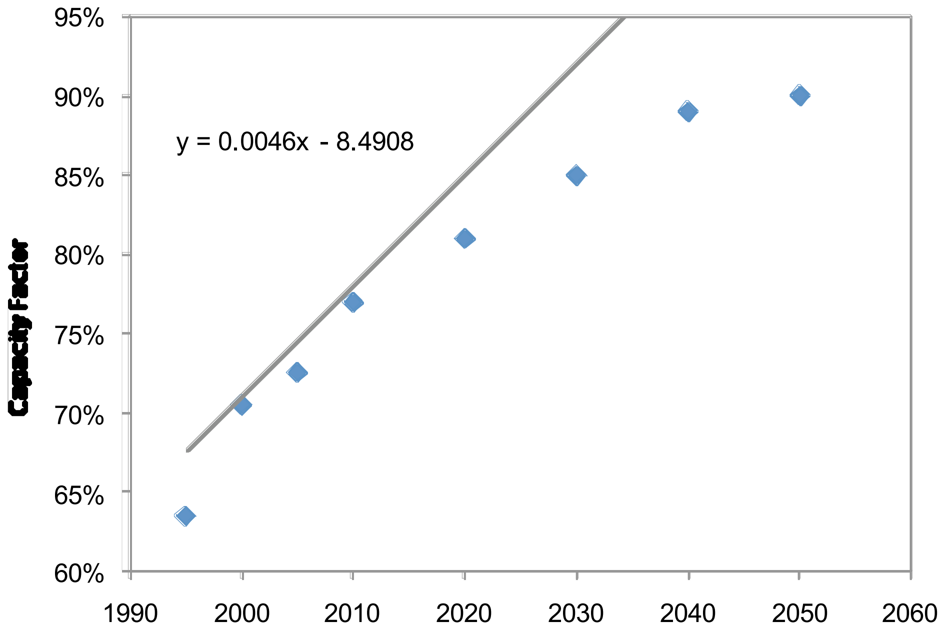

Figure 11. Capacity Factor of geothermal power plants in the world 1995-2005 and forecasts for 2010-2050, (Fridleifsson et al., 2008).

Geothermal electricity production of about 100 TWh/yr in 2050 will mitigate up to 1000 of million tons CO_2/yr (if the substituted fuel would be coal).

The standard GEA world division of regions is shown in the following figure 12

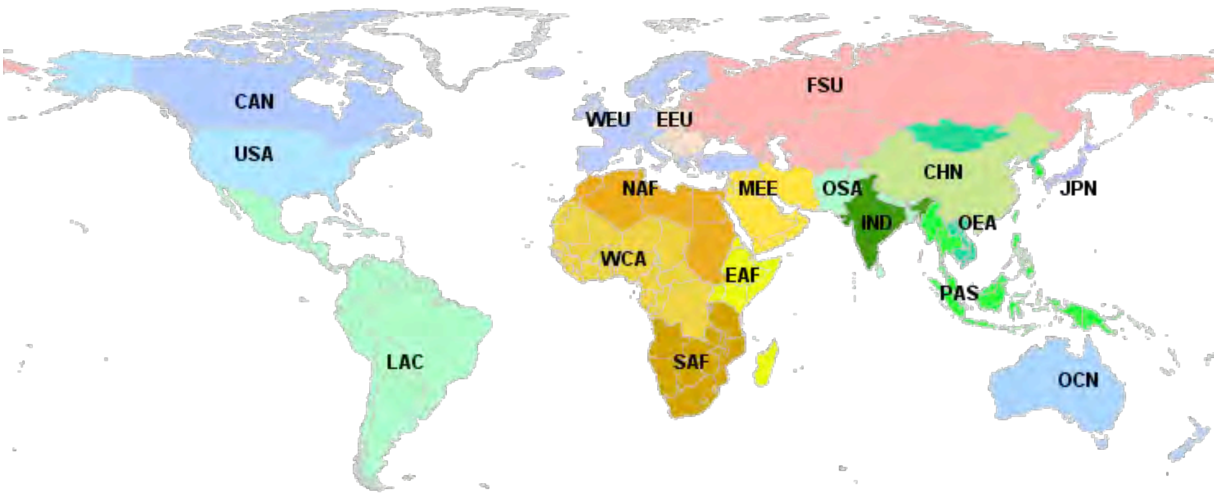

Figure 12. GEA World regions.

For each region we identified the 2010 installed capacity, the Resources and the Reserves as expected in year 2050.

Table 5: 2050 forecasting by GEA regions

REGION	**2010 CAPACITY (GW)**	**2050 CAPACITY (GW)**	**RESOURCES (GW)**
United States of America	2.82	60	110
Canada		1	2
Western Europe, incl. Turkey	1.65	15	20
Central and Eastern Europe		3	6
Former Soviet Union	0.19	9	17
Northern Africa			
Eastern Africa	0.17	3	6
Western and Central Africa			
Southern Africa			
Middle East		2	12
China	0.03	5	20
Other East Asia			
India		2	29
Other South Asia			
Japan	0.54	2	4
Other Pacific Asia	3.24	20	26
Australia, New Zealand, and other Oceania	0.59	3	5
Latin America and the Caribbean	1.78	15	23
TOTAL	**11**	**140**	**280**

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. 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.

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 Figures 13 and 14. 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.

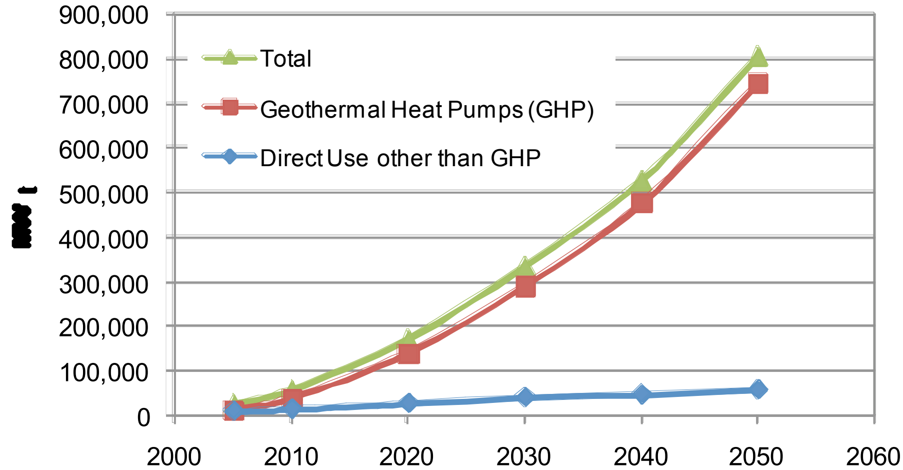

Figure 13. Likely case scenario for growth in direct use and GHP installed capacity, (Fridleifsson et al., 2008).

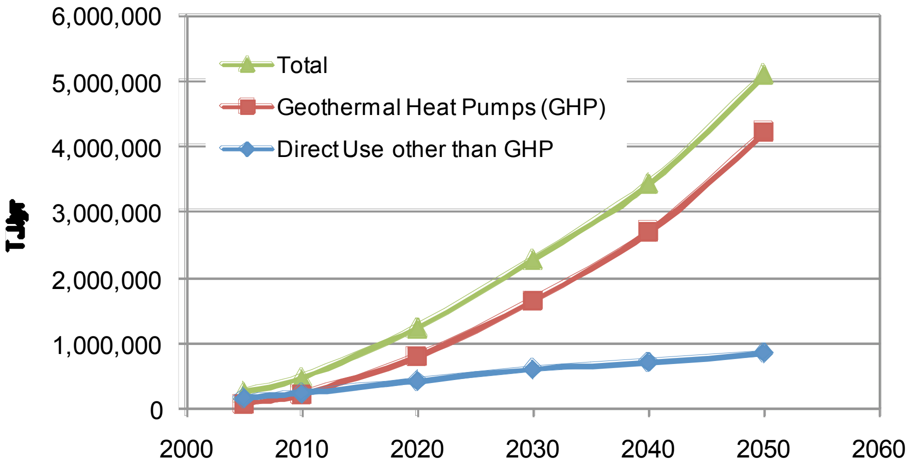

Figure 14. Likely case scenario for growth in direct use and GHP energy production, (Fridleifsson et al., 2008).

The mitigation potential of CO_2 for the heat provision is large for GHPs as long as GHPs substitute fossil energy. 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.

3. ADVANCED RESEARCHES

3.1. 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 (Tester et al., 2006) determined a large potential for the USA: recoverable resources > 200,000 EJ, corresponding to 2,000 times the annual primary energy demand. 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 (figure 17).

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.

Figure 17: view of the European Soultz EGS project.

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3.2. 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. This would mean that much more energy could be obtained from presently exploited high-temperature geothermal fields from a smaller number of wells.

4. 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 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.

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