A CLEAN ENERGY FUTURE
FOR THE UNITED STATES:
THE CASE OF GEOTHERMAL POWER

Testimony

by

the President of Iceland

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at a Senate Hearing

Committee on Energy and Natural Resources

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1. INTRODUCTION

It is an honour and a privilege for me to be invited to give testimony to your distinguished committee on my country's story and to discuss how the United States can take important steps in increasing the use of geothermal energy.

I will be describing how Iceland transformed its energy system from being based on peat, imported coal and oil to one in which 100 percent of its energy production is based on clean energy resources, with roughly 72% of its entire energy consumption coming from indigenous renewable sources (54% geothermal, 18% hydropower). The rest of Iceland's energy requirements, for the fishing fleet and transportation, are met by imported fossil fuel.

This change has happened in the lifetime of only one generation, and thus my country has developed from being one of the poorest countries in Europe into one of the most affluent in the world.

It is my hope that many other countries can follow our lead and understand that what is one day considered a tough challenge can become a reality if the right forces and the right policies are put to work.

For the United States of America, geothermal energy can become a major energy resource, contributing to the security of the country, limiting dependence on the import of fossil fuels, reducing the risks caused by fluctuating oil prices and providing opportunities for new infrastructures supporting the cities and regions where the resources are located.

I hope to outline how technical, scientific, business and policy-making cooperation between Iceland and the United States can help the US to achieve this transformation and thus become one of the leading clean energy countries in the world and at the same time strengthening the US economy and enhancing the security of the nation.

I will also show that geothermal energy is a reliable, flexible and green energy resource which can supply significant amounts of power to households and industry. Furthermore, it uses land economically, gives social returns and it is cost-effective.

It is <u>reliable</u> because it provides base-load power 24 hours a day and is available throughout peak hours.

It is <u>flexible</u> and can be tailored to needs accordingly. This is a clear shift from the public debate, which has been preoccupied by "big solutions" in the field of energy, centred on coal, oil and nuclear programmes. In many places, geothermal energy can provide a "big" solution, but in many others it can serve a single city, large industries, a small town or as little as a single household. This flexibility can bring significant advantages.

It is <u>green</u>: When coal is used to produce an equivalent amount of energy, the CO2 emissions are 35 times greater, according to information from the NREL. Emissions from geothermal power plants contain mostly water vapour and they do not emit particulates, hydrogen sulphide or nitrogen oxides.

It uses <u>land economically</u>: Geothermal plants require by far the least land for electricity production per energy unit compared with all other available renewable sources.

It gives social returns: Many more jobs are created through the harnessing of geothermal energy than by developing other types of renewable energy resources.

And it is cost effective: The cost of electricity produced with geothermal energy in the US is expected to be between five and eight cents per kWh. This is more expensive than the cost of our geothermal power in Iceland which is closer to two or three cents, but according to a new market report from Glitnir Bank it is still far lower than the cost of energy from solar or other renewable sources. This would represent a significant saving for individuals and communities.

2. CLIMATE CHANGE-ENERGY SECURITY-CLEAN ENERGY

For many years now, I have been warning that in the coming decades we will see catastrophic effects of global climate change if humanity does not take immediate precautionary action. Unfortunately, when I first spoke about this threat in my New Year address to the Icelandic nation in 1998, not many people had yet begun to take the issue with sufficient seriousness. Now, however, the world's leading scientists no longer question the reality of climate change but only how much time remains until we reach the point of no return.

For a country such as Iceland, climate change can have disastrous consequences. As an island high in the Northern seas, we are dependent on the Gulf Stream bringing warm water from the Gulf of Mexico. As with other island states and coastline territories, rising water levels can have a devastating effect on our future livelihood. Like most other countries, Iceland has experienced irregularities in weather patterns. We are fighting the biggest desert in Europe and we have the largest glaciers in Europe, which have been rapidly retreating in recent years, allowing us to witness the effects of climate change at first hand and encouraging us to be in the forefront of global action, creating solutions with the best possible partners.

In discussions on climate change that have taken place internationally, frequent reference has been made to the significance of the polar regions, where evidence of the impact of global warming has been most pronounced.

At the Reykjavík Ministerial Meeting of the Arctic Council, an inter-governmental organization embracing the countries in the North, including Iceland, the United States and Russia, in November 2004, the eight member states received the main findings of the Arctic Climate Impact Assessment (ACIA). This report, completed during Iceland´s Chairmanship of the Arctic Council, is the world´s most comprehensive and detailed regional climatic and ultraviolet radiation assessment to date and documents impacts that are already being felt throughout the Arctic region. It clearly demonstrates that the Arctic climate is now warming rapidly, presenting a range of challenges for human health, culture and well-being among the people of the region.

The importance of the ACIA, which drew on the work of more than 300 leading researchers, indigenous representatives and other experts from fifteen nations, goes well beyond its regional relevance. According to the authors, Arctic warming and its consequences will have worldwide implications, affecting in a profound manner vegetation patterns, biological diversity, marine transportation, access to resources and the survival of coastal communities, to name only a few examples.

Barely three years after the ACIA was presented, it would seem that future projections, based on its findings, may have been somewhat conservative. In our own Icelandic neighbourhood, the Greenland ice cap is melting at an accelerating rate, with potentially catastophic consequences in terms of global sea-level rise. As the leading ACIA scientist, Robert Corell, recently observed, one Greenland glacier alone, at Ilulissat, is now putting enough fresh water into the sea to provide drinking water for a city the size of London.

Therefore, the message from the North is clear; all countries need to start taking the issue of global climate change seriously and work together in a deliberate way towards the adaptation to, and the mitigation of, its accelerating impacts.

This explains the vital interest that Iceland has in working with other nations to campaign hard against climate change and play a role in persuading others, policy-makers, scientists, experts, corporate leaders and other individuals to take action.

There are many steps that need to be taken. In this hearing, the focus will be on the aspect where I believe my country can make a significant input. I see the increased utilization of clean energy resources as one of the most vital parts in the fight against climate change.

The International Energy Agency (IEA) forecasts that US$ 20 trillion in new investment will be required to meet world energy needs by 2030. Much of this investment will be needed in the world's fastest-growing economies and expectations for China alone amount to 18% of the total. Innovative policies and technologies present significant opportunities to ensure economic growth and social development while minimizing the unwanted consequences of investments, such as urban air pollution, resource depletion, health damage, water stress and climate change. Geothermal energy can play an important role in this aspect in many parts of the world.

We have approached the issue of energy in Iceland from the point of view of the importance of achieving energy security. As geothermal energy and hydroelectric power have been developed within Iceland’s borders, this means that we have become independent of fuel imports for electricity production. Thus we have less reason than many other nations to worry about fluctuating prices of oil except as they affect the transport sector and the fisheries fleet, and in these areas too, we are working on decreasing our dependence on oil.

3. GEOTHERMAL UTILIZATION

Although geothermal energy is categorised in international energy tables among the “new renewables”, it is not a new energy source at all.

People have used hot springs for bathing and washing of clothes since the dawn of civilisation in many parts of the world. Late in the nineteenth century, people began experiments utilizing geothermal energy for outdoor gardening and early in the twentieth century, geothermal sources were first used to heat greenhouses. Around the same time, people started using geothermal energy to heat swimming pools and buildings.

Electricity has been generated by geothermal steam commercially since 1913, and geothermal energy has been used on the scale of hundreds of MW for five decades now, both for electricity generation and direct use. The scale of utilization has increased rapidly during the last three decades.

Conventional electric power generation is mostly limited to geothermal fields with a fluid temperature above 150°C, but considerably lower temperatures can be used with the application of binary fluids which utilize the geothermal fluids down to about 80°C. The unit sizes of steam turbines are commonly 20-50 MWe. The efficiency of geothermal utilization is enhanced considerably by co-generation plants which produce both electricity and hot water for district heating and other direct uses.

In many countries, the most significant direct application is for district heating, using the geothermal fluid directly or extracting the heat with the aid of heat exchangers or heat pumps. In Iceland, most of the direct use of geothermal heat is in the form of central heating; 85% of all houses in Iceland are heated this way.

Geothermal water also has many other applications, including swimming pools, soil warming, fish farming, animal husbandry, aquaculture pond heating and industrial heating and processing such as drying of timber, wool and seaweed.

Reykjavík Energy currently operates the world's largest and most sophisticated geothermal district-heating system in Reykjavik, Iceland's capital city. In terms of size, it will be rivalled only a project that Icelanders are building in Xian Yang in China.

A single geothermal resource can be used as the basis of many different profit-making ventures, from delivering hot water to municipalities to developing tourist centres with spas, hotels and health clinics. This has been done at the "Blue Lagoon", a geothermal site in Iceland, where cosmetics and skin balms made from the silica precipitates in the run-off water have been developed into a significant source of income.

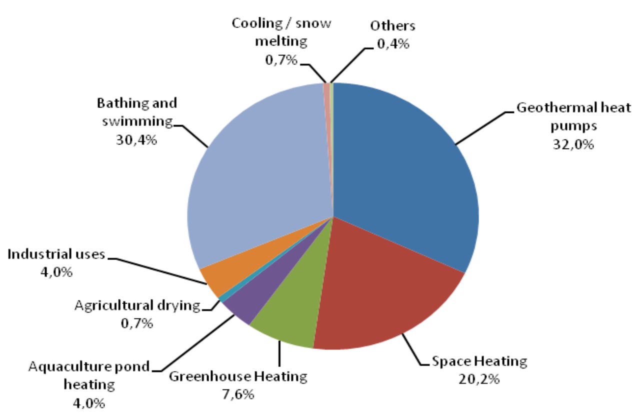

Fig. 1 Direct applications of geothermal heat worldwide by percentage of total energy use.

3.1 Sustainable Utilization of Geothermal Resources

Geothermal energy is a renewable energy source, meaning that the source itself has the potential to recover following utilisation. It may be utilised in either a sustainable manner or an "excessive" manner.

Excessive production from a geothermal field – in excess of the capacity of the resource to recover – can only be maintained for a relatively short time. After a period of prolonged excessive use, production must be brought down to, or below, the level of maximum sustainable use. Stepwise development is employed to avoid excessive production.

Stepwise development takes into consideration the individual conditions of each geothermal system, and minimises the long-term production cost. The cost of drilling is a substantial component, both in the exploration and the development of geothermal fields. With the stepwise development method, production from the field is initiated shortly after the first, successful wells have been drilled.

The production and response history of the reservoir during the first development step is used to estimate the size of the next development step. In this way, favourable conditions are achieved for the timing of the investment in relation to the timing of revenue, resulting in lower long-term production costs than could be achieved by developing the whole field in a single step.

A combination of the stepwise development method with the concept of sustainable development results in an attractive and economical way to utilize geothermal energy resources.

4. GEOTHERMAL DEVELOPMENT IN ICELAND

Iceland is a country of 300,000 people, located on the mid-Atlantic ridge, between Europe and America. It is mountainous and volcanic, with much precipitation. The country's geographical peculiarities have endowed Iceland with an abundant supply of geothermal resources and hydropower.

Iceland's energy use per capita is among the highest in the world, and the proportion of this provided by renewable energy sources exceeds that in most other countries. Nowhere else does geothermal energy play a greater role in providing a nation's energy supply. Almost three-quarters of the population live in the south western part of the country, where geothermal resources are abundant.

The current utilization of geothermal energy for heating and other direct uses is considered to be only a small fraction of what this resource can provide. The potential to generate electricity is more uncertain. Hydropower has been the main source of electricity, but in recent decades geothermal power plants have also contributed an important share of production.

In 2006, geothermal plants generated one fourth of the total 9,920 GWh produced. In 2009, the total production is forecast to be about 15,000 GWh, with 20% generated in geothermal plants. At the same time, 80% of the electricity will be used in the energy intensive industry.

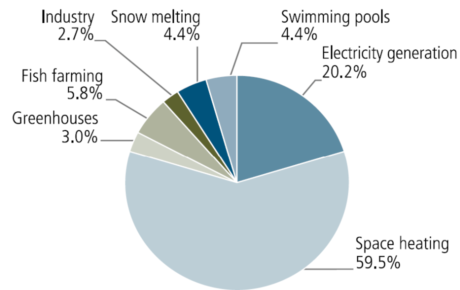

Fig. 2 Utilization of geothermal energy in Iceland in 2005

This figure gives a breakdown of the utilization of geothermal energy for 2005. These percentages are for energy utilized rather than primary energy. As the figure reveals, the 60% share of space heating was by far the greatest, followed by electricity production, accounting for 20%.

Iceland possesses relatively extensive untapped energy reserves. However, these reserves are not unlimited. Only rough estimates are available as to the size of these energy reserves in relation to the generation of electricity. Therefore, there is considerable uncertainty when it comes to assessing to what extent they can be harnessed with regard to what is technically possible, cost-efficient, and environmentally desirable.

For the potential generation of electricity, these energy reserves are estimated at roughly 50,000 GWh per year, some 60% coming from hydropower and 40% from geothermal resources. By 2008, the generation will amount to about 30% of that total potential.

A master plan comparing the economic feasibility and the environmental impact of the proposed power development projects is being prepared. It is hoped that this comparison will aid in the selection of the most feasible projects to develop, considering both the economic and environmental impact of such decisions, including which rivers or geothermal fields should not be harnessed due to their value in terms of natural heritage and recreation. Final results are expected by 2009.

4.1 Space Heating

In a cold country like Iceland, home heating needs are greater than in most countries.
Coal imports for space heating were begun after 1870. The use of coal for heating increased in the beginning of the twentieth century, and coal was the dominant heat source until the end of World War II. Iceland's dependence on oil began with the twentieth century.

Oil for heating purposes first became significant after World War II. By 1950 about 20% of families used oil for heating, while 40% used coal. At that time about 25% enjoyed geothermal heating services. In the 1950s, the equipment to utilize oil for heating improved, obviously leading to increased consumption.

As a result, coal was practically eliminated from space heating in Iceland around 1960. At the same time, control systems for central heating developed rapidly, and the first automatic temperature regulators for radiators became common.

The first uses of geothermal energy to heat houses can be traced back to 1907. In Reykjavik, large-scale distribution of hot water for heating homes began in 1930. In addition to the development in the capital area, many communities around the country built their heating distribution systems in places where hot springs, or successful drilling, yielded suitable geothermal water. Community schools in the countryside were also preferably located close to supplies of geothermal water, which was available for heating and swimming.

When the oil crisis struck in the early 1970s, fuelled by the Arab-Israeli War, the world market price for crude oil rose by 70%. About the same time, roughly 90,000 people enjoyed geothermal heating in Iceland, around 43% of the nation. Heat from oil still served over 50% of the population.

The oil crises of 1973 and 1979 (following the Iranian Revolution) caused Iceland to change its energy policy, dropping the emphasis on oil and turning to domestic energy resources: hydropower and geothermal heat. This policy meant searching for new geothermal resources, and building new heating services across the country. It also meant constructing transmission pipelines (commonly 10-20 km long) from geothermal fields to towns, villages and individual farms.

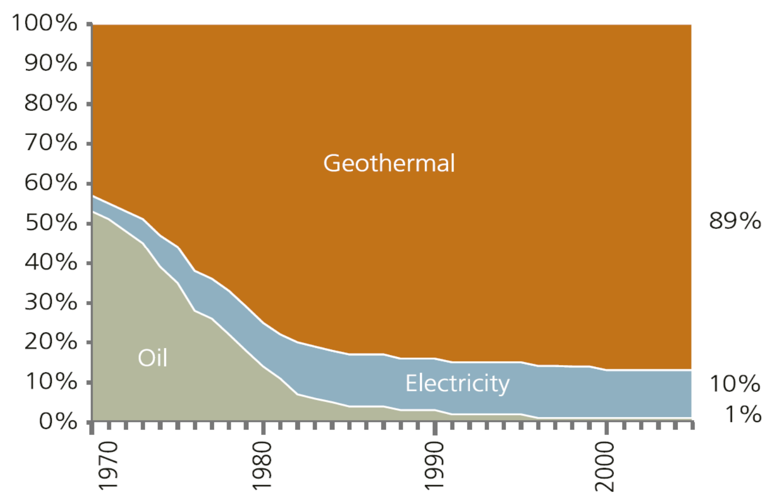

Fig. 3 Relative share of energy resources in the heating of houses in Iceland

4.2 Electric Power Generation in Iceland

Generating electricity with geothermal energy in Iceland has increased significantly in recent years. Three of the plants are co-generation plants producing both electricity and hot water for district heating. One of them uses a water-ammonia mixture as its working fluid (Kalina-process), extracting heat from 120°C geothermal water for electricity generation followed by a series of other direct uses for industrial processes of boiling and drying, district heating, swimming pools, fish farming and snow melting, reducing the temperature of the water to 25°C before it is finally discarded.

As a result of a rapid expansion in Iceland's energy-intensive industries, the demand for electricity has increased considerably. Fig. 5.4 shows the development from 1970-2005, and planned production up until 2008. Total electricity production in 2005 from geothermal sources came to 1,658 GWh, which was 19.1% of the country's total electricity production. Enlargements of the existing power plants and two new plants increased the installed capacity by 210 MWe in 2007, bringing the total capacity up to 410 MWe.

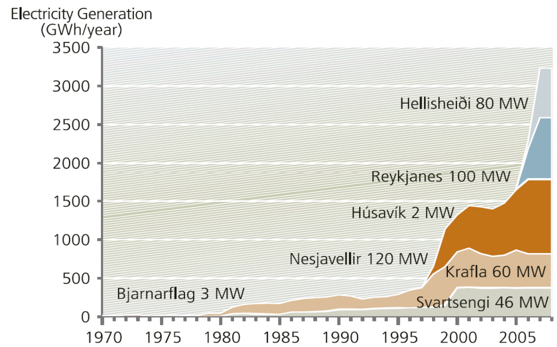

Fig. 4 Generation of electricity using geothermal energy 1970 – 2008.

4.3 Benefits of using geothermal heat instead of oil

The economic benefits of the policy of increasing the utilization of geothermal energy can be seen when the total payments for hot water used for space heating are compared to the consumer costs of oil.

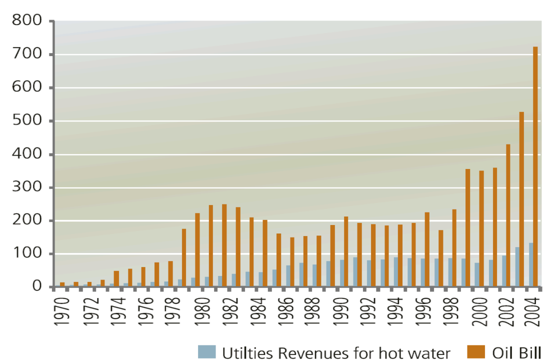

Fig. 5 Cost of space heating with geothermal water versus oil

Fig. 5 compares the cost of geothermal water to what would have been spent on oil to yield the same energy for heating (1970 to 2005). All costs are priced in the corresponding year.

Direct annual savings stood at a peak level from 1980 to 1983, about $200 million per year. They rose above $200 million in 2000, and savings continue to climb as oil prices increase. In 2000, the present value of the total savings between 1970 and 2000 was estimated at $8,200 million or more than three times Iceland's national budget in 2000. The economic savings garnished by using geothermal energy are substantial, and have contributed significantly to Iceland's prosperity.

Assuming that geothermal energy used for heating homes in 2003 was equivalent to the heat obtained from the burning of 646,000 tons of oil, the use of geothermal energy reduced the total release of CO_2 in the country by roughly 37%.

Besides the economic and environmental benefits, the development of geothermal resources has had a desirable impact on social life in Iceland. People have preferred to live in areas where geothermal heat is available, in the capital area and in rural villages where thermal springs can be exploited for heating dwellings and greenhouses, schools, swimming pools and other sports facilities, tourism and smaller industries. Statistics show improved health of the inhabitants of these regions.

The significant fluctuations of oil prices caused by political unrest in key oil-producing regions should encourage governments to focus on indigenous energy sources to meet their basic energy requirements.

4.4 Heat Pumps

Until recently, geothermal energy has been economically feasible only in areas where thermal water or steam is concentrated at depths of less than 3 km in restricted volumes, analogous to oil in commercial oil reservoirs. The use of ground-source heat pumps has changed the economic norms. In this case, the earth is the heat source for the heating and/or the heat sink for cooling, depending on the season.

This has made it possible for people in all countries to use the earth's heat for heating and/or cooling. It should be stressed that heat pumps can be used basically anywhere.

It is considered likely that heat pumps will become competitive where water above 50°C is not found. In such places, heat pumps can be used instead of direct electrical heating to raise the temperature of warm spring water.

4.5 The Public Sector's role in developing geothermal energy in Iceland

Governments in Iceland have encouraged exploration for geothermal resources and research into the various ways geothermal energy can be utilized. This work began in the 1940s at the State Electricity Authority, and was later, for decades, in the hands of its successor, the National Energy Authority (Orkustofnun), which was established in 1967. The aim has been to acquire general knowledge of geothermal resources and make the utilization of this resource profitable for the national economy.

This work has led to great achievements, especially in finding alternative resources for heating homes. This progress has been possible thanks to the skilled scientists and researchers at the National Energy Authority. This research is now in the hands of a new state institute, Iceland GeoSurvey, which was born out of the National Energy Authority in 2003. New and effective exploration techniques have been developed to find geothermal resources.

This has led to the development of geothermal heating services in regions that were thought not to contain suitable geothermal resources. Iceland's geothermal industry is now so developed that the government can play a smaller role. Successful power companies now take the lead in exploitation, either developing geothermal fields that are already being utilized, or finding new fields.

The Icelandic government set up an Energy Fund by merging two funds in 1967 to further increase the use of geothermal resources. Over the past few decades, this has granted numerous loans to companies for geothermal exploration and drilling. Where drilling failed to yield the expected results, the loans were converted to grants.

The country's larger district heating services are owned by their respective municipalities. Some 200 smaller heating utilities have been established in rural areas. Recent changes in the ownership structure of many district-heating systems in Iceland have had their effect. The larger companies have either bought or merged with some of the smaller systems. Also it is becoming increasingly common to run both district heating and electricity distribution in a single municipally-owned company. This development reflects increased competition in the energy market of the country.

5. GEOTHERMAL ENERGY WORLD-WIDE

The people of Iceland live in a harsh natural environment in terms of the weather and the danger of earthquakes and volcanic eruptions; however, nature also provides them with access to the heat inside the earth for energy production. But Iceland is not unique in this respect: the same opportunities exist in many countries and can benefit their people if they are fortunate enough to make use of them.

Geothermal resources have been located in some 90 countries and there are quantified records of geothermal utilization in 72 countries. Electricity is produced from geothermal sources in 23 countries. Five of these obtain 15-22% of their national electricity totals from geothermal sources. In 2004, the worldwide use of geothermal energy amounted to about 57 TWh/a of electricity (Bertani, 2005), and 76 TWh/a for direct use (Lund et al., 2005).

Electricity production increased by 16% between 1999 and 2004 (an annual growth rate of 3%). Direct use rose by 43% during the same period (an annual growth rate of 7.5%). Only a small fraction of the geothermal potential has been developed so far, and there is ample space for accelerated use of geothermal energy both for direct applications and for electricity generation.

Over two billion people, a third of the world's population, have no access to modern energy services. A key issue for improving the standard of living of the poor is to make clean energy available to them at prices they can afford. The world population is expected to double by the end of the 21st century. To provide sufficient commercial energy (not to mention clean energy) to the people of all continents is an enormous task.

More and more countries are seriously considering how they can use their indigenous renewable energy resources. The recent decision of the Commission of the

European Union to reduce greenhouse gas emissions by 20% by 2020 compared with the 1990 level throughout its member countries implies a significant acceleration in the use of renewable energy resources. Most of the EU countries already have considerable geothermal installations.

5.1 Geothermal energy for development

The top fifteen countries in electricity production from geothermal sources include ten developing countries. The top fifteen countries in direct use of geothermal energy include five developing and transitional countries.

In the electricity sector, the geographical distribution of suitable geothermal fields is restricted and mainly confined to countries or regions on active plate boundaries or with active volcanoes. Central America is one of the world's richest regions in geothermal resources. The geothermal potential for electricity generation in Central America has been estimated at about 4,000 MWe (Lippmann 2002), and less than 500 MWe have been harnessed so far. Geothermal power stations provide about 12% of the total electricity generation of four countries in the region: Costa Rica, El Salvador, Guatemala and Nicaragua.

With an interconnected grid, it would be easy to provide all the electricity for these four countries from renewable energy sources. With its large untapped geothermal resources and its significant experience in both geothermal and hydro development in the region, Central America may become an international example of how to reduce overall emissions of greenhouse gases over a large area. Similar developments can be foreseen in the East African Rift Valley and in several other countries and regions rich in high-temperature geothermal resources.

Geothermal energy can play a significant role in the electricity production of countries and regions rich in high-temperature fields which are associated with volcanic activity. Examples can be found in many developing countries of rural electrification and the provision of safe drinking water and the development of schools and medical centres in connection with the exploitation of geothermal resources. Thus, the projects are in line with the United Nations' Millennium Development Goals.

Kenya was the first country in Africa to utilize its rich geothermal resources and in the foreseeable future will be able to produce most of its electricity from hydro and geothermal sources. Several other countries in the East African Rift Valley can follow suit. Icelandic experts from Reykjavik Energy are now developing the geothermal fields in Djibouti. Indonesia is probably the world's richest country in geothermal resources and will be able to replace a considerable part of its fossil-fuelled electricity plants with geothermal stations in the future.

The main commercial application of geothermal energy for direct use in Kenya is in flower farms near the Olkaria geothermal power station where greenhouses are heated during the night and kept dry using geothermal heat. Around 60,000 people work on the flower farms in the region and it is estimated that some 300,000 people derive their livelihood from them. The flower companies, which export cut flowers (mainly roses) by air to Europe, provide the staff and their families with good housing, water, electricity, schools and medical centres.

Another interesting example of the benefits of geothermal development in Africa is in Tunisia where greenhouses replace cooling towers to cool irrigation water from 2-3 km deep wells in the Sahara desert. Due to the Earth's thermal gradient, the temperature of the water from the wells is up to 75°C and needs to be cooled to 30°C to be used for irrigation. Some 110 hectares of greenhouses have been built in the oasis. The main products are tomatoes and melons which are exported to Europe. This has created many jobs for men and women. Here the geothermal energy development is a by-product of the irrigation project.

5.2 Direct use of heat world-wide

In the direct use sector, the potential is very large, as space heating and water heating constitute a significant part of the energy budget in large parts of the world. In industrialised countries, 35 to 40% of 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.

As I have mentioned, the European Union's commitment to reduce greenhouse gas emissions by 20% by the year 2020 opens up a huge potential for further applications, and most EU countries already have considerable geothermal installations. The same applies to the USA, where the use of ground source heat pumps is widespread both for space heating and cooling.

The largest potential is, however, in China. Owing to 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 also for tap water in the summer.

It is very important for 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.

5.3 Iceland as an active international partner

Capacity building and transfer of technology are key issues in the sustainable development of geothermal resources. Many industrialised and developing countries have significant experience in the development and operations of geothermal installations for direct use and/or electricity production. It is important that they open their doors to newcomers in the field. We need strong international cooperation for the transfer of technology and the financing of geothermal development in order to meet the Millennium Development Goals and tackle the threats of climate change.

Iceland has made a significant contribution to transfer technology from its geothermal industry to other countries, to enable them to build up capacity in geothermal science and engineering. The Government of Iceland and the United Nations University (UNU) decided in 1978 to establish the UNU Geothermal Training Programme in Iceland (UNU-GTP). Specialized training is offered in geological exploration, borehole geology, geophysical exploration, borehole geophysics, reservoir engineering, chemistry of thermal fluids, environmental studies, geothermal utilization, and drilling technology (www.os.is/unugtp/). The aim is to assist developing countries and Central and Eastern European countries with significant geothermal potential to build up groups of specialists covering most aspects of geothermal exploration and sustainable development. The UNU-GTP is financed mostly by the Government of Iceland.

The Government of Iceland has secured core funding for the UNU-GTP to expand its capacity-building activities by holding annual workshops/short courses in geothermal development in selected countries in Africa (these started in 2005), Central America (these started in 2006), and later in Asia (where they will probably start in 2008).

In many countries in Africa, Asia, Central America and Central and Eastern Europe, UNU-GTP graduates are among the leading specialists in geothermal research and development. They have been very successful, and have contributed significantly to energy development in their parts of the world.

Icelandic geothermal experts have been on missions of various lengths (ranging from a few weeks to several years) to over 70 countries around the world. The countries are: Albania, Algeria, Argentina, Azerbaijan, Bulgaria, Burundi, Cape Verde, Canada, Chile, China, Costa Rica, Croatia, Djibouti, Egypt, El Salvador, Eritrea, Ethiopia, the Faeroes (Denmark), France, Georgia, Germany, Greece, Greenland, Guadeloupe (France), Guatemala, Honduras, Hungary, India, Indonesia, Iran, Jordan, Kenya, North Korea, Le Reunion (France), Lithuania, Madagascar, Macedonia, Malaysia, Martinique (France), Mongolia, Nepal, New Zealand, Nicaragua, Norway, Panama, Papua New Guinea, the Philippines, Poland, Portugal (Azores), Romania, Russia, Saba (Dutch Antilles), Salomon Islands, Serbia, Slovakia, Slovenia, St. Lucia, St. Vincent, Syria, Sweden, Taiwan, Tanzania, Thailand, Tunisia, Turkey, Uganda, USA, Vanuatu, Vietnam, Yemen, and Zambia.

In the beginning most of the missions were for United Nations agencies, but the number of projects with direct contracts between Icelandic companies and agencies/companies in the respective countries has grown steadily during the last fifteen years and has been accelerating over the past few months.

The projects have involved project management, geothermal exploration, drilling and well testing, field development, reservoir evaluation and resource management, design and construction of geothermal power stations and district heating systems and also specialist courses on various aspects of geothermal research and development.

6. THE GEOTHERMAL POTENTIAL OF THE UNITED STATES

It is not generally known that the United States is the global leader in geothermal electric power production. Production in the US came to about 18,000 GWh_e in 2005, out of a world total of about 57,000 GWh_e. For comparison, the Philippines ranked number two with about 9,200 GWh_e and Iceland number 8 with about 1,500 GWh_e. Direct use of geothermal energy is also considerable in the US. It is ranked number three after China and Sweden and contributes about 8,700 GWh_{th} to the World total of 75,900 GWh_{th}. Table 1 shows the top 10 countries in geothermal energy utilization.

Electricity Production (2005)	In GWh electric	Direct Use (2005)	In GWh thermal
United States	17,917.00	China	12,604.6
Philippines	9,253.00	Sweden	10,000.8
Mexico	6,282.00	United States	8,678.2
Indonesia	6,085.00	Turkey	6,900.5
Italy	5,340.00	Iceland	6,806.1
Japan	3,467.00	Japan	2,861.6
New Zealand	2,774.00	Hungary	2,205.7
Iceland*	1,483.00	Italy	2,098.5
Costa Rica	1,145.00	New Zealand	1,968.5
Kenya	1,088.00	Brazil	1,839.7
Sum of Top 10	**54,834.00**	**Sum of Top 10**	**54,124.5**
All Other	**1,952.00**	**All Other**	**19,978.7**
World Total	**56,786.00**	**World Total**	**75,942.9**

Table 1: *The US compared to the top 10 countries in geothermal energy utilization.*

Geothermal electric power plants are located in California (2,492 MW), Nevada (297 MW), Utah (26 MW), Hawaii (35 MW) and Alaska (0.4 MW) with current installed gross geothermal capacity at about 2,851 MW

6.1 US Geothermal Capacity in Perspective

The total installed capacity in North America is about 3,517 MW, of which 2,851 MW is installed in the US and 666 MW in Mexico. Globally, the installed capacity is about 8,933 MW (8,9 GW). The total potential for North America is considered to be 30,000 MW (30 GW), which means that only 12% of the estimated potential is now being utilized (Glitnir Energy Research, 2007 and Geothermal Energy Association, 2007).

Active volcanoes and high-temperature geothermal systems are manifestations of terrestrial energy flow from the mantle to the surface of the Earth. The volcanic and geothermal activity is more intense at plate boundaries than within the tectonic plates and the distribution in the world in fairly well known.

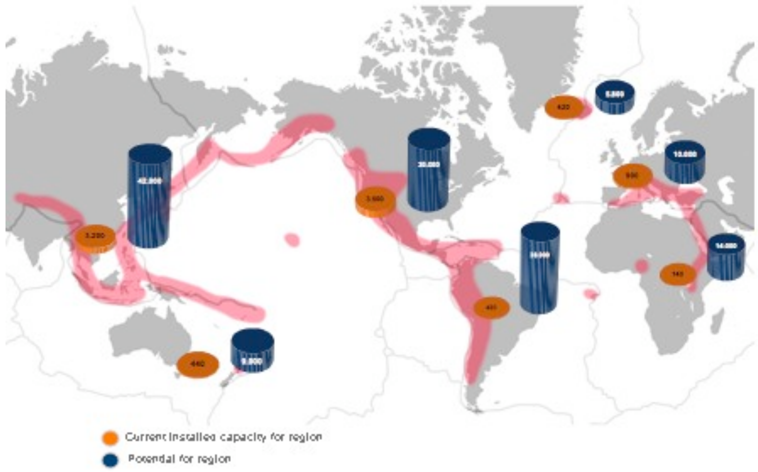

Fig. 6 World map showing volcanic and geothermal activity, the associated tectonic plate boundaries and the current installed geothermal power capacity and potential in various regions (Glitnir Energy Research, 2007).

	Installed Capacity (MWe 2005)	Potential (MWe)
North America	3,517.00	30,000
Asia	3,290.30	42,000
Europe	1,124.40	15,800
Oceania	441.20	9,000
Central & South America, Carribean	424.00	38,000
Africa	136.30	14,000
World Total	**8,933.20**	**148,800**

Table 2: *Global geothermal capacity and potential.*

The world potential for geothermal electric power generation is estimated at about 148,800 MW, or 149 GW. The figures presented here are considered to be conservative, since geothermal assessments have only been carried out for a limited number of countries and regions. Theoretical considerations based on the situation in Iceland and the US reveal that hidden resources suitable for electric generation are expected to be 5-10 times larger than the estimate of identified resources (Stefansson, 2005). The production potential presented here only takes account of the current state of technology, and not Enhanced Geothermal Systems or Hot Dry Rock techniques.

According to the MIT report "The Future of Geothermal Energy", geothermal energy from Enhanced Geothermal Systems (EGS) in the United States could have a major impact on the national energy outlook. According to the report, this energy could provide over 100 GW of cost-competitive base-load electricity in the next 50 years.

Unfortunately, the utilization of EGS is not yet considered cost-effective but significant advances towards commercial viability have been demonstrated in international projects (e.g. in Germany and Australia). This has led US experts to become optimistic about achieving commercial viability in the US, given reasonable governmental investments to support research, development and demonstration projects over the next 10 to 15 years.

The main areas in which R&D needs to be focused in the United States are drilling technology (drilling through high-temperature rocks), power-conversion technology (broadening the temperature range that can be utilized) and reservoir technology (stimulating flow through reservoirs and improving downhole pumps). Successful demonstration projects are needed for future growth of the industry.

6.2 Current Projects and Potential

The current installed geothermal capacity in US is about 2,851 MW in five states: California, Nevada, Utah, Hawaii and Alaska, with Idaho and Wyoming soon to be added to the list. Most geothermal activity is in California and Nevada, which have the greatest geothermal potential. At least 69 geothermal projects are in the initial drilling exploration, production drilling or construction phase. Of these projects, 31 are in Nevada. The estimated generation capacity of these projects is about 2,500 MW.

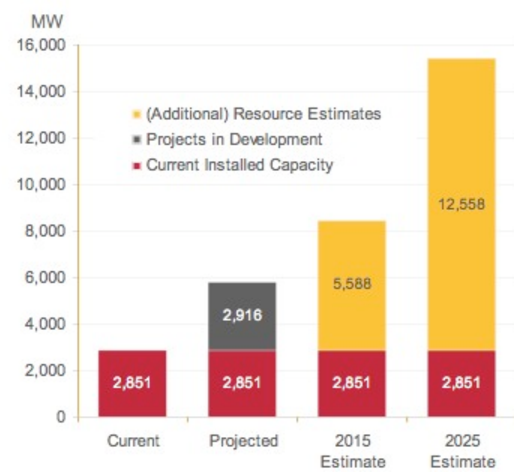

Fig 7 US Geothermal installed capacity estimates (Glitnir Energy Research, 2007).

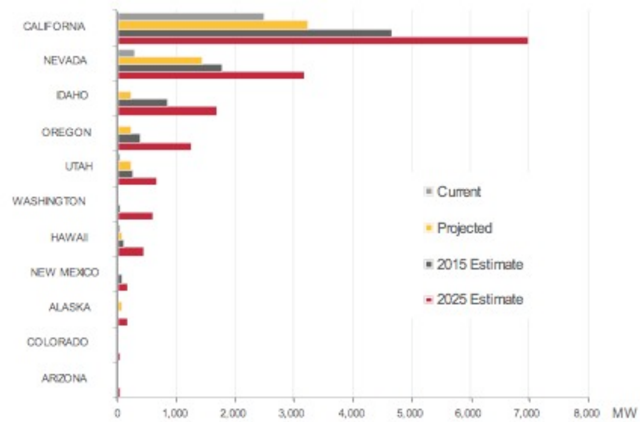

Fig 8 Current installed geothermal capacity by states and projected estimates (Glitnir Energy Research, 2007).

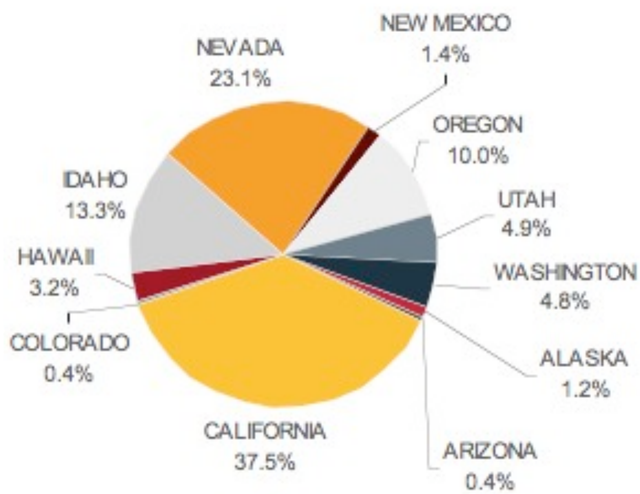

Fig 9 Exploitable geothermal resource estimates in the US, by states (Glitnir Energy Research, 2007).

6.3 The kinds of expertise and cooperation needed using current technology

The keys to successful geothermal development are efficient and comprehensive interdisciplinary geothermal research (both during the exploration and production phases), together with proper resource management during utilization. Today, Iceland is producing electricity from geothermal resources at a cost of about 2-3 US cents per kWh – as compared to some 7-9 US cents/kWh for most geothermal plants in the USA. There may not be one single reason for this discrepancy, rather it may be due to a combination of several factors.

One important difference between the USA and Iceland is that in Iceland, wherever applicable, a “holistic approach” is used to harness geothermal resources. This means using a sequence of applications so that as much energy as possible is extracted out of the ground before disposing of the spent geothermal fluid. Starting with electricity production from the flashed geothermal steam, or from turbines using binary heat-exchangers, the heat content of the fluids is exploited in industrial processing, domestic space heating, greenhouse heating, fish farming, snow melting, etc., before the fluid is finally disposed of.

This concept can be taken a step further, e.g. by cultivating algae on a large scale using both geothermal warm water and CO_2 to induce growth. The algae can then be used as food for aquatic life-forms, or to produce bio-fuel by utilizing the geothermal steam, and so on.

The holistic approach does not stop there; in Iceland, tourism is linked to the geothermal production plants, with balneology, health centres, cultural and educational centres, and cosmetic products based the geothermal chemicals, and so on. There is no limit to the spin-offs.

Probably the best Icelandic example of this holistic approach is demonstrated by the Svartsengi power plant, which produces both electricity and hot water for domestic space heating. The geothermal effluent from the plant has been used to create the world famous "Blue Lagoon", with multiple spin-off revenues in health care, cosmetics, tourism and education.

While a holistic approach of this kind, with a large component of space heating, may be more suitable in a relatively cold country like Iceland similar approach could also be applied in parts of the USA that have a warmer climate, e.g. by using the effluent energy for large-scale cooling and refrigeration and other spin-offs tailored to the specific environment.

Another important characteristic of the Icelandic geothermal industry is a willingness to share information, rather than keeping it proprietary. There is hardly any closed file; almost everything is published one way or another, and experience and expertise are carried from one geothermal field to the next, to the mutual benefits of all the energy companies involved. More or less the same geoscience companies serve the whole industry, and geoscientists in different disciplines work hand-in-hand from exploration to production. This culture may be partly related to the smallness of the nation – but essentially, open-file reporting has little to do with population size.

Yet another factor needs to be mentioned. In geothermal prospecting worldwide, some targets are easy to reach and others are less so. Many of the most accessible and attractive geothermal prospects, in locations such as national parks and reserves, etc., must be left intact due to ever-growing environmental restrictions, while others which are less promising can only be approached after protracted and costly permitting procedures. This affects the overall economics of the industry.

In one sense, it seems somewhat paradoxical that, at the same time we are seeking sources of green and renewable energy in order to reduce the emission of greenhouse gases, we are also limiting their development by environmental regulation which, in some cases, may be unduly restrictive. Different, and probably more costly, measures will be necessary to resolve this environmental dilemma. International collaborative efforts on environmental issues of the geothermal industry would be desirable.

7. AREAS OF POSSIBLE US-ICELANDIC COOPERATION

7.1 Geothermal Exploration and Assessment

The 1970s resource estimates by the United States Geological Survey indicated that low- to medium-temperature geothermal resources are located widely throughout the USA, but many of them were not economic. Given the escalating cost of competing fossil fuels since then, a re-evaluation of the nature, extent, and economic potential of these resources would be prudent.

There are considerable known conventional high-temperature geothermal resources in the western states, and also in Hawaii and Alaska. Most are associated with young volcanic rocks, which should be attractive targets for the generation of electric power. In some of these locations geothermal production is already taking place, including California where 5% of the installed electrical generating capacity is geothermal. More effort is evidently needed to remove technical, regulatory, environmental, and fiscal barriers to the further economic development of these resources.

However, to make a really significant impact on the overall renewable energy picture, new approaches to geothermal development will be necessary. In the USA a recent comprehensive assessment of the potential for "enhanced" or engineered geothermal systems (EGS) within the USA, indicates that a cumulative capacity of more than 100,000 MWe from EGS can be achieved in the United States within 50 years with modest government investment.

In Iceland, a different approach to the future of geothermal energy is under way; this involves investigation of the economic potential of producing supercritical geothermal resources by the Iceland Deep Drilling Project (IDDP). Supercritical geothermal production, in which water and vapour are in the same phase under heat or pressure, is an especially attractive component of enhanced geothermal systems. The environmental and economic incentive is to produce an order of magnitude more energy from geothermal wells occupying the same area as conventional resources, but at less than half an order of magnitude of increased cost.

Such deep, unconventional, geothermal resources (DUGRs) are not restricted to Iceland. For example, in the USA, the resource base of conventional hydrothermal resources is estimated to be 2,400-9,600 Exajoules (1 EJ = 10^{18} J), whereas the supercritical volcanic EGS resource base is estimated to be as much as 74,100 EJ, excluding geothermal systems in national parks (DOE, 2007). A systematic survey of the potential of DUGRs in the USA is therefore desirable, and plans should be developed to investigate these potentially large resources further.

Despite the fundamental differences between the geology of Iceland and the United States, there are topics where collaboration would be of mutual benefit, in data sharing, e.g. on methods of geophysical exploration and assessment of both low-temperature, high-temperature, and Deep Unconventional Geothermal resources. As an example, one such cooperative venture between universities in North Carolina and Iceland GeoSurvey geoscientists on geophysical methods in geothermal exploration has been in progress for some years now.

7.2 Drilling technology

Drilling technology is another area where cooperation between the USA and Iceland is needed. The development and application of the drilling techniques involved in the multilateral completion of wells is an example. These have been developed by the oil industry, but seldom in the geothermal industry.

Multilateral completions are used to improve output when the well yield is inadequate. In this way, the heavy investment in steel casings and cement in the upper parts of such well are not lost. This is not a common practice in the geothermal industry. However, one can envisage scenarios where the drilling of such multilateral wells would lead to considerable economic improvement, at the same time having lower environmental impact by reducing the need for surface installations.

Other possible areas for cooperation in drilling involve advances in coring techniques in exploration and research wells, for example in relation to the IDDP. Continuous core drilling is slow and extremely costly compared to conventional rotary drilling which is used almost exclusively in the geothermal industry.

Similarly, cooperation on improving techniques of well stimulation would be desirable. Other technical developments of mutual interest that are greatly needed are in the areas of high-temperature logging, measurement while drilling, and downhole fluid sampling. Sandia National Laboratory (SNL) in the USA has had a long-term programme of technological development in these areas. Further collaboration between SNL and Icelandic geothermal scientists would be highly desirable.

7.3 Science and research

In Iceland there is a healthy collaboration between government and industry that could provide numerous opportunities for participation by US government agencies. One excellent example where the USA is already cooperating with Iceland in geothermal research is the Iceland Deep Drilling Project (IDDP).

In 2005, the United States National Science Foundation committed USD 3.2 million to support the acquisition and scientific study of drill core samples to be recovered by the IDDP. This has enabled a team of US investigators to participate in the project.

Further cooperation between the DOE, the USGS, and the NSF and the Icelandic GeoSurvey (ISOR) and the National Energy Authority of Iceland (Orkustofnun) on scientific investigation as part of such advanced geothermal research and development projects would be mutually beneficial.

Iceland is a favourable locale for scientific studies related to geothermal systems. For example, more than 100 international scientists and engineers are already involved in the IDDP project, in collaboration with the Icelandic energy industry. Many of these scientists and engineers are from US universities and institutes, which will draw funds from domestic US sources. The US NSF is already supporting some of these scientists, and also a considerable part of the cost of core drilling for scientific studies.

7.4 Technological advancement

The success of the geothermal industry is partly linked to the use of long-proven technology. Nevertheless, there is always a need for improvements. On the cost-effectiveness side, advancement in casing technology and cementing technique in drill holes would be most beneficial.

The IEA International Implementing Agreement on Geothermics is an example of an international effort that could lead to technological advancements in drilling and geothermal harnessing. Within the US, one of the roles of the Geothermal Department of the DOE has been to participate in this implementing agreement. Drilling costs is one of the chief factors affecting the geothermal economy.

7.5 Management of geothermal resources

Some cooperative studies involving US scientists and engineers and their Icelandic counterparts are already under way in the areas of reservoir management, reservoir modelling and tracer techniques. In most cases water or steam extraction from a geothermal reservoir causes some decline in reservoir pressure.

The only exception is when production from a reservoir is less than its natural recharge. Consequently, the pressure decline manifests itself in further changes, such as temperature conditions (cooling), phase conditions (increased boiling), chemical composition, surface manifestations and land elevation (subsidence).

The energy production potential of a geothermal system is not only dependent on the available energy in the ground, but is predominantly determined by this pressure decline. The pressure decline is determined by the rate of production, on the one hand, and the nature and properties of the system, on the other.

Comprehensive and efficient management is an essential part of successful geothermal resource utilization. Such management implies controlling the energy extraction from the geothermal system so as to maximise the resulting benefits, without over-exploiting the resource.

Geothermal resource management involves deciding between different courses of action, and the operators must have some idea of the possible outcome of the different alternatives. Geothermal resource management is a field where co-operation between the US and Iceland has the potential to be very fruitful because geothermal fields have common characteristics and the experience of utilizing one field may be of benefit to operators of other fields.

Modelling the nature of a geothermal system is one of the most powerful tools available for resource management in order to understand and predict its behaviour. Reservoir models are also helpful in estimating the outcome of different management actions. The field of numerical geothermal modelling has evolved greatly during the last two decades. A lot of the relevant development of methods and tools has taken place at the Lawrence Berkeley Laboratory in California. A significant contribution to this effort has come from co-operation with Icelandic scientists and the modelling of Icelandic geothermal systems.

Reinjection is an integral part of any sustainable and environmentally-friendly geothermal utilization, both as a method of waste-water disposal and to counteract pressure draw-down by providing artificial water recharge (Stefánsson, 1998, 2005). Reinjection is essential for sustainable utilization of geothermal systems that have limited natural recharge. However, one of the dangers associated with reinjection is the cooling of production wells, but this can be minimised through careful testing and research. Tracer testing, combined with comprehensive interpretation, is probably the most important tool for this purpose. Some significant advances in tracer testing techniques have come about through US-Icelandic co-operation, and these need to be developed further.

Sustainable geothermal utilization involves energy production at a rate which may be maintained for a very long time, such as 100-300 years (Axelsson *et al*., 2004). This requires efficient management in order to avoid overexploitation, which mostly occurs because of lack of knowledge and poor understanding, and also in situations when many users draw on the same resource without common management. An example of the latter is at the Geysers Geothermal Field in California.

Geothermal resources of highly variable nature may be managed in a sustainable manner. Good examples are the vast geothermal resources in sedimentary basins in different parts of the world (Axelsson *et al.*, 2004). Further cooperation between US and Icelandic geothermal engineers in the area of resource management would be mutually beneficial.

7.6 Business aspects and financing of projects

One field where Icelandic companies have scored greater success than their counterparts elsewhere is that instead of the renewable energy companies being heavily subsidised by taxpayers' money, they generate substantial revenue for their owners. This means that the resources are well managed from the financial point of view.

Recently, Icelandic financial institutions have decided to put emphasis on financing and investing in geothermal projects world-wide. One of Iceland's largest banks, Glitnir Bank, has stated that sustainable energy will be one of the three main fields of expertise on which it focuses globally. The bank took part in establishing an investment company, called Geysir Green Energy, which has been actively looking for opportunities in the United States. Iceland-America Energy is a geothermal company with projects under way in California and elsewhere. Its mother company, Enex, has also been active in many countries.

Reykjavik Energy is probably the best known Icelandic geothermal company. It has grown into becoming Iceland's largest power company, overtaking the National Power Company last year, which mainly is involved in hydropower. Reykjavik Energy has founded an investment company, Reykjavik Energy Invest, which has ambitious plans in the sphere of developing geothermal resources in the world and is participating in projects in the Philippines, Indonesia, Djibouti and elsewhere.

Icelandic geothermal energy companies are open to partnerships with leading financial institutions and developing companies for their overseas operations, and this could become an interesting area in the cooperation between Iceland and the United States.

7.7 CO2 capture and sequestration – zero-emission power plants

According to data from Kagel *et al*. (2005) the average emission of CO_2 from fossil-fuelled electric power plants in the USA is about 620 kg/MWh, whereas the average emission of CO_2 from a flashed steam geothermal plant is only 27 kg/MWh. Nonetheless, one environmental impact of geothermal production is the emission of some undesirable gases to the atmosphere, and the major geothermal gas is CO_2. Therefore, reduction in its emission is a desirable goal in geothermal utilization.

Wells already drilled for reinjection of liquid have been made available by Reykjavík Energy for mineral sequestration studies in an attempt to devise a new way of disposing of the CO_2. At the same time, studies are under way as regards the disposal of H_2S, the other troublesome gas emitted by geothermal plants, and there is a good chance that both these studies may lead to the establishment of a "zero-emission power plant." The studies are being done in collaboration with US scientists from Columbia University, among others.

A possible means of storing CO_2 underground is to use chemical bonding of injected CO_2 in a mineral phase. Igneous rocks such as basalt provide the necessary base cations to effect the precipitation of carbonate minerals from injected CO_2-saturated fluids (See, e.g., Matter *et al*., 2007). Upon injection into basalt aquifers, CO_2 will acidify the groundwater and the acid will be neutralized by water-rock reactions, where, for example, the Mg^{+2} and Ca^{+2} released supply cations that react with the dissolved CO_2 to form carbonates.

Even though the physical and hydrological conditions in the geothermal reservoirs are not the most favourable conditions for CO_2 mineral sequestration, results of determination of calcite in high temperature geothermal boreholes can nevertheless provide critical background information for the planning of field-scale CO_2 mineral sequestration experiments. Such determinations have been carried out in some geothermal areas in Iceland and suggest that a significant portion of CO_2 is captured, and that experiments under more favourable conditions should be worthwhile (Ármannsson *et al.* 2007).

Planned studies of sequestration at Hellisheiði in Iceland will be done under more favourable conditions than in previous studies already carried out, i.e. at lower temperatures, and will be designed so as to obtain as much information as possible. The results of this experiment will not only be of use in geothermal studies but also to any emitter of CO_2 that can use the results to devise a possible means of disposal of CO_2 by sequestration in basalts. This is another area where US-Icelandic cooperation would be desirable.

8. NEW TECHNOLOGY DEVELOPMENTS – THE NEXT PHASE OF SCIENTIFIC EXPERTISE

8.1 Deep Drilling

Studies indicate that it would be possible to increase the output of high-temperature geothermal fields ten times, without increasing their area, by producing supercritical geothermal fluids, at higher temperatures and pressures and from much deeper wells than are currently used. Thus, the Iceland Deep Drilling Project (IDDP) is investigating the technical and economic feasibility of producing energy from such supercritical geothermal systems on land in Iceland, similar to those responsible for black smokers associated with mid-ocean ridge hydrothermal systems.

In Iceland this will require drilling to depths of 4 to 5 km in order to reach temperatures of 400–600°C. It is estimated that wells producing supercritical fluid would have an energy output ten times greater than conventional shallower geothermal wells.

This project is being funded by a consortium of three Icelandic energy companies, the US aluminium company Alcoa, and the Government of Iceland. If this project proves successful, it could lead to a major step forward in the economics of developing high-temperature geothermal resources by developing DUGRs worldwide.

The IDDP has engendered considerable international interest. The International Continental Scientific Drilling Program (ICDP) and the US National Science Foundation (NSF) are contributing funds to this program. There could be a role for an interagency group of US organizations (NSF/DOE/USGS) to play in the IDDP. Similarly, Icelandic scientists and engineers could collaborate with these agencies in the investigation of DUGRs in high-temperature geothermal fields in the USA, for example at the Geysers Geothermal Field in California and in many other high-temperature systems in the USA.

Drilling to produce a supercritical fluid of an unknown chemical composition presents a dilemma. The fluid need to be sampled and chemically analyzed before proper material with respect to scaling or corrosion can be selected for heat-exchangers or power generators. The choice of technology to be applied for power generation cannot be decided until the physical and chemical properties of the fluid have been determined. Nonetheless, it appears likely that the fluid will be used indirectly, in a heat-exchange circuit of some kind. In such a process the fluid from the well would be cooled and condensed in a heat-exchanger and then injected back into the field. This heat-exchanger would act as an evaporator in a conventional closed power-generating cycle. There are numerous opportunities for US agencies to participate in this advanced engineering project.

8.2 Hot Dry Rocks – Enhanced or Engineered Geothermal Systems

During the last two decades or so, several projects have been aimed at heat mining by injecting cold fluid into hot rocks. Considerable work has been done on inducing steam production in declining operational geothermal fields by injecting cold water into deep boreholes, e.g. in the Geysers Geothermal Field in California. These heat-mining projects have operated under different names, such as “Hot Dry Rocks (HDR)”, “Hot Wet Rocks

(HWR)", "Hot Fractured Rock (HFR)", "Enhanced Geothermal Systems (EGS)" or "Engineered Geothermal Systems (EGS)", and have been tested to various extents in the USA, Europe and Japan. Heat mining by injecting cold fluid into hot rocks is common to all these projects. In Europe the hot rock temperatures tested at 4-5 km depths ranged from 200-300°C; in the USA they were from 300-400°C and above 500°C in Japan.

Recently, the IDDP added the acronym DUGR [for Deep Unconventional Geothermal Resources] to the list of acronyms above, in an attempt to distinguish geothermal reservoirs at supercritical conditions from HDR, HWR, HFR or EGS. DUGRs have temperatures in the 400-600°C range, and can produce supercritical fluids, if permeable zones are intersected by drilling.

The greatest unknowns in the DUGR systems are uncertainty about fluid composition and the permeability properties. We do not know how permeable fracture systems respond to production at semi-brittle temperatures, i.e. at 500-700°C in basaltic rocks and at 400-600°C in volcanic rocks of rhyolitic to intermediate chemical composition. If drilling a DUGR intersects a supercritical system of marginal permeability, then the possibility of using the EGS approach should be considered.

Injection of cold water to induce fracture permeability (hydro-fracturing) might be a more productive way of utilizing a DUGR system than simply attempting to flow the supercritical reservoir fluid directly. Given the much higher enthalpy of the DUGR systems, the power output available would be much higher than that produced by any EGS existing to date. The experience gained in investigating DUGRs in Iceland will be directly transferable to the USA.

8.3 Ocean floor drilling – Advanced technology

Considerable advances have been made in drilling technology within the oil and gas industry by developing the technology in drilling what has been called multilateral completion of wells (branched or fingered wells). This technology has been developed in order to harness relatively thin oil-yielding zones, e.g. in permeable sandstone beds of only a few metres' thickness, at great depths beneath the sea floor.

A similar approach, using the technology of multilateral wells, could open new dimensions in harnessing geothermal resources, e.g. in environmental sensitive fields, and should be considered closer by geothermal prospectors.

The opportunity exists for a very comprehensive scientific programme, investigating the anatomy of a mid-ocean rift system by combining land–based and ocean-based deep borehole studies with complementary geological and geophysical and seismic imaging studies and putting the drilling activities into a broader regional geological context.

8.4 Technology projects – What is in the pipeline?

There are numerous areas of research and development by the geothermal industry in the USA and Iceland where collaboration would be highly desirable. For example, deep drilling to produce high-temperature and high-pressure hydrous fluid requires advanced drilling technology – special casing materials and advanced cementing techniques. Conventional and proven technology needs be improved.

The most sensitive parts in a drillhole, with respect to its performance and lifetime for production, are the steel casings and cementing integrity. Improper casing selection and handlings, poor cementing jobs, or too frequent thermal cycling, may all lead to well failure. The casing in DUGR wells need be stressed to the limits of material tolerance due to the extremely high pressures and temperatures involved.

Steam turbines for high-temperature and high-pressure supercritical steam require heat-exchangers for electricity production. Depending on the fluid geochemistry, advanced corrosion and scaling studies may be required before power can be produced economically from the DUGR systems. Cooperative research projects and pilot studies would not only be beneficial to US-Icelandic collaborators, but to the geothermal industry at large.

Development and deployment of advanced downhole logging and fluid sampling tools for use at high fluid pressures and temperatures is needed to deal with the DUGR systems. Discussions about collaboration between Sandia National Laboratory (through the DOE) and the IDDP on this topic have been in progress since 2002. Unfortunately, this collaboration has not been realized yet due to lack of funding from the US side.

However, a less ambitious collaboration for downhole tool development and testing has been established between Iceland and several European countries, funded by the European Commission. Some of the tool components to be used have been developed and tested by Sandia.

At the moment, only a few of the available downhole tools so far developed can withstand the range of temperatures that will be encountered in the DUGR systems. Advances in high-temperature tool development and monitoring technique are badly needed.

In addition to investigations and sampling of fluids at supercritical conditions, the IDDP will permit scientific studies of a broad range of important geological issues, such as investigation of the development of a large igneous province, and the nature of magma-hydrothermal fluid circulation on the landward extension of the Mid-Atlantic Ridge in Iceland.

Furthermore, the IDDP will require use of techniques for high-temperature drilling, well completion, logging, and sampling, techniques that will have a potential for widespread applications in drilling into oceanic and continental high-temperature hydrothermal systems.

The addition of a scientific program to the industry-driven IDDP drilling venture has obvious mutual advantages. The IDDP provides opportunities for scientists to become involved in an ambitious project that has a budget larger than can be funded by the usual agencies that fund scientific drilling on land. In turn, the industrial partners will benefit from strong scientific contributions that will expand opportunities for innovation and provide a perspective that can be of critical importance in the context of poorly understood natural systems such as supercritical geothermal reservoirs. Clearly, improved collaboration between the USA and Iceland in these diverse scientific and technical areas will be mutually beneficial.

CONCLUSION

I hope that in this testimony I have managed to demonstrate how geothermal resources can significantly contribute to the emerging clean energy economy of the United States and thus strengthen the security of the country.

In order to achieve this goal in the coming years, cooperation between Iceland and the United States can play an important role. I have outlined a number of areas where such cooperation on technical, scientific and business projects is either already taking place or could be speeded up and enhanced with the creation of a supporting network. The result would be to enhance tremendously the utilization of geothermal power in the United States.

In this process the US Senate and the House of Representatives could, and must, play an important role.

I hope that my testimony and our willingness in Iceland to provide further information and to engage in the necessary cooperation will help the Congress in its important deliberations.

This new energy cooperation between Iceland and the United States would be a great homage to our long-standing alliance and friendship.

I am deeply grateful to the following experts who have assisted in preparing my testimony:
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