Deep Unconventional Geothermal Resources: a major opportunity to harness new sources of sustainable energy

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ABSTRACT

The 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 (DUGR). 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 long-term plan is to drill and test a series of such deep boreholes in Iceland at the Krafla, the Hengill, and the Reykjanes high temperature geothermal 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. Modeling 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.

1 INTRODUCTION

1.1 The Iceland Deep Drilling Project (IDDP)

The Iceland Deep Drilling Project was implemented in 2000 by an Icelandic energy consortium, Hitaveita Sudurnesja Ltd. (HS), Landsvirkjun (LV), Orkuveita Reykjavikur (OR) and Orkustofnun (OS). Representatives from these companies compose the steering committee of IDDP, called Deep Vision (DV). The principal aim of the IDDP is to enhance the economics of high temperature geothermal resources by producing from deep reservoirs at supercritical conditions. In June 2000, at the World Geothermal Congress in Japan, the IDDP idea was presented to the geothermal community with an invitation for international collaboration (Fridleifsson and Albertson, 2000). This resulted in a widespread international interest and the establishment of an international Sciences Application Group of Advisors (SAGA). To date, six international workshops have been held in Iceland, and a central science team established with participation, from Iceland, USA, Japan, New Zealand, Italy, Germany and France. Other scientists and geothermal experts involved are from Russia, Spain, Norway, UK, Luxemburg, Greece, Turkey and Portugal. Some 40-50 research proposals and 100-150 scientists and their students are currently active in the project. Some research projects have already begun, while others wait for the first IDDP deep drillhole to be drilled.

A feasibility study on the IDDP concept was concluded in 2003 and presented later the same year at an International Geothermal Conference in Reykjavík (Elders et al. 2003, Fridleifsson et al. 2003 a, b, c, Albertsson et al. 2003 a, b, Thorhallsson et al. 2003 a, b). The Feasibility Report is available at the IDDP website: http://www.iddp.is/.

Over the next several years the IDDP plans to drill a series of boreholes to penetrate into supercritical fluids believed to be present beneath three currently exploited geothermal systems in Iceland (**Figure 1**). This requires drilling to depths greater than 4 to 5 km, and sampling hydrothermal fluids at temperatures of 450 to 600°C. The physics and chemistry of natural supercritical geothermal fluids in the Earth’s crust are of great interest, while hitherto no attempts have been made to put such natural supercritical fluids to practical use. Study of the supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of “fossil” supercritical systems exposed in mines and outcrops. The IDDP will drill deep enough into already known geothermal reservoirs in Iceland to reach supercritical conditions believed to exist at depths. Iceland is a particularly favorable location for research on supercritical fluids as seismic and volcanic activities in an environment of active rifting create high permeability and high temperatures at drillable depths.

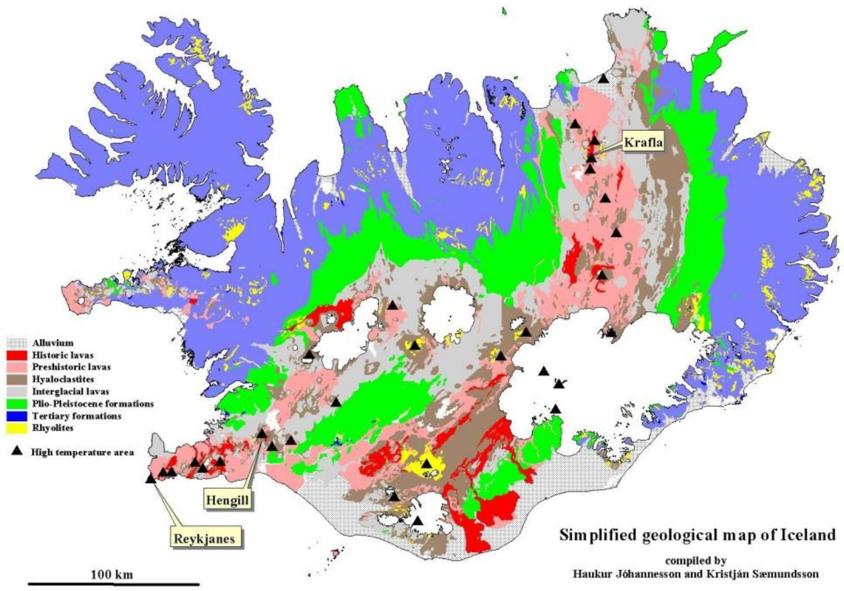

Figure 1. A geological map of Iceland showing the location of the three high-temperature hydrothermal systems being considered as sites for deep boreholes by the IDDP.

1.2 Utilization of geothermal energy in Iceland

Viewed from an international perspective, energy use in Iceland is in a class by itself. Per capita energy consumption is the highest known, is rising rapidly, and the proportion that is provided by renewable energy sources is greater than in any other country. A large part of the growth in demand in Iceland is due to meeting the needs of the rapidly growing energy-intensive industry of aluminium smelting. Nowhere else does geothermal energy play a greater role in energy supply, as Iceland is among those nations with the highest utilization of this energy resource, not only per capita but also in absolute terms. In addition to geothermal energy, energy supply in Iceland is based on hydropower and imported fossil fuels. The share of renewable and sustainable energy among domestic sources has grown significantly in recent decades and amounts now to over 70% of the total energy consumption. The development of primary energy consumption in Iceland is shown in **Figure 2.**

The main use of geothermal energy in Iceland is for space heating and almost 90% of all houses are heated by this energy source. Other sectors of direct use are swimming pools, snow melting, industry, greenhouses and fish farming. Following the oil price hikes of the 1970s, the government took the initiative in expanding district heating utilities, with the result that the share of geothermal energy in space heating increased considerably. An expansion in the energy intensive industry has led to rapid increase in electricity demand in the country. This has stimulated the development of geothermal power production and resulted in new plants as well as extension of existing plants during the last ten years. In 2006 the total installed capacity of geothermal power plants in the country was 422 MWe.

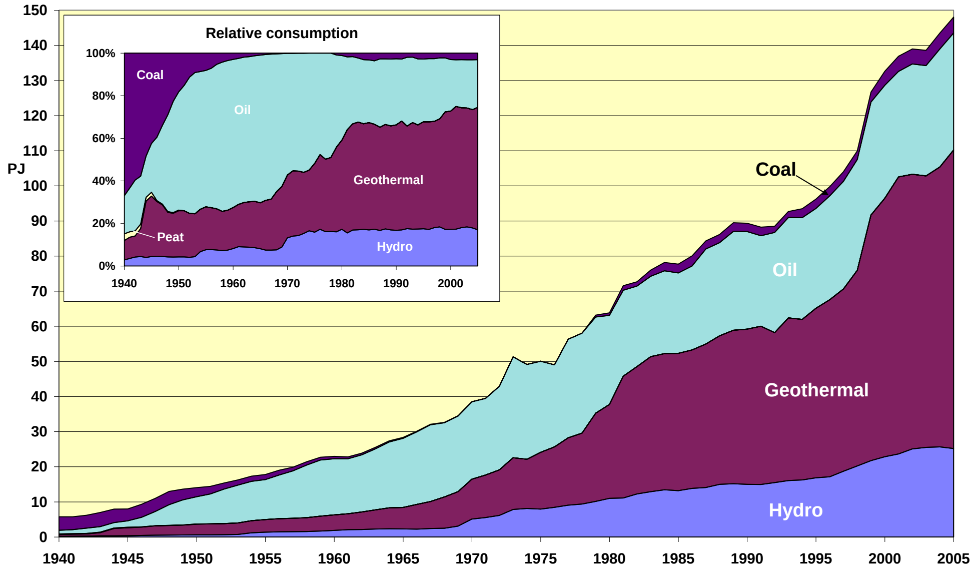

Figure 2. Primary energy consumption in Iceland 1940-2005 in Petajoules (10^{15} J).

Despite the fact that Iceland possesses extensive unexploited energy reserves, they are not unlimited and only very rough estimates are available on their size. This results in considerable uncertainty in assessing their potential to be harnessed with regard to technical economic, and environmental criteria. The generally accepted estimate for potential electricity production from renewable or sustainable resources in Iceland totals 50 TWh per year (1 Terawatt = 10^{12} Watts) consisting of 30 TWh annually of hydropower and 20 TWh annually from geothermal resources. These numbers exclude resources which are unlikely to be developed for environmental reasons. In 2005, electricity production in Iceland amounted to around only 17% of this estimate of potentially harnessable energy (see **Figure 3**). Current utilization of geothermal energy for heating and other direct uses is considered to be only a small fraction of what this resource could provide.

	Hydro	Geo-thermal	Together
Economic and environmentally benign	**30**	**20**	**50**
Harnessed thereof 2005	**7,0**	**1,7**	**8,7**
In relation to econ. + env.	**23%**	**8%**	**17%**

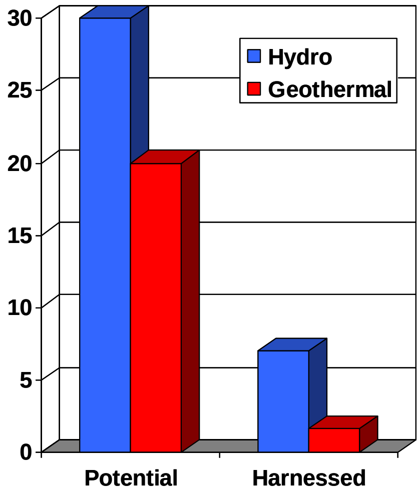

Figure 3. Potential for electricity production in Iceland (in units of TWh/a).

1.3 World utilization of geothermal energy

As a background for discussion of the potential contribution that Deep Unconventional Geothermal Resources (DUGR) could make to the world energy picture, it is worthwhile to review the role that conventional geothermal resources currently play. **Table 1** shows the world primary energy consumption in 2001 (WEA, 2004). Fossil fuels provide close to ~80% of the total, with oil (~35%) in first place, followed by coal (~23%) and natural gas (~22%). The "renewables" collectively provide about 14% of the primary energy, mostly in the form of traditional biomass (9%) and much less by large (>10MW) hydro power stations (~2%) and the "new renewables" (2%). Nuclear energy provides ~7% of the world primary energy.

TABLE 1: World Primary Energy Consumption in 2001.
Source: World Energy Assessment (WEA, 2004) 1 EJ (exajoule) = 10^{18} J.

Energy Source	**Primary energy (exajoules)**	**Percentage**
Fossil fuels	**332**	**79.4**
Oil	147	35.1
Natural gas	91	21.7
Coal	94	22.6
Renewables	**57**	**13.7**
Large hydro (>10 MW)	9	2.3
Traditional biomass	39	9.3
"New renewables" (biomass, geothermal, solar, small Hydro (<10MW), tidal, wind)	9	2.2
Nuclear	**29**	**6.9**
Nuclear	29	69
Total	**418**	**100 %**

Although this compilation of international energy consumption categorises geothermal energy among the "new renewables", it is certainly not a *new* energy source. People have used hot springs for bathing and washing of clothes since the dawn of civilisation in many parts of the world, as is detailed in an excellent book concerning historical records and stories of geothermal utilisation from all over the world (Cataldi et al., 1999).

TABLE 2: Electricity generation and direct use of geothermal energy in 2004.
Data from Bertani (2005), and Lund et al. (2005).

	Electricity generation			Direct Use		
	Installed capacity MWe	Total production GWh/a	%	Installed capacity MWt	Total production GWh/a	%
Africa	136	1088	2	190	763	1
America	3941	26794	47	8988	12119	16
Asia	3290	18903	33	5044	17352	23
Europe	1124	5745	12	13628	42916	56
Oceania	441	2791	5	418	2793	4
Total	**8933**	**56786**	**100**	**28268**	**75943**	**100**

In 2005 on the global scale geothermal resources were identified in some 90 countries, and the statistics of geothermal utilisation exist from 72 countries. Electricity is produced from geothermal energy in 23 countries. In 2004, the worldwide use of geothermal energy was about 57 TWh/a of electricity (Bertani, 2005) and 76 TWh/a for direct use (Lund et al., 2005) (**Table 2**). Geothermal electricity production increased by 16% from 1999 to 2004 (annual growth rate of 3%). Geothermal direct use increased by 43% from 1999 to 2004 (annual growth rate of 7.5%). The main types of direct use 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 fish farming 4% (Lund et al., 2005). During the last decade, the main growth in the direct use sector has been in the 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. Almost all of the installations of the ground-source heat pumps occur in North America and Europe, increasing from 26 countries in 2000 to 33 countries in 2005 (Lund et al., 2005).

Among the top fifteen countries with electricity production from geothermal resources there are ten developing countires (**Table 3**, Fridleifsson, I.B., 2006 a). Similarly among the top fifteen countries with direct use of geothermal resources, there are six developing and transitional countries. There is a large scope for expansion of geothermal utilization in these and tens of other developing countries. The framework of the Millennium Development Goals of the United Nations will hopefully guide speeding up this process.

TABLE 3: Top fifteen countries in geothermal use in 2004 (Fridleifsson, I. B. 2006 a). Data on electricity from Bertani (2005) and on direct use from Lund et al. (2005).

Geothermal electricity production		**Geothermal direct use**	
	GWh/a		**GWh/a**
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

Table 4 shows the top fifteen countries with the highest % share of geothermal energy in their national electricity production (Fridleifsson, I.B. 2006 b). Many of the leading geothermal experts in the top countries have received specialized geothermal training at the United Nations University Geothermal Training Programme (UNU-GTP) in Iceland. The UNU-GTP was established in 1979 and has since 2003 been the only international graduate school offering specialized training in all the main fields of geothermal science and engineering.

The countries of Central America can serve as an example of the development potential that exists in densely populated geographical regions. Special attention is drawn to that El Salvador, Costa Rica and Nicaragua are among the six top countries in Table 4, 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 the four countries Costa Rica, El Salvador, Guatemala and Nicaragua, according to data provided from the countries at 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). With the large untapped geothermal resources and the significant expertise and experience in geothermal development in the region, Central America may become an international example of how to reduce the overall emission of greenhouse gases in a large region (Fridleifsson I.B., 2006 a). This will require considerable human capacity building in geothermal research and development in the region (Fridleifsson, I.B., 2006 b).

TABLE 4: Top fifteen countries with highest % share of geothermal in their national electricity production and number of UNU Fellows trained in Iceland (Fridleifsson, I.B., 2006 b).

Geothermal electricity production			
Country	**GWh/a**	**% national electricity**	**Number of UNU-GTP Fellows**
El Salvador	967	22.0	22
Kenya	1,088	19.2	39
Philippines	9,253	19.1	31
Iceland	1,483	17.2	
Costa Rica	1,145	15.0	13
Nicaragua	271	9.8	5
Guadeloupe (France)	102	9.0	
New Zealand	2,774	7.1	
Indonesia	6,085	6.7	20
Mexico	6,282	3.1	4
Guatemala	212	3.0	3
Italy	5,340	1.9	
USA	17,917	0.5	
Japan	3,467	0.3	
China	96	30% of Tibet	64

The feature that the countries listed in Table 4 have in common is that they have extensive volcanic terrains with numerous high-temperature geothermal systems. If the test of Deep Unconventional Geothermal Resources being carried out in Iceland is successful, then we can anticipate that the geothermal potential of all of the countries listed could increase by a large factor, as is discussed below.

2. SUPERCRITICAL GEOTHERMAL FLUIDS

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

At temperatures and pressures above the critical point, which for pure water is at 221 bars and 374°C, only a single phase supercritical fluid exists. **Figure 4** shows the pressure-enthalpy diagram for pure water, showing selected isotherms (from Fournier 1999). Steam turbines in geothermal plants generate electricity by condensing the steam separated from the two phase field (liquid and steam field in Figure 4) which, depending upon the enthalpy and pressure at which steam separation occurs, is often only 20-30% of the total mass flow. The concept behind the Deep Vision program is to bring supercritical fluid to the surface in such a way that it transitions directly to superheated steam along a path like F-G in Figure 4, resulting in a much greater power output than from a typical geothermal well.

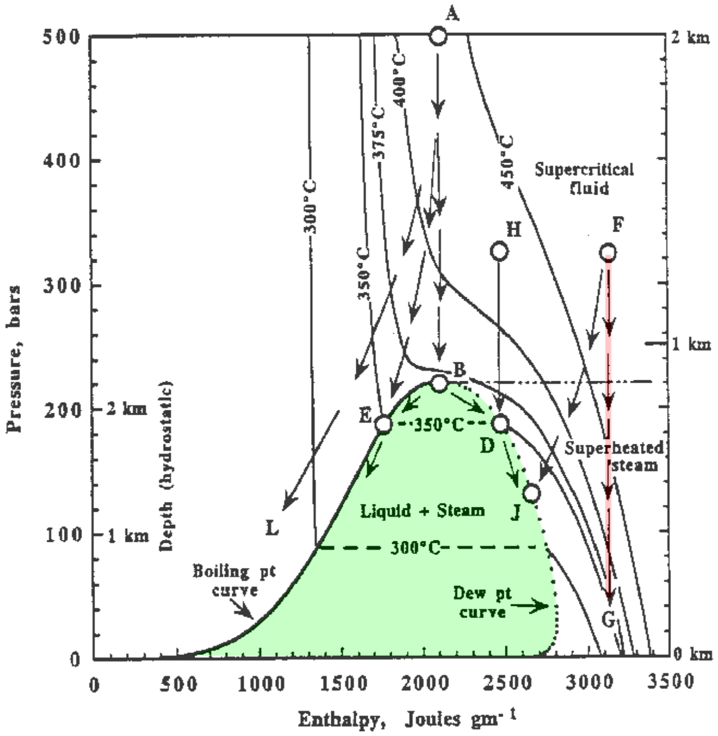

Figure 4: Pressure enthalpy diagram for pure H_2O with selected isotherms. The conditions under which steam and water coexist is shown by the shaded area, bounded by the boiling point curve to the left and the dew point curve to the right. The arrows show different possible cooling paths (from Fournier, 1999).

The depth scales marked at the left and right sides of the diagram correspond to pressures in geothermal reservoirs – respectively controlled by cold water-hydrostatic conditions and by lithostatic load. Cold water is much denser than superheated steam. Thus if the pressure is controlled by cold water, such as on the ocean floor, the critical pressure in a dilute water column would be reached at about 2.3 km depth. That is the reason why >400°C hot hydrous fluids can be expelled directly into the oceans in the black smokers on mid-ocean rifts without boiling occurring. On the other hand, hot water is less dense than cold. If a natural hydrostatic hydrothermal system is boiling from the surface down to the critical point, the maximum pressure and temperature at each depth is determined by the boiling point depth curve (BPD-curve), and the critical point would be reached at about 3.5 km depth. Commonly the BPD-curve controls the maximum P-T in most water dominated high-temperature geothermal systems, while lower temperatures are common. This can simply be due to the dominance of conductive cooling such as the enthalpy pressure path A-L in Figure 4. On the other hand, other scenarios are possible, depending on how the hydrothermal fluid systems couple with magmatic heat sources.

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

The Iceland Deep Drilling Project intends to meet the hostile conditions expected in supercritical geothermal reservoirs by proper well design and by adopting the necessary safety measures. An intermediate cemented casing will be cemented down to 2.4 km before drilling down to 3.5 km depth or deeper to reach the critical point. Once beyond that the production casing will be cemented in order only to produce the supercritical fluid. By releasing the pressure the supercritical fluid will expand and move upwards to the surface through the well bore as superheated dry steam following a path like F-G in Figure 4. The deep casings will prevent the fluid from mixing with the two phase field and by lowering the pressure the less likely condensation occurs. A pilot study for harnessing the fluid will need to be undertaken, especially with respect to the fluid chemistry which will only be known after drilling. Albertson et al (2003 a, b) in the IDDP feasibility study assumed that the superheated steam would be brought into a heat exchanger with a clean water circuit, and then re-injected into the ground. Despite the heat loss, an order of magnitude increase in power output as compared to conventional high-temperature drillholes would be realized by utilizing such a fluid, assuming the same volumetric inflow rate of steam in both cases.

3 DRILLING IDDP WELLS

Conventional geothermal drilling technique will be used in drilling the IDDP wells. In order to meet the major goals set by the project sponsors the first well was designed as a dual purpose hole. Firstly, to meet the engineering goals of the power companies it is designed as an exploration/production well, and secondly, to meet the scientific goals of understanding the supercritical environment, it will be continuously cored in the lowest part of the drill hole, which hopefully will be the supercritical zone.

Initially two wells of different diameters, called designs A and B, were designed and compared in the feasibility study (Thorhallsson et al., 2003 a, b). Design A allows the well, after initial continuous coring of the slim hole, to be reamed to 8 ½” production size and a 7” perforated liner to be inserted. As the IDDP progressed, well design C, was added to meet the option of deepening an existing conventional production well, a so-called “well of opportunity”. In 2003 one of the sponsors, Hitaveita Sudurnesja (HS) offered to allow the IDDP to deepen one of their production wells, RN-17 at Reykjanes and IDDP accepted this offer. HS had that well drilled in autumn 2004 and completed in February 2005 to 3082 m depth. In the meantime IDDP had secured funds from the Icelandic energy consortium sponsors, and from the International Continental Scientific Drilling Program (ICDP) and the United States National Science Foundation (NSF), for deepening well RN-17 in two phases, first by rotary drilling and spot coring to 4 km in 2006, and then to 5 km in 2007 by continuous coring. However this well collapsed during a flow tested by HS in November 2005. It was abandoned in February 2006 after subsequent attempts to recondition the well failed. In April 2006, when it became clear that another suitable well of opportunity at Reykjanes was not immediately available, the IDDP looked at the available options for drilling at the other high-temperature systems. The conclusion was that it was most sensible to drill a new IDDP well, using the well design A of the feasibility study, the widest diameter well program. In June 2006, a provisional decision was made to move the IDDP drill site from the Reykjanes field in SW-Iceland to the Krafla drill field in NE-Iceland (Fig. 1), which is operated by Landsvirkjun (LV). The Krafla geothermal system has higher temperature gradients and more dilute fluid chemistry than the Reykjanes system. In autumn 2006 tenders were solicited for the necessary casings and wellhead valves and fittings, as well as for drilling contractors. The drilling of the first IDDP well is likely to take place in the summer of 2008.

As for the drillhole design, the top part of the anchor casing has to be of special creep resistant steel, but conventional API grade K-55 can be used for other casing strings. The well casing has to withstand extreme temperatures and pressures and the safety aspects received a special attention in the design process. The greatest danger to the casing is thermal cycling, as the steel is stressed beyond the yield point due to limited thermal expansion. The greatest strain on the casing is due to expansion during heating and cooling of the string. The highest strain is expected when the casing string is cooled from flowing conditions to 20°C.

The depth of each casing string was determined, based on expected pressures in a flowing two-phase well, in such a manner as to be able to control underground blow-out conditions with heavy mud of 1.4 g/cm^3 density. Underground blow-out condition means that an internal flow occurs within the well bore from a deep feed zone (fracture) to a shallower feed zone in the hole. Such conditions, for instance, were met in one well of the Hengill drill fields in 1985, involving flowing supercritical or superheated fluid (>380°C hot) from a deep feed zone at 2.2 km depth up to a shallower feed zone at 1.1 km depth (Steingrimsson et al. 1990). The IDDP wells are designed to meet such conditions at all depths and also, if necessary, to flow test such conditions.

Predictions of fluid circulation temperatures show that the drill bits can be cooled substantially while drilling a full size hole with a tri-cone bit (40-60 l/s) to extreme temperatures, while conventional coring drill bits receive little cooling due to low circulation flow rate (~5 l/s). Nevertheless, continuous coring, if possible, would be most desirable though to thoroughly understand the water-rock interaction at supercritical conditions in situ, during the developing phase of the IDDP project. Study of the coupling of the chemical and mineral alteration, fracture propagation, pressure solution, and fluid flow need be based on analysis of data on mineral chemistry, isotopes, geothermometry (fluids and fluid inclusions in minerals), and fracture geometry. Unravelling the nature and chronology of fracture failure and vein in-filling and detection of time serial fracture events and determination of constitutive rock properties is impossible without drill cores. Similarly, understanding the nature and formation of permeability requires study of cores. Measurements of mechanical and thermal properties of core as a function of temperature are necessary to quantify processes related to brittle-ductile behaviour. The permeability and thermal diffusivity of fractured and intact, fresh and altered, basalt comprise essential baseline information for fluid circulation models. In addition, there are also practical reasons for coring. Lost circulation during drilling, which is common in highly permeable zones in Iceland, would prevent recovery of drill cuttings. Similarly, the use of borehole televiewers and most other geophysical logging tools is impossible in the deepest part of the IDDP wells because of extremely high temperatures. Recognizing when supercritical conditions are reached during drilling will best be done by studying mineral assemblages and fluid inclusions in cores as they are recovered. However, as continuous coring is both much slower and therefore much more expensive than conventional rotary drilling, IDDP decided to reserve continuous coring for the supercritical zone and to take only spot cores in the upper part of the well. Nevertheless, in the event of total loss of circulation in the deeper part of the well, it may be possible to use special down-hole logging tools rated up to 300°C, by sufficient cooling of the well down to the feed point. A down-hole tool developing project, called HITI, for meeting such conditions, is currently being supported by the 6th Framework Program of the European Commission. However, when down-hole logging is not possible and there is loss of circulation and no return of drill cuttings in the supercritical zone, the only alternative is to obtain drill cores from the zones of greatest interest.

The IDDP recognized that a thorough understanding of geothermal reservoirs at supercritical conditions in natural settings is a difficult assignment. Accordingly, from the very onset, IDDP has welcomed international participation in the project for sharing both the science and the funding, for the mutual benefits of all concerned.

3.1 Potential Drill Sites

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

Figure 5 shows a simplified model of a possible geologic environment and utilization concept. The depth of production casing is of paramount importance for successful exploitation to avoid mixing supercritical with subcritical fluids, as explained in section 2 above.

While all active volcanic complexes are potential targets for finding deep geothermal systems at supercritical conditions, these volcanic complexes are of different ages and at different stages in their evolution; some are at infancy, others are mature and some are close to extinction. The simple sequence of the evolution of volcanic complexes observed in Iceland is useful to illustrate this concept. They evolve from infancy inside an active segment within the volcanic rift zones that cross the Iceland, mature into evolved central volcanoes, with magma chambers or accumulation of magmatic intrusions at shallow depths, and, eventually drift out of the active rift zones, cooling down as replenishment of magma stops, and become a subject for uplift and erosion. Altogether about one hundred such volcanic complexes are exposed within Iceland, while only about a third of them are presently active. Most commonly, high temperature geothermal systems accompany these volcanic complexes, and all these geothermal systems ripen to maturity and onwards to extinction. The lifecycle of a typical Icelandic volcanic centre is about 1 ma and the lifetime of a typical high-temperature geothermal system is about a third of that time. Due to heavy erosion during glacial episodes some of the old volcanic complexes were eroded to their roots, down to 2-3 km depth. In SE-Iceland for example, the former magma chambers now are exposed as intrusive complexes. Studies of such complexes show clear evidence of interaction between the magmatic heat sources and the hydrothermal systems, involving supercritical conditions (e.g. Fridleifsson 1984). This is a style of volcanic evolution exemplary of the world-encircling mid-ocean ridges, where submarine hot springs (black smokers) are fueled by supercritical reservoirs at depth.

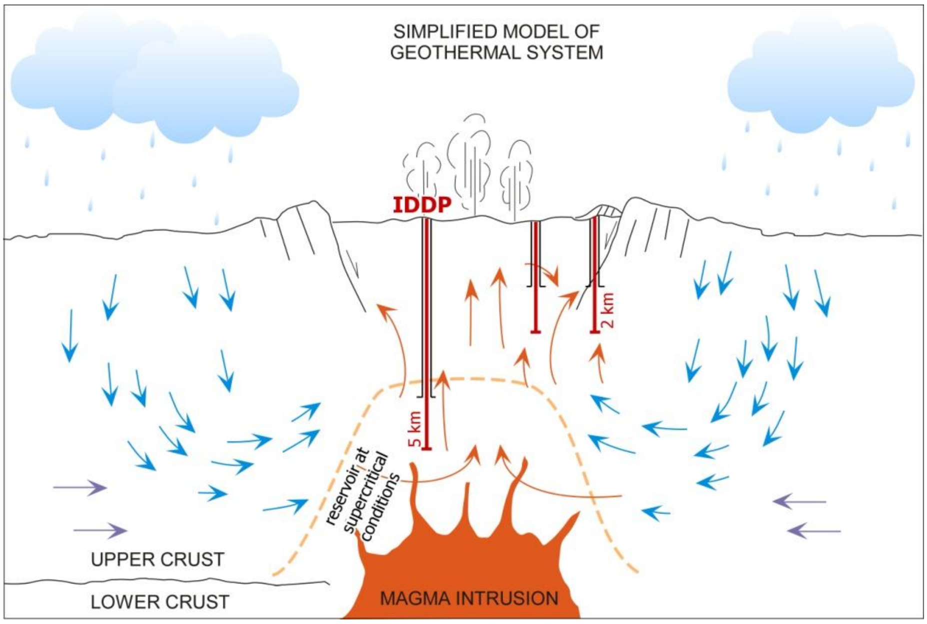

Figure 5. A simplified geothermal model showing schematically a reservoir at supercritical conditions surrounding a magmatic heat source. It is of vital importance that the IDDP production casing reaches down into the supercritical reservoir.

Volcanic complexes elsewhere in the world also evolve through geological time, while their geological settings, lifecycle, and evolutionary paths may be quite different. Studies of such eroded complexes reveal their high-temperature hydrothermal evolution, and also, in some cases, economic ore deposits of different types, e.g. the so-called epithermal porphyry-copper deposits. Fluid inclusion studies show that some of these ore deposits may have formed from saline or hyper-saline brines at supercritical conditions. While the geothermal conditions from one volcanic complex to the next may be quite variable with respect to time, depth, fluid composition etc., all volcanic-related high-temperature geothermal systems have in common magmatic heat sources. But because of the variety in volcanic settings, each high-temperature hydrothermal system needs site specific attention in order to seek locations of potential reservoirs at supercritical conditions.

The three Icelandic examples deemed to be prime targets for DUGR exploration, the Reykjanes, Hengill and Krafla geothermal systems (Fig. 1), demonstrate different stages in the evolution of their magma-hydrothermal evolution, the first being at infancy, the second being "middle aged" and the third being mature. Accordingly, deep drilling at all three will permit studying different stages in the development of supercritical conditions at depth. Additionally, they exhibit different fluid compositions, the first involving modified seawater, but the other two dilute fluids of meteoric origin. Extensive production drilling in all three drill fields has guided us to the hottest parts of the hydrothermal up-flow zones. However, the nature of their heat sources is somewhat poorly known, except in the mature case of the Krafla system, where a magma chamber has been identified at only 3-4 km depth. (e.g. Einarsson, 1978, Einarsson and Brandsdottir, 2006).

The IDDP plans to site the wells in such way that they do not reach the supercritical temperatures at too shallow a depth, but rather we intend to drill into seismogenic zones along the margins of the heat sources, to depths where supercritical pressures and temperatures with permeability are likely to be encountered. At Reykjanes and Hengill the heat sources appear to be somewhat deeper and thus the safest approach would be to drill close to the centers of the up-flow zones. The exact shape and extent of supercritical reservoirs below 4 km depth in these three volcanic systems, remains to be determined by a combination of geophysical studies and drilling. However, based on what is currently known, the indications are that supercritical conditions will be met in all three cases at less than 5 km depth (Fridleifsson et al., 2003 a). Similarly, we hypothesize that semi-brittle conditions extend from the surface down to the top of the lower crust, at 4-5 km depth at the three IDDP sites. We infer that the depth to the brittle-ductile transition is defined by the depth where seismicity declines rapidly with depth. The bottom of the seismogenic part of the crust is at 6-7 km depth at all three of the IDDP sites. In basaltic rocks the semi brittle boundary occurs at temperatures of about 600°C and the brittle ductile boundary at temperatures well above 700°C (Fridleifsson and Elders, 2005 and references therein).

3.2 Flow Tests, Pilot Studies, Production Tests, and Production.

Drilling to produce a fluid of an unknown chemical composition presents a dilemma. The IDDP feasibility study (Albertsson et al., 2003 a, b) discussed a strategy for down-hole testing.. This involves using a 4” retrievable casing, loaded with pressure and temperature detectors as well as metal plates for corrosion and scaling tests at different depths, to be inserted to the top of the cored part of the drillhole at 3.5 or 4 km depth, inside the much wider production casing. The basic idea is to protect the production casing and the outer casings from corrosion or scaling during the initial testing phase by flow testing through this 4” pipe. In case the 4” pipe becomes plugged by scaling, it would be retrieved and a new one inserted for a second test. On the other hand, if a rapid corrosion occurs there could be complications in retrieving the 4” casing for a second test. Although the primary function of the pipe would be to protect the outer casings during the initial flow test, it would play another role. By retrieving the liner, it would be possible to make a thorough inspection of it, section by section, as well as studying scaling plates of different materials. A quantitative model of the fluid flowing through the pipe showed that the enthalpy of the fluid at the wellhead would be higher than that of steam from conventional wells only if the reservoir temperature is 450 °C or higher.

Of major concern was the estimated cost (5-6 million USD) necessary to install the flow-test liner and to operate it for a period of six months. About half of that cost would be allocated to rig rental, BOP and lifting equipment rental, well monitoring, and fluid and scale analyses. Since 2003, both steel prices and rig rentals have escalated. During the final planning phases of IDDP, and in order to find out if a simpler approach for fluid sampling and flow testing in the initial phase could be applied, the 6th IDDP workshop is to be held in March 2007. The IDDP has plans to apply for funds to the 7th Framework Program of the European Commission for the development and prototype pilot study needed prior to production testing of the natural supercritical fluids.

3.3 DUGR, Re-injection and Heat Mining

In the last two decades there have been several projects involving heat mining by injecting cold fluid into hot rocks and considerable efforts have been taken to induce 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 Rock (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 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, and from 300-400°C in USA, and above 500°C in Japan.

Recently, in an Expression of Interest letter (EoI-letter) to the European Commission, 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. DUGR's 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 rhyolitic to intermediate volcanic rocks. If drilling a DUGR intersects a supercritical system of marginal permeability, then the possibility of using the EGS approach can be considered. Injection of cold water to induce fracture permeability (hydro-fracturing) might be more productive utilization of 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.

4 POTENTIAL BENEFITS

4.1 Power generation

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

Albertsson et al. (2003 a, b) have estimated the electric power output that can be expected from an IDDP well compared with that from a conventional geothermal well. For comparison a conventional well was considered to be producing only dry steam, with a volumetric rate of inflow to the well is 0.67 m^3/s (~2400 m^3/h), at a wellhead pressure of 25 bar_a and a downhole pressure of 30 $bar_{a.}$ This would yield steam at a rate capable of generating about 5 MW electric. On the other hand a DUGR well tapping a supercritical reservoir with temperatures of 430–550°C and pressures of 230-260 bar may be expected to yield 50 MW electric given the same volumetric inflow rate, 0.67 m^3/s. Thus, if similar conditions apply, an DUGR well could yield an order of magnitude improvement in power output compared to a typical conventional well.

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

4.2 Cost Performance

A primary goal of IDDP is to find out if electric power can be economically produced from deep unconventional geothermal reservoirs (DUGR) at supercritical conditions. Until we know the results from the power production from DUGR, after the pilot and production tests, meaningful cost performance estimates are impossible. Nevertheless, we can compare the cost of drilling 5 km deep wells as compared to 2 km deep wells, using the considerable data from the experience in drilling geothermal wells in Iceland. Irrespective of the recent cost increases in steel and drilling, which affect both deep and shallow wells, the deeper wells are roughly 3-4 times more expensive than the shallower wells, assuming rotary drilling in both cases. If, as we expect, power output from the average deep well will be an order of magnitude greater than the power output from the average conventional well, the comparison would obviously be in favor of the deep wells. To this we would need to add risk analysis on the success rate of the deep wells as compared to the shallow once. However, a deep unsuccessful well can be made a shallow well by side-tracking a deviated hole out of the cemented casings, but not vice versa, and thereby part of the cost in drilling a deep well is retrievable. A deep low yielding but permeable hot well could also be used for re-injection of cold fluids, to be retrieved by shallower wells for steam production. Accordingly, while they are expensive, deep wells have other potential benefits.

4.3 Scientific Studies

In addition to investigations and sampling of fluids at supercritical conditions the IDDP will permit scientific studies of a broad range of important geological issues, such as investigation of the development of a large igneous province, and the nature of magma-hydrothermal fluid circulation on the landward extension of the Mid-Atlantic Ridge in Iceland. In addition, the IDDP will require use of techniques for high-temperature drilling, well completion, logging, and sampling, techniques that will have a potential for widespread applications in drilling into oceanic and continental high-temperature hydrothermal systems. The prospect opens up the opportunity for a very comprehensive scientific program investigating the anatomy of a mid-ocean rift system, by tying together land–based and ocean-based deep borehole studies with complementary geological and geophysical and seismic imaging studies, putting the drilling activities into a broader regional geologic context.

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.

4.4 Economic Benefits

Most of the potential economic benefits of the IDDP project have been discussed to some extent above, and thus we only list them below:

1. Increased power output per well, perhaps by an order of magnitude, and production of higher-value, high-pressure, high-temperature steam.
2. Development of an environmentally benign, high-enthalpy energy source beneath currently producing geothermal fields.

3. Extended lifetime of the exploited geothermal reservoirs and power generation facilities.
4. Re-evaluation of the geothermal resource base.
5. Industrial, educational, and economic spin-off.
6. Knowledge of permeability within drill fields deeper than 2-3 km depth.
7. Knowledge of heat transfer from magma to water.
8. Heat sweeping by injection of water into hot, deep wells.
9. Possible extraction of valuable chemical products.
10. Advances in research on ocean floor hydrothermal systems**.**

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

4.5 Environmental Issues

Developing environmentally benign high-enthalpy energy sources below the depth of currently producing geothermal fields is not only of economic value in relation to the already installed infrastructures, but it is also of environmental value by diminishing the environmental impact geothermal utilization. Producing more power without increasing the "foot print" of the exploited drill field is an obvious benefit. Most high temperature geothermal surface manifestations occur within some sort of active volcanic settings, and many such fields around the world are preserved as national parks. If the production of supercritical reservoirs through deep holes proves more economic than production of the conventional upper parts of the geothermal systems, it would be economically feasible to use deep directional drilling similar to that becoming common in the oil industry. This could revolutionize the approaches available for developing high enthalpy geothermal resources underneath environmentally sensitive areas.

5 POTENTIAL IMPACTS

We believe that a successful outcome of the IDDP project could lead to a major step forward in using high temperature geothermal energy on a global scale. Increased use of such a sustainable source of non-polluting energy sources would help to counterbalance the threat of global warming by due to the release of greenhouse gases from the use of hydrocarbon fuels.. The potential impact of utilizing geothermal resources at supercritical conditions could become quite significant. Not only would this call for re-evaluation of the geothermal energy resource base on a local scale, but also on a global scale. If producing supercritical fluids became widespread it would lead to a major enlargement of the accessible geothermal resource base.

5.1 Local Impact

In a report delivered by the Minister of Industry to 117th parliament of Iceland, 1993-1994, the total geothermal energy accessible in the active high temperature systems in Iceland was estimated as potentially capable of yielding some 3,500 MW electric, if it was all utilized for electric production, and could yield over 28,000 GWh/y for 50 years (see also Fig. 3). These numbers are only indicative of the size of the conventional accessible geothermal resource base in Iceland, without considering the possible impact of harnessing deep geothermal resources at supercritical conditions. If the power output from a single well were to be increased by an order of magnitude, what would be the total increase in power output from a developed geothermal system? Can we double or triple the production, or more? Clearly there must be a limit, but presently we do not know this limit. Accordingly, multiplying the numbers presented in the Minister's report from 1994 would be meaningless given the present state of knowledge. Nevertheless, it is obvious that any increase would have a positive impact on the sustainable energy budget of an environmentally benign energy source.

Additionally, indirect results from our studies of the 4-5 km deep IDDP wells, could have significant local impacts on questions such as: (i) How far down do the conventional hydrous fluid systems reach?, and (ii) Can mining of supercritical thermal energy stored in DUGR systems, by injecting cold fluid into deep drillholes become economically viable.

5.2 Global Impact

Positive results from the IDDP experiments could have similar impacts on a global scale as those on a local scale in Iceland. The economics, and the efficiency, of harnessing geothermal energy for power production, might change to increase usage of the sustainable and environmentally friendly geothermal resource base. Apart from favorable impact within the individual geothermal countries, increased utilization of geothermal energy would also have a favorable impact on the global emission of greenhouse gases, if geothermal energy replaces more polluting energy sources.

High temperature geothermal resources are located at most plate boundaries around the globe, mostly above the subduction zones (convergent plate boundaries), where oceanic plates creep under continental crust (like on the so-called Circum Pacific ring of fire), or at constructive plate boundaries were new crust is created like along the mid-ocean ridges (including Iceland), the African rift valley and elsewhere. Potential impact on a global scale, if DUGR systems can be harnessed, would undoubtedly involve many of the Circum Pacific geothermal systems. Many of those systems, like in Central America, are already within national parks and as such will be difficult or impossible to access, except by directional drilling from outside the parks. Improved economics in geothermal utilization might make extensive directional drilling feasible, like in the sea floor oil industry.

Some of the potential DUGR systems are on remote oceanic islands, like on the Aleutian island arc in the Pacific Ocean, the Azores in the Atlantic Ocean, and elsewhere, far away from the larger energy markets. Improved economics by harnessing DUGR systems at such remote locations, and improved economics in the conversion of thermal energy into potable energy carriers, like hydrogen or synthetic diesel or alike, might justify the harnessing of such remote DUGR systems.

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

5.3 Potential Impact on Greenhouse Gases

Today global warming is a major issue that calls for increased usage of sustainable, non-polluting, energy sources, including geothermal energy. A recent discussion of the economics of climate change appears in the Stern Review to the British Government 2006 (www.sternreview.org.uk). Since industrialization, greenhouse gas (GHG) levels have risen from 280 ppm CO_2 equivalent (CO_2e) to 430 ppm CO_2e today, and they increase by 2 ppm each year. The risks of the worst impacts of climate change can be substantially reduced, according to the review, if the GHG levels can be stabilized between 450 and 550 ppm CO_2e. Stabilization in this range would require emissions to be at least 25% below current levels by 2050, and perhaps much more. In any case, stabilization at whatever level, requires annual emissions to be brought down to more than 80% below current levels. The message of the Stern Review was quite simple: "we don't have the choice not to respond". Up to 5°C global warming could be realized within this century if we do nothing - with severe impact on our ecosystem, failing crops in many areas, sea level rise threatening many major cities, shortage of water supply in other areas, more extreme climate events, and so on - unless we cut the GHG emissions immediately – but how? According to the Review, three measures need be taken, (1) taxation on GHG emission, (2) new techniques, and (3) removal of hindrances against economic energy usage. Quoting the Stern Review onwards, central estimates of the annual costs of achieving stabilization between 500-550 ppm CO_2e are around 1% of global GDP, if we start to take strong action now. This should be compared to estimates of the overall costs and risks of climate change if nothing is done to mitigate the impact, estimated to be equivalent to loosing at least 5% of global GDP each year, now and forever. And further, if a wider range of risks and impacts were taken into account the estimate of damage could rise to 20% of GDP or more (Stern Review). According to the Stern Report the main sources of the polluting greenhouse gases are 24% in the Power Sector, 14% in the Industry sector, another 14% in the Transport sector, and 5% in other energy related activities, altogether some 57%. Attempting to decrease CO_2e emission in any of these sectors would be a logical step to respond to the Stern Review.

The World Energy Council (WEC) has presented several scenarios for meeting the future energy requirements with varying emphasis on economic growth rates, technological progress, environmental protection and international equity (Nakicenovic et al., 1998). All the scenarios provide for substantial social and economic development, particularly in the developing countries. They provide for improved energy efficiencies and environmental compatibility. During 1990-2050, the primary energy consumption is expected to increase by some 50% according to the most environmentally conscious scenario and by some 275% according to the highest growth rate scenario. In the environmental scenario, the carbon emissions are expected to decrease slightly from 1990 levels. The high growth rate scenario is expected to lead to a doubling of the carbon emissions.

In all WEC´s scenarios, the peak of the fossil fuel era has already passed (Nakicenovic et al., 1998). Oil and gas are expected to continue to be important sources of energy in all cases, but the role of renewable energy sources and nuclear energy vary highly in the scenarios and the level to which these energy sources replace coal. In all the scenarios, the renewables are expected to become very significant contributors to the world primary energy consumption, providing 20-40% of the primary energy in 2050 and 30-80% in 2100. They are expected to cover a large part of the increase in the energy consumption and to replace coal.

Whether these scenarios are realistic is a very legitimate question. Table 5 shows the technical potential of renewable energy resources (WEA, 2000). The technical potential is the yearly availability of the renewable resources. These estimates suggest that the technical potential of the renewables is sufficiently large to meet future world energy requirements. However, at issue is the question of how large a part of the technical potential can be harnessed in an economical, environmentally and socially acceptable way. This will probably vary between the energy sources. It is worth noting, however, that the present annual consumption of primary energy in the world is about 400 EJ (Table 1).

TABLE 5: Technical potential of renewable energy sources in Exajoules/a. Source: World Energy Assessment (WEA, 2000)

	EJ per year
Hydropower	50
Biomass	276
Solar energy	1575
Wind energy	640
Geothermal energy	5000
TOTAL	7600

Evidently, a large opportunity to cut the GHG emission exists with the geothermal energy sector. However this estimate did not include the innovations with which the IDDP is involved. The impact of DUGR and the utilization of supercritical fluids could have a major impact on the geothermal industry both locally and globally.

6 CONCLUSIONS

The long-term program to improve the efficiency and economics of geothermal energy by harnessing Deep Unconventional Geothermal Resources (DUGR) in Iceland is an ambitious project to produce electricity from natural supercritical hydrous fluids from drillable depths. Producing higher-temperature fluids for generation of electric power offers two advantages over using the fluids from conventional wells: (i) higher enthalpy, which promises high power output and higher efficiency per unit mass, and (ii) higher pressure, which keeps the fluid density high and thus contributes to a higher mass-flow rates. Modeling indicates that IDDP wells could yield an order of magnitude improvement in power output compared to a typical conventional wells. The choice of technology to be applied for the power generation from these high-temperature fluids will be decided after determining the physical and chemical properties of the fluids that are produced. The IDDP has plans to apply for funds to the 7th Framework Program of the European Commission for the development and prototype pilot study needed prior to production testing of the natural supercritical fluids.

There are three obvious approaches to improve the economics of the geothermal industry worldwide: (i) Cascading the usage of geothermal energy by using the effluent water from electricity production for industrial processes and for domestic heating, (11) Reducing the cost of drilling and completing geothermal production wells, and (iii) to reduce the number of wells needed by increasing the power output of each well. The best way to achieve the latter is to produce supercritical fluids. Accordingly, the successful completion of the IDDP project is of considerable importance for the geothermal industry at large. A successful outcome would be a major step forward for the geothermal industry on a global scale, which in turn, could help to counterbalance the threat of global warming by increased use of the sustainable, non-polluting energy resources.

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