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NATIONAL ENERGY AUTHORITY
GEOTHERMAL DIVISION

Geothermal Energy in Iceland

Electricity Production and Direct Heat Use

Paper presented at the UNIPEDE-HYDRENEW meeting in Pisa, June 15, 1992

Guðmundur Pálmason

OS-92047/JHD-24 B November 1992

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Introduction

Iceland is situated in the North Atlantic Ocean, at latitude 65 °N, just south of the Arctic circle. Geologically it is a part of the Mid-Atlantic Ridge and has been built up entirely by volcanic rocks. About 10 % of the area of 103,100 km^2 is covered by lava flows younger than about 10,000 years. The geological processes of crustal spreading and the associated volcanism are responsible for the occurrence of geothermal fields, providing the heat source and the necessary aquifer permeability to keep the geothermal systems going.

The population of about 260,000 is mostly concentrated in the coastal areas. About one half lives in the southwestern part of the country, where the capital Reykjavík is situated.

The climate is tempered by the Gulf Stream. Precipitation varies with location from 400 to 4000 mm/yr. The average annual temperature in Reykjavík is 5.0 °C, the monthly averages ranging from -0.5 °C in January to 11.2 °C in July. Days with temperatures less than -5 °C are on the average fewer than 10 in any one year in Reykjavík. House heating is required all the year around.

The porous volcanic rocks and ample precipitation also provide the basis for the relatively abundant hydropower resources. On the other hand, the country is devoid of fossil fuels (coal, petroleum, natural gas) and nuclear fuels.

Overview of Domestic Energy Sources

The technically harnessable hydropower potential is estimated at about 64 TWh/yr, of which about 44 TWh/yr may be economical for power intensive industries at the present time. An estimate, albeit a much rougher one, has also been made for the geothermal resources. It should be stressed, however, that the geothermal resource is not strictly renewable in the same sense as the hydropower. The heat reservoir in the crust is a vast one, but can only be mined at a certain rate. The lifetime of a geothermal field is largely determined by the size of the reservoir and the rate at which the heat can be extracted. The rate is in turn determined by the hydrological properties of the crustal reservoir rocks.

The geothermal resources occur mainly in the active volcanic zone (high-temperature fields) traversing the country from southwest to northeast, and on the flanks of the zone (low-temperature fields) (Fig.1). They are hydrothermal in nature, i.e. consist of hydrothermal circulation systems in the crust. An assessment of the total potential for electricity production from the 19 high-temperature geothermal fields gives a value of about 1,480 TWh. The largest one, Torfajökull, yields an estimated 422 TWh. The main results of the geothermal assessment and the status of exploration and utilization are given in Table I.

Energy Production and Use

Only about 11% of the economical hydropower resources has been harnessed as yet. The availability of this relatively cheap energy explains why the geothermal resources have so far been used only to a limited extent for electric power generation, in contrast to their extensive use for direct heat applications. The economically most favourable situations arise when, in high-temperature fields, both electric power and heat for district or other heating can be produced in co-generation plants. The limiting factor here is the size of the heating market.

Geothermal Field	**Size**	**Energy potential**		**Status**	
	km²	*Heat (>5 °C)* *10¹⁸ J*	*Electricity* *TWh*	*Exploration*	*Utilization*
Reykjanes	2	0.9	12.3	complete	production
Svartsengi	11	4.4	47.3	complete	production
Krísuvík	60	16.8	132.3	mostly complete	
Brennisteinsfjöll	2	0.5	5.3	started	
Hengill	100	28.2	301.8	complete	production
Geysir	3	1.1	11.8	not explored	protected
Kerlingarfjöll	11	3.1	33.3	started	
Hveravellir	1	0.4	3.9	not started	
Torfajökull	140	39.4	422.2	started	
Grímsvötn	65	0	0	not explored	(inaccessible)
Köldukvíslarbotnar	8	2.6	27.6	not started	
Vonarskard	11	2.7	28.5	not started	
Kverkfjöll	25	2.1	21.5	not started	
Askja	25	3.0	32.4	started	
Fremrinámar	4	1.4	15.3	started	
Námafjall	7	2.8	38.5	complete	production
Krafla	30	12.3	164.7	complete	production
Theistareykir	19	6.1	65.7	started	
Öxarfjördur	30	10.9	116.5	started	
Total	554	138.7	1480.9		

Table I. The estimated technically harnessable potential for electricity generation from high-temperature geothermal fields in Iceland

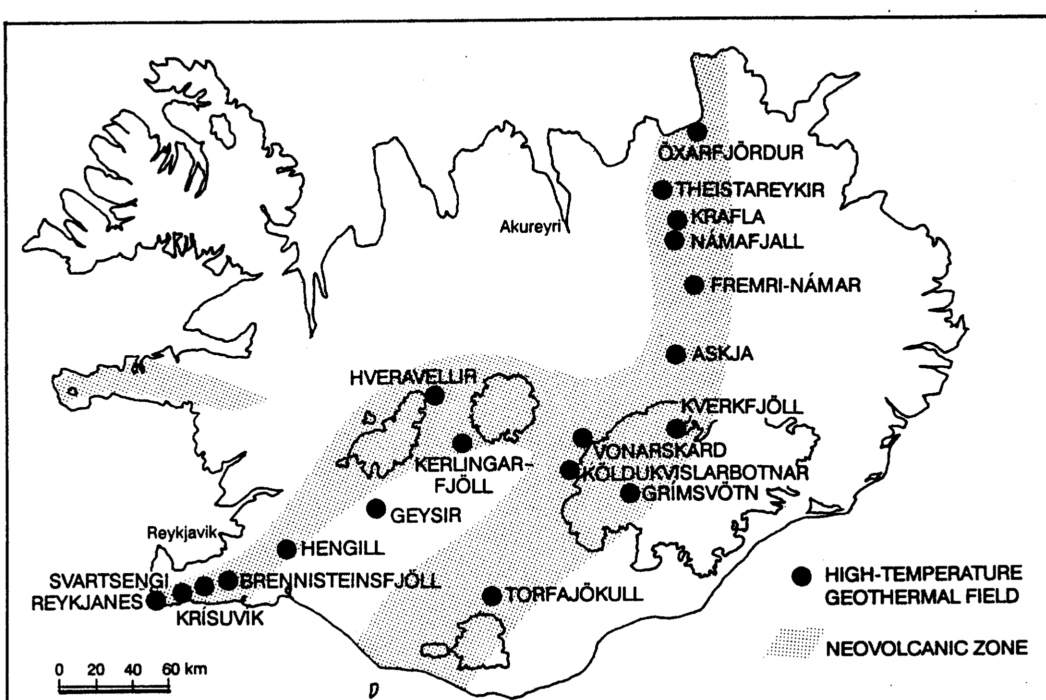

Fig. 1. Location of the high-temperature geothermal fields.

The energy consumption has increased rapidly in the last decades. The present per capita supply of primary energy of 334 GJ/yr, and the per capita production of electricity of 17,455 kWh/yr, are among the highest in the world. The gross domestic product per capita in terms of US$(1985) was in 1990 US$ 13,081. The two domestic energy sources, hydropower and geothermal, account together for about two thirds of the total supply of primary energy. The share of geothermal is 31.4 %, when calculated in oil equivalents (Fig.2), and 45.4 % when calculated in energy units (Fig.3). These percentages for geothermal energy are higher than in any other country, and reflect the importance of geothermal in the energy economy of Iceland.

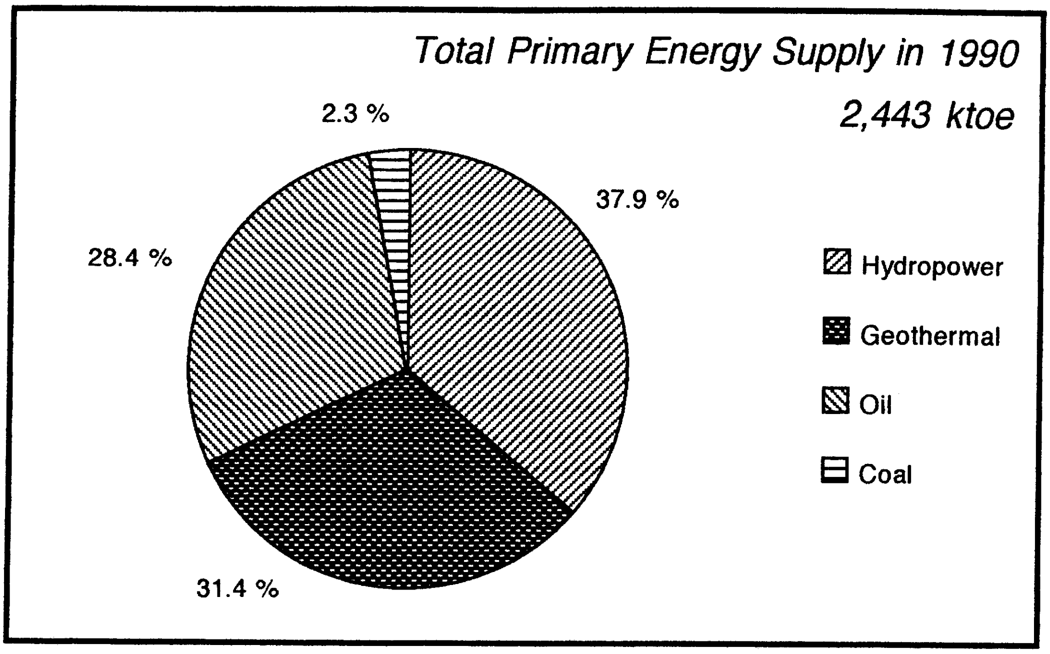

Fig. 2. Primary energy supply in 1990, in terms of oil equivalents (method of the World Energy Council in 1989).

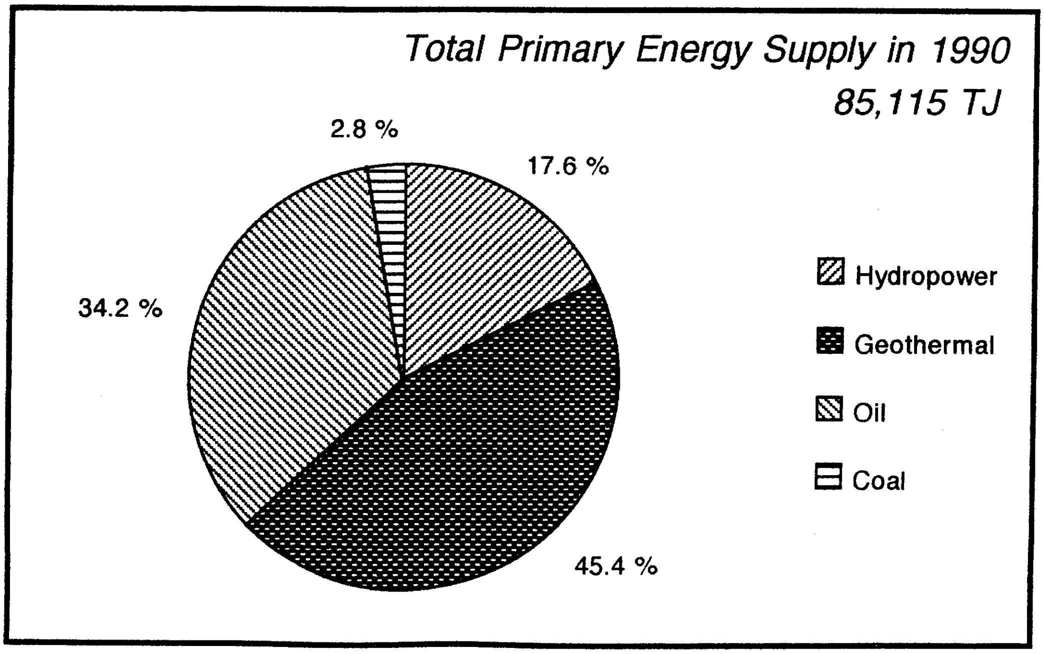

Fig.3. Primary energy supply in 1990, in terms of energy units (method of the World Energy Council in 1992).

Electricity Production from Geothermal Resources

As mentioned above geothermal energy does not play a major role as yet in the electricity generation sector in Iceland because of the abundant and relatively cheap hydropower resources. Of the total electricity production of 4,428 GWh/yr in 1991, only 267 or 6 % came from geothermal while 94 % was from hydro. During the last two decades steps have been taken to develop the high-temperature resources for electricity production as well as for other uses. They have shown both the benefits and the risks which are associated with the location of the geothermal fields in more or less active volcanic areas.

Electric power production began in 1969 with the installation of a 2.6 MW_e backpressure turbine/generator unit in the Námafjall field in northeastern Iceland. Altogether about 45 MW_e have been installed today, which constitutes 4.7% of the total installed capacity in the country (962 MW_e).

There are currently five high-temperature fields successfully exploited, two in the north of Iceland and three in the south. In four of them electricity is generated and the fifth one will also be used for this purpose in the future. All these fields are intimately associated with the axial volcanic zone of the Mid-Atlantic Ridge.

In the following a short description is given of the geothermal plants in each of these areas.

The Svartsengi Co-generation Plant

This plant is in the axial zone of the Mid-Atlantic Ridge in southwest Iceland. It was built in 1976/77 for the purpose of providing the neighbouring communities of about 14,500 inhabitants with district heating. In 1978 the first electrical generating unit of 1 MW_e was added, and others followed. The current installed capacity is 125 MW_{th} of useful heat and 12 MW_e. The electrical generation units area 6 MW_e Fuji backpressure unit, two 1 MW_e AEG backpressure units and three 1.3 MW_e Ormat Energy Converters (binary system using the organic Rankine cycle). The three Ormat units were installed in 1989. They feed on low-pressure excess steam from the backpressure units, that is not needed for the heat exchangers in the thermal plant. An extension with six additional Ormat units is planned bringing the total installed capacity to 19.2 MW_e. The Svartsengi Plant is owned and operated by the Sudurnes Regional Heating Company, which was established in 1974 by the local municipalities and the state to provide district heating in the area.

The geothermal reservoir was discovered during the drilling of two exploration holes in 1971-72, after geophysical and geological reconnaissance work had been carried out. The pre-drilling indications of the field were weak emanations of steam through the surface of a 1-2,000 years' old lava field and some thermally altered rocks nearby. The geothermal reservoir fluid is a brine of 235-243 °C and a salinity of about two thirds that of sea water. The heat is transferred to fresh water in heat exchangers and the heated water is pumped to the district heating systems of 7 different communities and the international airport at Keflavík. The liquid effluent from the plant is discharged untreated to the highly permeable surface lava, where it has gradually formed a surface pond growing in size because of silica deposition. This pond, known as the Blue Lagoon, is used for bathing by people who suffer from rheumatism and psoriasis, with considerable alleviating effects claimed. The gaseous effluent from the plant is discharged into the atmosphere through stacks without prior abatement.

No permanent re-injection of the waste fluid is used as yet, but experiments have been carried out to test the permeability conditions in the reservoir rocks and interference between wells. The liquid-dominated reservoir has in recent years developed steam pockets at shallow depth near some of the production holes. The effect of this on the production characteristics of the holes is being investigated as well as the risk of possible hydrothermal explosions.

A flow diagram of the Svartsengi Power Plant II which includes the Ormat binary units is shown in Fig. 4.

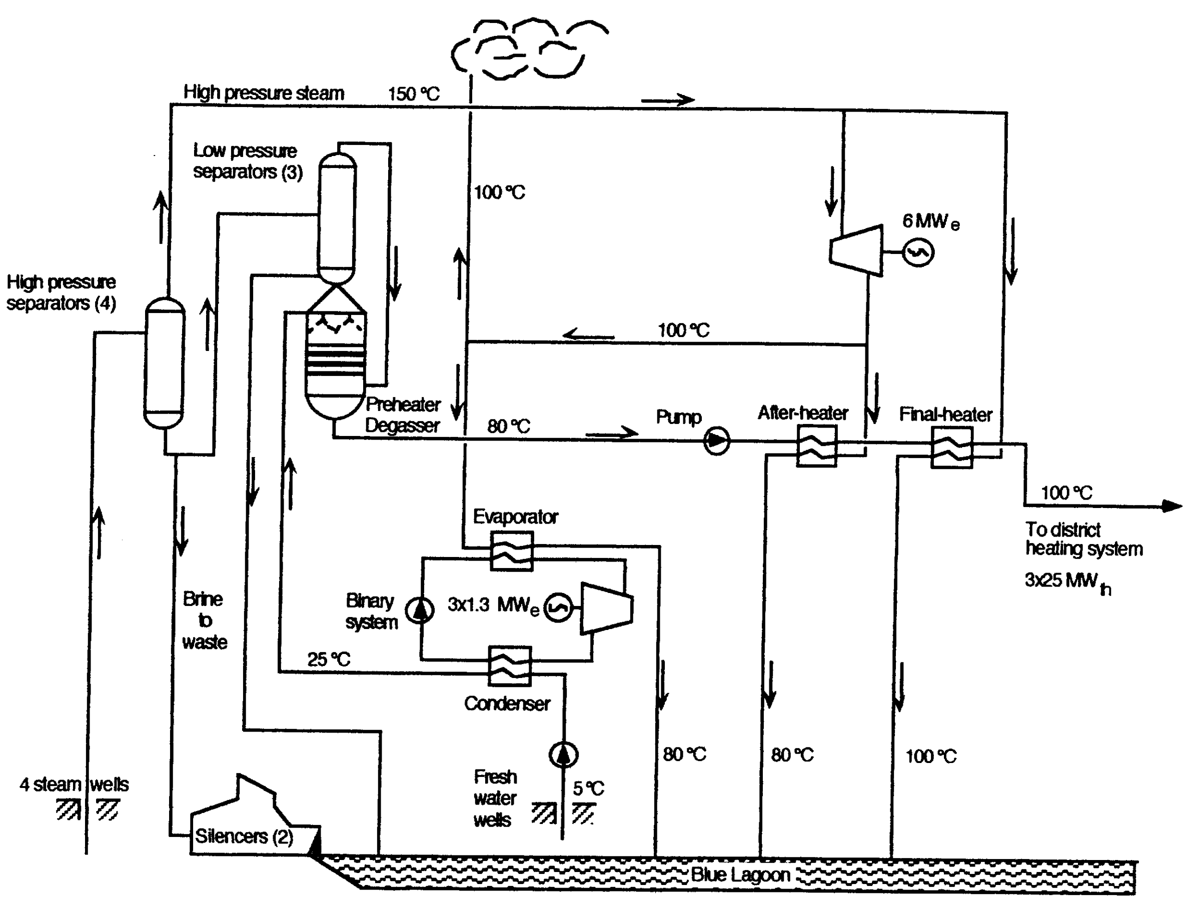

Fig.4. The Svartsengi Power Plant II

At the Reykjanes high-temperature field, about 15 km west of Svartsengi, a plant for the production of high grade sea-chemicals has just begun operation. A 0.5 MW_e backpressure unit has been installed there to provide electricity for local needs. The reservoir temperature is about 290 °C. The fluid is sea-water with a modified composition due to water-rock chemical interaction.

The Nesjavellir Geothermal Power Plant - Future Co-generation

Also in the axial zone of the Mid-Atlantic Ridge in southwest Iceland, this plant is under stage-wise construction. The first stage with an output of 100 MW_{th} was commissioned in September 1990 and a second stage is currently under construction. The electric generation part of the plant is on hold because of a current over-abundance of electricity in Iceland. The primary purpose of this plant is to provide hot water for space heating in Reykjavík and the surrounding communities with a total population of about 141,000. The low-temperature fields which have supplied water for these needs for decades are now showing signs of declining reservoir pressure, leading to a production decrease of about 4 % per year on the average. The new plant will alleviate the load on these fields and provide water for new users as well. The space heating market in the Reykjavík area is close to 600 MW_{th}, increasing by 3-4 % annually. The high-temperature field will in the future also produce electricity. The fully developed plant is projected for 400 MW_{th} for space heating and 80 MW_e of electric power. A flow diagram for the first stage is shown in Fig. 5.

The geothermal reservoir temperature is 300-400 °C. The average output of the 13 production wells presently available is 60 MW_{th}, or 8 MW_e if used to generate electricity. In the heating plant the heat is transferred to fresh water in heat exchangers and the heated water is pumped to the district heating system. The hot-water steel pipeline from the plant to Reykjavík is 27 km long (diameter 800-900 mm). It is designed to transport 1870 l/s of up to 97 °C water (445 MW_{th}). The pipeline is laid mostly above ground, resting on concrete pillars. The fluid effluent from the plant is deposited untreated on the surface, where it disappears into the lava, and the gaseous effluent discharged unabated to the atmosphere.

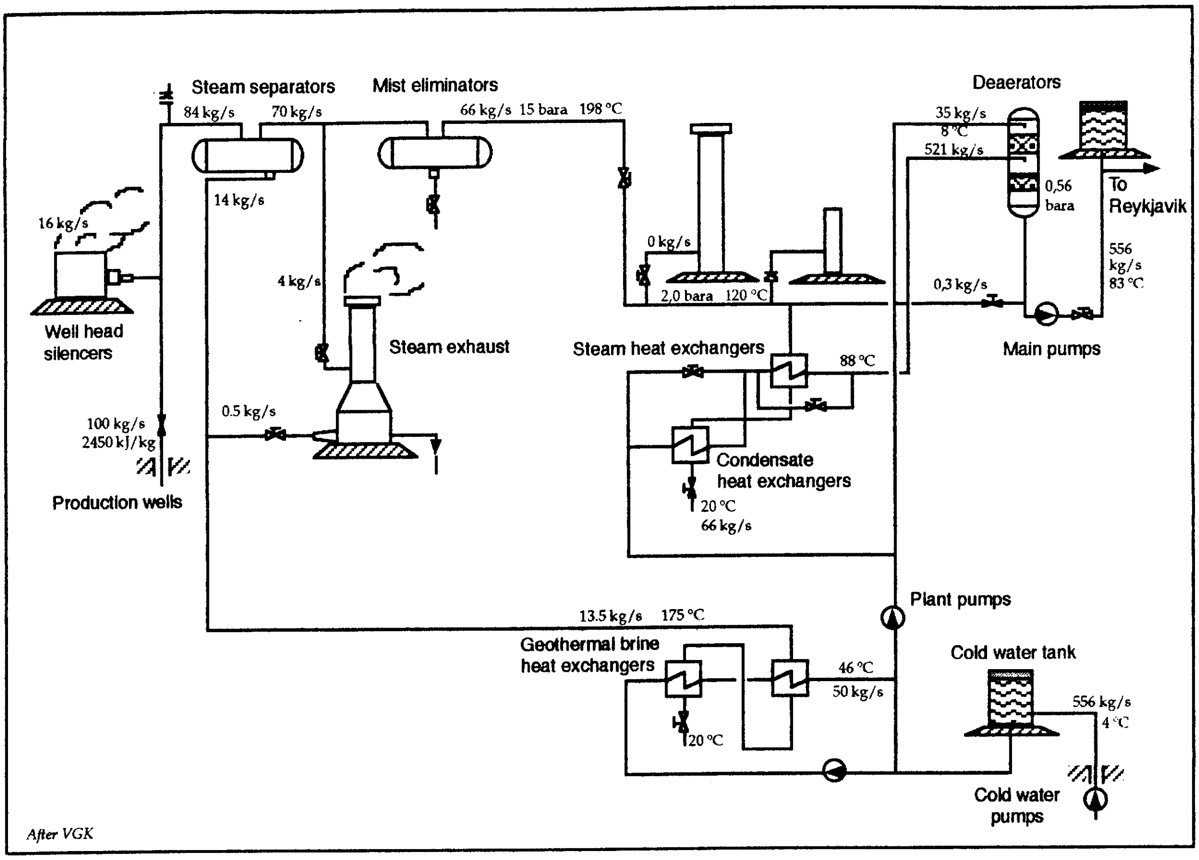

Fig 5. The Nesjavellir Geothermal Power Plant, Phase I

At the present time the Reykjavík area is supplied with hot water from both the new Nesjavellir plant and from the low-temperature fields that have provided water for district heating for decades. Some problems were encountered due to magnesium silicate scaling in the distribution system where heated fresh water from Nesjavellir was mixed with the geothermal water from the low-temperature fields. Experiments indicate that if the scaling is to be avoided it may be necessary to keep the two water types separate, each supplying its own part of the distribution system.

The Námafjall Geothermal Power Plant

This plant in the northern part of the axial volcanic zone was built in 1966/68 and commissioned in 1969. It is located close to the Kisilidjan Diatomite Plant which was the first major industrial user of geothermal steam for drying purposes in Iceland, starting its operations in 1967.

The Námafjall 2.6 MW_e backpressure plant is the oldest geothermal electric power plant in Iceland, and has been operated successfully for over 20 years. Both these plants use steam from the Námafjall geothermal field (reservoir temperature about 280 °C), which is the area where in 1977 magma entering a well at depth was ejected as tephra through a steam producing well-head during the Krafla Fires of 1975-1984. The well was damaged during the associated earthquake event, but is still in use for district heating albeit at a lower output than before. Two new production wells, drilled in 1979-80, were more productive than the older ones, with steam output equivalent to 7-8 MW_e each.

The Krafla Geothermal Power Plant

The Krafla Power Plant lies in the axial volcanic zone in northern Iceland, about 10 km north of the Námafjall field. The development of the considerably larger Krafla field started in 1970-73, and in 1974 two exploration wells were drilled. Construction of a 2x30 MW_e

power plant and the drilling of production wells began a year later. At the end of 1975 a series of volcanic events started only 1-2 km from the drilling area. The immediate effect of the eruption was a contamination of the geothermal fluids by the volcanic gases. Surface lava flows and earthquakes did not harm he installations. The initial eruption in 1975 was followed by eight eruptive events, the last one in September 1984.

It was decided in 1977 to move the steam procurement to two smaller areas located along the south-east boundary of the main geothermal area initially scheduled for development. At the same time it was decided to delay the installation of one of the two turbine/generating sets purchased for the project until the magmatic effects on the geothermal fluid due to the volcanism subsided. The operation of the power plant began in early 1978 with 8 MW electric generation at the start, but reached the present 30 MW_e in 1982.

The volcanic activity at Krafla has not disturbed the daily operation of the power plant. The magmatic gases in the geothermal steam have, however, caused operational problems in some production wells in a certain part of the well field, mostly due to rapid scaling of complex iron silicates and corrosion in the wells. Expansion of the power plant to 60 MW_e is, however, still being considered as soon as the power market warrants it. Not a single well has been mechanically damaged due to direct seismic effects and all but two of the wells initially connected up are still in operation. The liquid effluent from the Krafla Power Plant is disposed of untreated into a brook disappearing into the lava, and the gaseous effluent is discharged unabated into the atmosphere.

The Krafla geothermal system is a complex one, consisting of an upper zone 600-1,000 m thick with temperature of about 210 °C, and a lower zone down to at least 2000 m with temperature of 300-350 °C. The lower zone is a boiling two-phase system. Recent drillings in the initial production area to 2,000 m have shown that there the lower reservoir is still contaminated by the volcanic gases to such degree as to render the reservoir unsuitable for production.

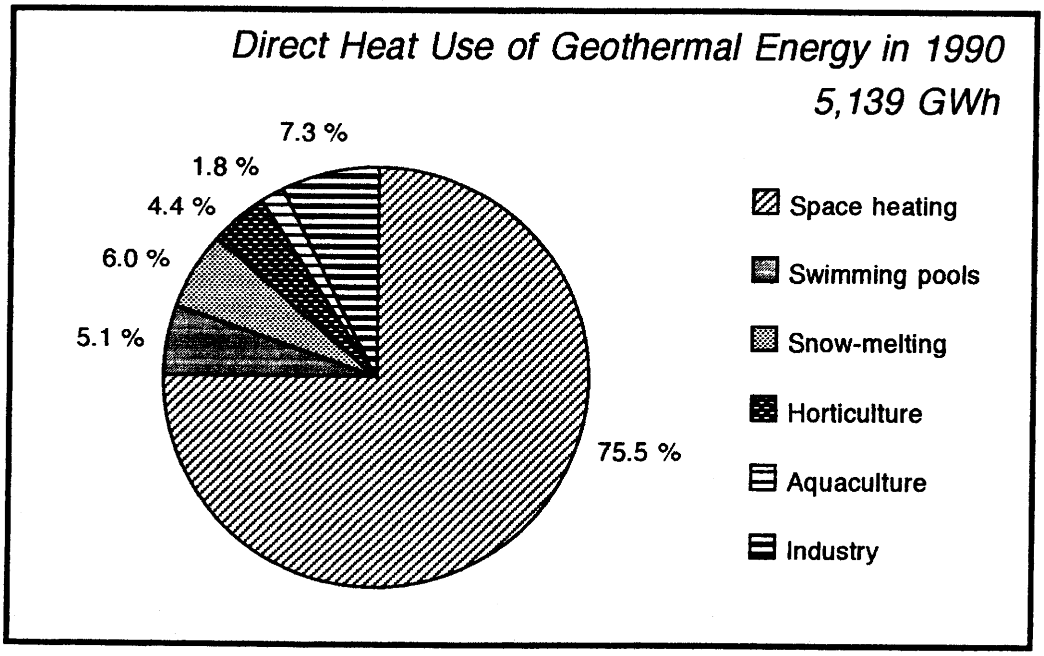

Fig.6. Non-electrical uses of geothermal energy in 1990, by sectors.

An Overview of Non-electrical Uses of Geothermal Energy

Geothermal energy is used in Iceland mainly for district heating at the present time, supplying about 85% of the needs for space heating. In the early years low-temperature resources were mainly used for this purpose, but in recent years high-temperature resources are used increasingly for this purpose. The possibility of combined heat and power production has made this especially attractive from an economic point of view. The two largest district heating services are now using high-temperature sources wholly or partly for their needs.

Other uses of geothermal heat are for industrial drying, for greenhouse farming and outdoor soil heating, for fish farming, for de-iceing or melting of snow on sidewalks, and for recreational uses such as heating swimming pools. Fig.6 gives some statistics on the non-electrical uses of geothermal energy.

Space Heating

There are at present 27 public district heating services based on geothermal resources. By far the largest is the Reykjavík Municipal District Heating Service (Hitaveita Reykjavíkur). It began operation on a modest scale in 1930, and was gradually extended to serve the whole of the city of Reykjavík. This was achieved in 1968. Subsequently the neighbouring communities were connected as well, which was completed in 1977. At the end of 1990 the RMDHS served about 141,000 people or 99.6 % of the population in the area.

A major economic incentive to geothermal heating was provided by the oil crises in the 1970's. In 1970 about 48 % of the heat used for space heating in Iceland as a whole came from geothermal sources, but in 1982 the share of geothermal had grown to 80 % (Fig.7).

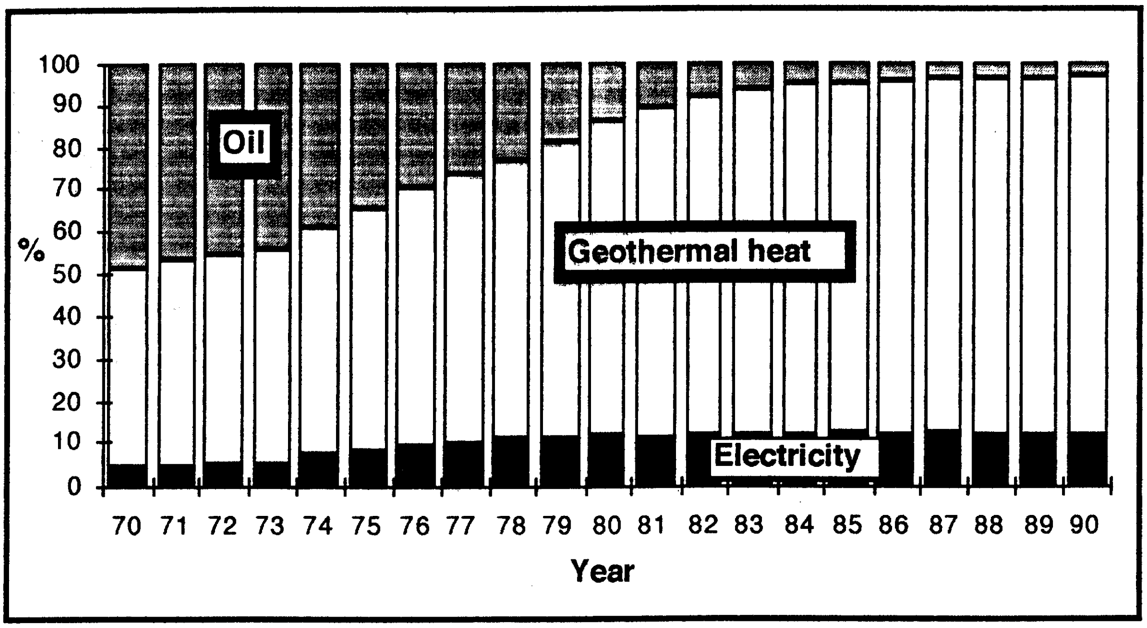

Fig. 7. Energy sources for space heating 1970-1990

The cost of geothermal heating varies considerably. It depends on the size of the market, the distance to the geothermal resource and the production cost at the source. The longest pipeline transporting geothermal water in Iceland is about 70 km.

The selling price of hot water in Reykjavik for house heating in 1991 was the equivalent of 0.8 US$ per cubic meter of 80 °C hot water, corresponding to an energy price of 0.016 US$/kWh of useful heat. This is about 30% of the cost of heating with oil and about 45% of the cheapest electrical heating. Many of the smaller district heating systems have considerably higher heating costs, but still lower than the alternatives.

Heat pumps are usually not used as a part of geothermal district heating systems in Iceland. The only example is in the Akureyri District Heating System in northern Iceland, where in 1984 two heat pumps (Sabroe) of 2.6 MW_{th} were installed to provide additional capacity to the existing geothermal capacity of about 35 MW_{th}. The main characteristics of the system are shown in Fig.8. The heat pumps have operated satisfactorily both from technical and economical points of view. A few small heat pump units are also in use on individual farms where low grade geothermal water is available.

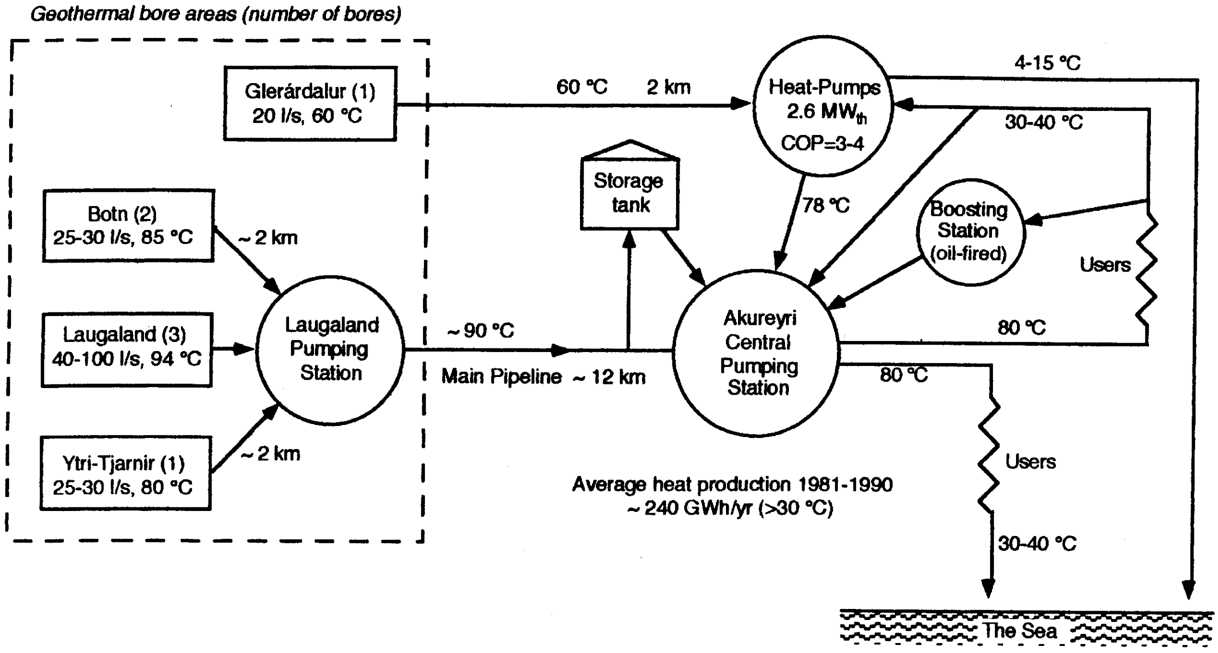

Fig.8. The Akureyri Geothermal District Heating System.

Other Direct Heat Uses

The Kísilidjan Diatomite Plant near the Námafjall high-temperature field in the NE-Iceland volcanic zone, which began its operation in 1967, is the second largest industrial user of geothermal steam in the world. It produces annually about 24,000 tons of diatomite filter aid which is exported. The steam consumption for heating and drying is in the range 40 - 50 tons/h at about 10 bara. The raw material for the production is diatomaceous earth deposits on the bottom of lake Mývatn about 3 km away. The mining takes place only in the summer, when the diatomite slurry is stored in reservoir ponds. The plant is operated the year around.

A new plant for the production of salts from geothermal brine has recently started operation on the Reykjanes Peninsula in SW-Iceland. It utilizes geothermal steam for evaporation. It will produce common salt for the domestic fishing industry as well as low-sodium health salt for export. The steam consumption will be similar to that of the Diatomite Plant.

Some 170,000 m^2 of geothermally heated greenhouses produce mainly flowers, tomatoes, cucumbers and other vegetables for the domestic market. About 105,000 m^2 of heated soil outdoors is used for growing vegetables.

Geothermal heating has been used to some extent in the fish farming sector, mainly for growing salmon and trout.

Environmental Aspects of Developing Geothermal Resources

In recent years environmental concern has sometimes been raised over possible harmful effects of developing the indigenous energy resources of the country. This despite the fact that these energy sources are much less harmful to the environment than the fossil fuel sources they replace.

Geothermal developments may have environmental impacts; among them the drying up of natural hot springs and the disappearance of other surface features. Development of high-temperature fields may cause air pollution by increasing the natural H_2S emission from the fields. It may also cause pollution of surface and ground water by power plant effluents having different chemical composition from the surface water at the site, which may affect soil and vegetation. Thermal pollution by these effluents can also be a problem. These effects are essentially restricted to high-temperature fields. Extraction of water from the geothermal reservoirs in excess of natural replenishment may result in land subsidence similar to that experienced in connection with oil production.

Against these essentially negative environmental impacts of geothermal developments must be weighted the very important positive effect of eliminating air and water pollution from the fossil fuels they replace. Moreover, while many of these effects are inevitable, their extent can be minimized by environmentally sound planning and construction and by pollution control equipment.

Geothermal energy has always enjoyed public support in Iceland, due to the obvious benefits of having access to this source of energy in a country devoid of petroleum resources and with a relatively cold climate, These benefits are obvious in most homes where heat is abundant and cheap, in public indoor and outdoor swimming pools, in heated sidewalks and parking places, and so on.

In fact, the availability of geothermal heat has in many places had a profound influence on rural development, with geothermal localities flourishing at the expence of those not enjoying the benefits of this energy source. There are of course many other factors affecting rural development, especially in the coastal areas where the fishing industries dominate the economy. But in some inland areas the availability of geothermal resources has been a decisive growth factor in local development.

The high-temperature geothermal fields in Iceland are located in the active volcanic zones, most of them in the core areas of central volcanoes. Some are located in calderas and are all traversed by fissure swarms that have been active during the Holocene period. Harnessing of high-temperature geothermal energy inevitably involves both volcanic and tectonic risk. An assessment of the risk associated with the development of these resources is an important part of the geological studies that have to be undertaken before decisions are made involving major investments.

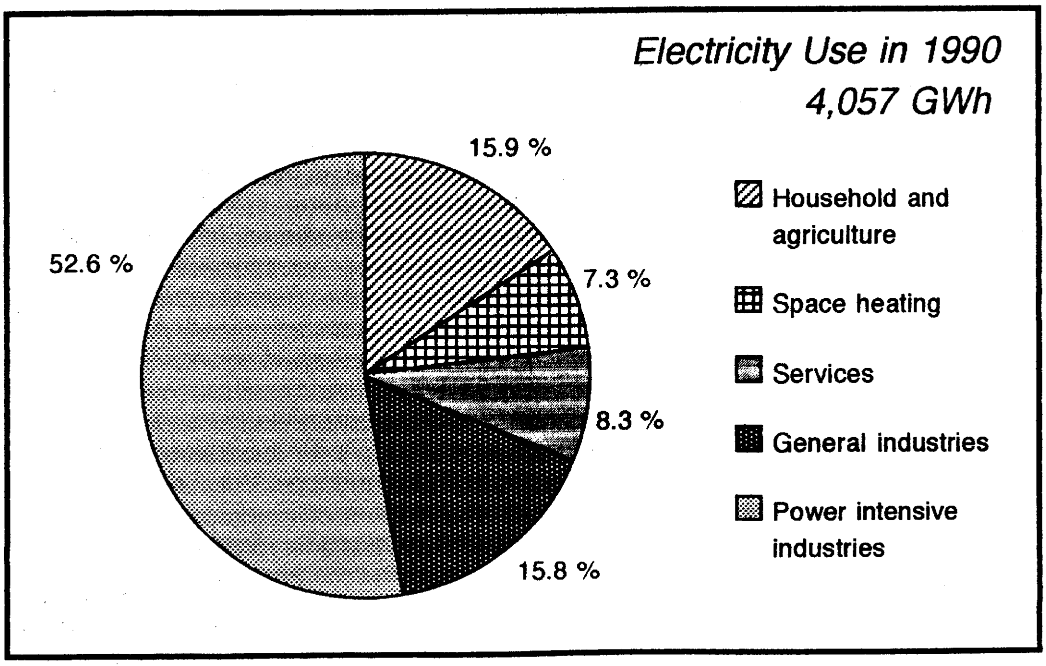

Fig.9. Electricity use by sectors in 1990.

Future Developments

There are two market directions that are envisaged to make use of the remaining untapped energy resources in Iceland, both hydro and geothermal. One is to attract power and/or heat intensive industries to Iceland, which has already been done to some extent (cf Fig. 9). Negotiations have been underway for some time for a new aluminium smelter producing

210,000 t/yr, but these are on hold due to an unfavorable market situation for aluminium. The other possibility is to export electricity via a DC submarine cable link from the east coast of Iceland to Scotland or England (Fig.10). Due to progress in DC technology this possibility has become increasingly realistic and is being studied at the present time.

In order to prepare for the future expansion of geothermal electricity generation, studies are being carried out aimed at lowering the overall cost of producing electricity from geothermal sources. Moderately sized modular units appear to be an attractive possibility. These studies are funded jointly by the state and the main utilities concerned. Since environmental considerations are likely to play an increasing role in the future, a similar study on the environmental effects of geothermal development is also being funded in the same way. Industrial uses of geothermal energy may also be of growing importance in the future.

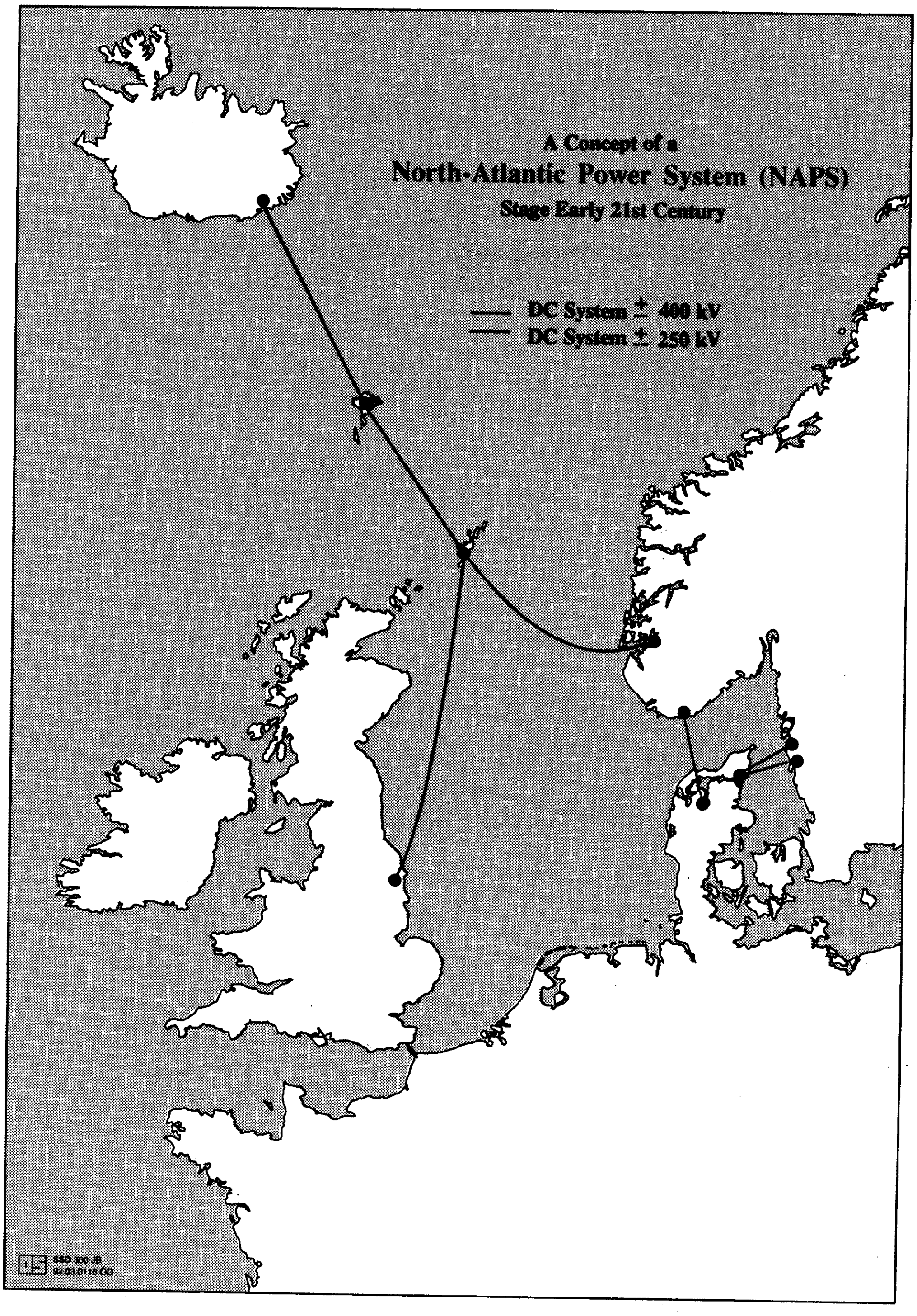

Fig.10. Possible DC submarine cable link to energy markets in Europe.