GEOTHERMAL RESERVOIR MANAGEMENT IN ICELAND

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ABSTRACT

At present, there are about 40 geothermal reservoirs under commercial exploitation in Iceland, and many have been exploited for more than 30 years. This exploitation of geothermal resources started in 1930. During the following 65 years geothermal reservoir management has become an integral part of the exploitation. Improvements in production technology, such as the use of down-hole pumps, have multiplied the energy extraction from the reservoirs. These improvements in production technology and improvements in management methods have made geothermal energy so attractive, both regarding price and reliability, that geothermal energy contributes 44% of the gross energy consumption in the country. An increasing demand for geothermal energy is met with management actions such as: more effective use of reservoir capacity, injection, improving production characteristics, and by extensions to new production fields. Never has the utilization of a geothermal reservoir in Iceland been abandoned because of a depletion of the reservoir. The basis for proper reservoir evaluation and successful management is the careful monitoring of the reservoirs and modeling work predicting their future response.

Keywords: ***reservoir management, reservoir sustainability, energy extraction, energy cost.***

1. INTRODUCTION

Management of a geothennal reservoir involves taking decisions during the operation of the reservoir in order to change its operational conditions. Most frequently, management actions are carried out m order to improve the operation m one way or another. Sometimes, management decisions are taken because. unfavorable conditions (cold water invasion, pressure drop) have evolved in the reservoir. In other cases, improvements in production technology (down-hole pumps, reinjection) might justify a change in production strategy aimed at prolonging the longevity of a geothermal resource.

Management of geothermal reservoirs relies on proper information on the reservoir. If some changes in production strategy are imposed upon the reservoir, the management concept means that the response of the reservoir is known in advance. Otherwise, it is not justified to talk about management actions. The information needed for a successful management of geothermal reservoirs is, in general, the following:

(i) Knowledge of the volume, geometry, and boundary conditions (f. ex. recharge) of a reservoir.
(ii) Knowledge of the internal properties of a reservoir such as permeability, porosity, density, heat capacity, and heat conductivity.
(iii) Knowledge of the physical conditions which are determined by temperature- and pressure distribution (f. ex. boiling).

Information about the time dependent parameters of a reservoir is usually collected with a proper monitoring program carried out during exploitation. Geothermal systems vary considerably in their nature, and the time constants involved in different processes have a considerable

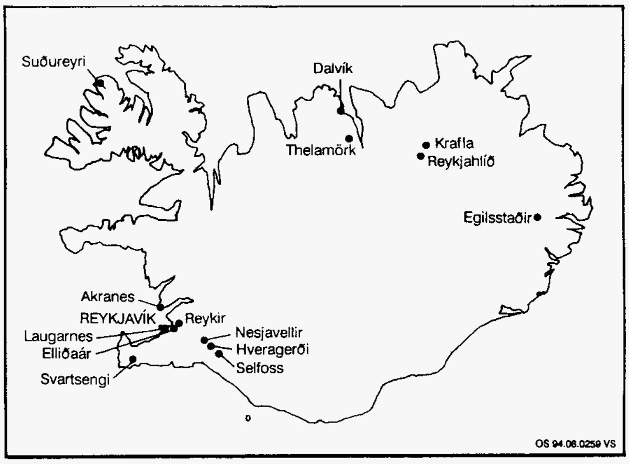

Figure 1. Location of the geothennal reservoirs discussed in the paper.

range. Therefore, the monitoring frequency is different for different parameters within a reservoir and for different reservoirs as well. The changes within a reservoir, affecting the production from the reservoir, usually take some months or years. Therefore, the management is a slow process and its long term objectives have to be well defined.

Reservoir management may have different objectives such as: to minimize the operational cost of a certain geothermal field, to maximize the energy extraction from a given resource, to ensure security of energy delivery, to minimize environmental effects, to avoid operational difficulties like scaling, to adhere to the energy policy of the respective country, and others. Quite often the objectives are a mixture of all the items listed above. In such cases it is necessary to put a preference order to the objectives because they may not all converge. It can be mentioned as an example, that keeping the operational cost low for two or three years might not agree with the goal to maximize the energy extraction for twenty or thirty years.

One of the most difficult aspects of reservoir management is to determine a time span for the management objectives. It may be neccessary to choose, for example, whether the maximum revenue of the resource should be obtained in 5 years or 30 years or even in 100 years. There are cases where depleting a given reservoir in 5 years instead of 30 years, is more viable from the pure financial point of view. Such cases are, however, usually unacceptable from the political or sociological point of view. Reliable availability of energy for a long time is considered more valuable than the internal rate of return of the investment in the development of the energy resource. The time usually chosen for the management objectiies is related to the expected lifetime of surface equipment. Power plants are frequently amortized in some 30-40 years and therefore the longevities of the reservoirs are matched to that time span. Several reservoirs have been exploited successfully for a much longer time and it is not obvious whether geothermal reservoirs should be considered as finite energy source (i. e. a mine) or as a renewable energy source.

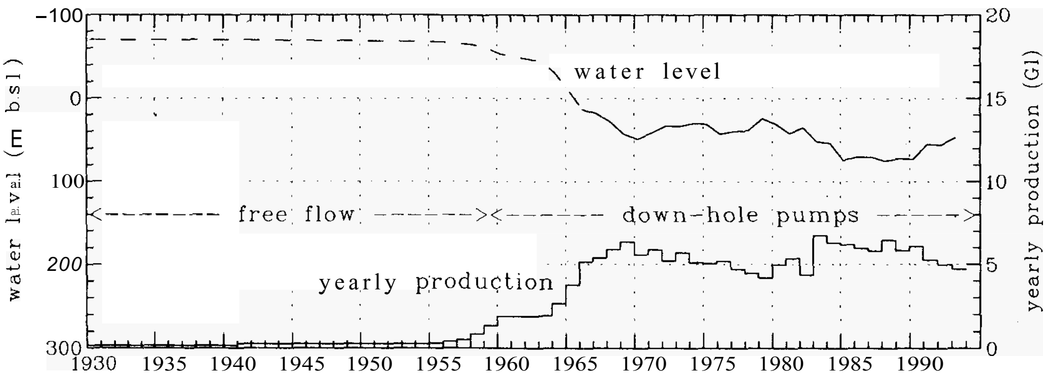

Figure 2. Production and drawdown in the Laugames geothermal field 1930-1994. Up to 1960 the production was free flow from wells, but pumping with down hole pumps has been the production method since 1962-1965.

At present, there are more than 30 geothermal reservoirs under commercial exploitation in Iceland. The largest number of these are low-temperature reservoirs utilized for hot water production. Direct use of geothermal energy is mainly for space heating in Iceland where more than 85 % of the houses in the country are heated with geothermal energy. In addition six high-temperature reservoirs are currently utiliid for electricity generation, space heating, and industrial purposes. In some of these geothermal reservoirs production has only caused minor changes in reservoir conditions whereas in other cases pressures have either declined continuously or the pressure drop has caused a considerable cold- and/or saline-water recharge. The management of these reservoirs has aimed at meeting an increasing energy demand as well as meeting the decreasing potential of reservoirs where major changes in subsurface conditions have occurred.

Mathematic models are presently used in Iceland to predict future conditions of the reservoirs. Lumped parameter models have been found very useful for predicting the reservoir responses of single-phase geothermal systems (Axelsson, 1989). In the case of two-phase reservoirs and m cases where large variations in temperature or pressure conditions prevail, distributed parameters models are used (Bodvarsson et al., 1990). Model predictions have always been found to be a reliable basis for management considerations. No geothermal reservoir in Iceland has been abandoned because of depletion.

The present paper describes several representative management actions applied m Iceland along with the reservoir conditions that have caused these actions. These actions include: production with down-hole pumps, improving the efficiency of geothermal utilization, injection (of waste water) into the reservoirs, actions to prevent or circumvent the effects of Scaling, search for improved production characteristics within the geothermal system under exploitation, and extension to new production fields. Location of the reservoirs discussed in the paper is given in Figure 1.

2. DOWN-HOLE PUMPS

Introduction of down-hole pumps, as a production method for low-temperature geothermal reservoirs, is the single management action that has caused the largest improvement in geothermal utilization in Iceland. The first down-hole pump was tested in Reykjavik in 1955. Severe operational difficulties were experienced in the early days and the lifetime of the first pumps was relatively short. The design of the pumps was improved during the years to follow under the leadership of Jóhannes Zoega, the former director of The District Heating Services of Reykjavik. By 1966 a reliable type of pump had been developed and this type of down-hole pump has been in use in Iceland ever since. At present there are about 100 down-hole pumps in operation in Iceland and the average lifetime of the pumps is about 10 years (Gunnarsson, 1992).

Figure 2 shows the production history of the Laugames field located within the town of Reykjavik. This is the first geothermal field m Iceland utilized for public district heating. The utilization started m 1928 and the production from the field from 1930 to 1993 is presented m Figure 2. Up to 1958 the production was only by free flow from wells but after 1964 the production has been entirely by down-hole pumps. The rate of free flow from the field was some 2040 l/s before pumping started but the average production in the years 1965-1993 has been about 160 l/s. An enhancement in production by a factor of 4 to 8 was, therefore, obtained by the introduction of down-hole pumps in the Laugarnes field. It should be noted that the production rate during the 30 years of pumping has been relatively constant and that the pressure (water level) in the reservoir has also been relatively stable during the pumping period.

A comparable enhancement factor by the introduction of down-hole pumps was also obtained for the Reykir field located just outside Reykjavik. The average rate of free flow before pumping was about 250 l/s but with pumping the average production has been about 1100 l/s, an enhancement by a factor of 4.

3. NEW GEOTHERMAL DEVELOPMENTS

The first management decision to be taken is whether a given reservoir should be developed for utilization. The price of geothermal energy as compared to the price of other energy sources is usually the deciding factor. One of the most sensitive parameters for the price of geothermal energy is the distance between the field and the consumer. Transportation of hot water is not economical over very long distances. Although geothermal fields are widely spread throughout Iceland, there are still some populated areas economically to far away from known geothermal resources. The longest pipeline transporting hot water from the field to the market is 64 km, serving a town with 5000 inhabitants (Akranes). Another long geothermal pipeline transports hot water produced at Nesjavellir to consumers in Reykjavik. The temperature decline along this 30 km long line is 1-2°C.

High oil prices in the last two decades made viable many hot water distribution projects that were formerly economically marginal. Furthermore, great emphasis was placed on efforts to discover new geothennal resources near large hot water markets. The result of this can be seen in Figure 3. In 1970 about 45% of residential buildings in Iceland were heated by geothermal energy. During a period of ten years (1975-1985) there was a rapid increase in the use of geothermal energy for space heating and at present more than 85% of buildings in Iceland are heated by geothermal energy.

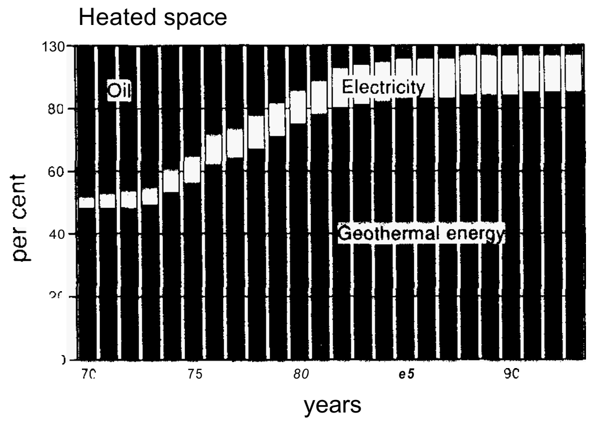

Figure 3. The effect of increased oil price on the utilization of geothermal energy for space heating in Iceland.

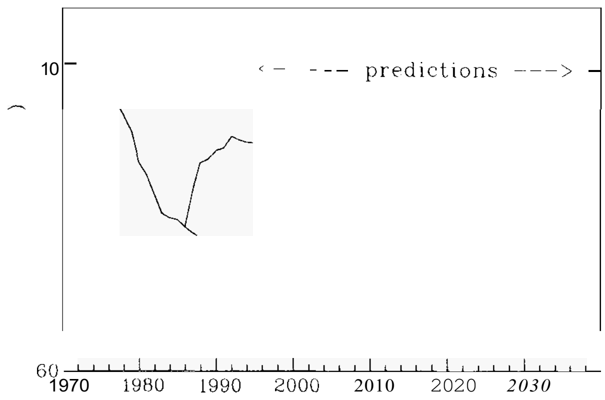

Figure 4. Measured and predicted draw-down in the Hamar reservoir. Power tariff for hot water sale used up to 1986, but energy tariff in use after 1986.

4. EFFICIENCY OF GEOTHERMAL UTILIZATION

The utilization of geothermal energy by the consumer may be priced in different ways. In Iceland two modes of selling hot water for space heating and other domestic uses have been employed. One method is to charge the consumers according to the energy consumed (actually the volume of hot water), the other method is to base the energy bill on the peak power demand of the consumer (maximum flow rate). A tariff based on the power is in some ways simpler in use for the district heating services. Each consumer pays a fixed price for the whole year and the administrative work for the distribution is minimal.

The experience of the two tariff systems has shown that the energy consumption of consumers paying according to the power tariff was much greater than those of consumers paying according to the energy tariff. This is quite natural. The consumers paying according to the power tariff use the power they have paid for, regardless of whether they need the power or not. The inefficient energy consumption by the district heating services applying the power tariff resulted in a greater burden on the geothermal reservoirs than actually was necessary. Great pressure drawdown was observed in the reservoirs, and it was foreseen that the geothermal resources would only sustain the load for a limited time. One way to prolong the life of the geothermal resource is to force the consumers to use the energy more efficiently. A relatively simple way to obtain this objective is to change the hot water tariff from the power method to the energy method. This has been done in several instances in Iceland.

Figure 4 shows, as an example, the pressure drawdown in the Hamar reservoir serving the district heating service at Dalvík (pop. 1,500) in North Iceland. Up to 1986 the hot water was sold to each consumer according to the power tariff. The average production rate was about 41 l/s during this period. In 1986 the tariff was changed and the hot water sold according to the volume of hot water used. The energy demand of the town decreased to about 27 l/s after the change of the tariff. Because of the reduced production from the reservoir the reservoir pressure has recovered by approximately 2 bars, as is shown in Fig. 4.

Figure 4 also shows the predicted drawdown in the reservoir up to the year 2040. Assuming that the production from the reservoir will be constant in the future, the 1986 drawdown will not be reached until the year 2070. This indicates that the action of changing the sales tariff for the hot water in Dalvík has prolonged the lifetime of the geothermal resource by at least 80 years. The value of this management action can be estimated by considering the price of 27 l/s of hot water for 80 years. By using the present average price of geothermal energy to the consumer in Iceland, the value of the prolonged lifetime of the Hamar resource is about 25 million US dollars. The cost involved in changing the tar8 was some. 50,000 US dollars. This shows that proper management actions in the operation of geothermal reservoirs can be very profitable.

5. INJECTION

Injection has not yet become an integral part of the operation of geothermal reservoirs in Iceland. This is partly because disposal of waste geothermal water has never been an environmental issue in Iceland in contrast to other countries. The concentration of dissolved solids in water from the Icelandic low-temperature fields is usually low enough for the water to be classified as drinking water according to norms issued by international organizations (EC, WHO, FAO). Waste water can therefore be disposed of at surface or into sewers. In the high-temperature fields, surface disposal of waste water has also been the common method. Investigations have not suggested that the waste water will cause adverse ecological effects. In fact, in one case (Nesjavellir) the waste geothermal water improves the living conditions of trout in the nearby lake Thingvallavatn. In another case (Svartsengi), a disposal lagoon in the lava field surrounding the power plant has become an important tourist attraction.

As a consequence of these circumstances, injection is primarily considered in Iceland as a tool to improve the operational conditions of the reservoirs rather than an environmental issue. Injection experiments have been carried out in some of the low-temperature geothermal fields in recent years (Axelsson et al., 1995), and limited injection has been applied in the Svartsengi high-temperature field since 1984 (Björnsson and Steingrimsson, 1992). In both the high-temperature and low-temperature cases, injection is into liquid dominated reservoirs such that the desired reduction in pressure drawdown was observed in all cases. Figure 5 shows the simulated response of the limited reinjection on the Svartsengi reservoir. The drawdown between 1976 and 1992 is about 22 bars and the average mass production since 1980 is about 250 kg/s. The injection rate during 1984-1992 varied between 20-40 kg/s, or about 8-16% of the production. The reduction in the pressure drawdown due to injection is about 4 bars as shown in Fig. 5. Injection of 75°C water in Svartsengi caused some. cooling in a nearby production well and the injection scheme was changed in 1988. Model calculations have shown that injection wells in Svartsengi need to be located some 3-5 km away from production wells in order to reduce their thermal influence (Vatnaskil, 1989).

Detailed studies of the effect of injection in four low-temperature fields (Axelsson et al., 1995) reveal that maximizing the benefit from injection can be a delicate problem where the injection rate, temperature of injected water, and distance between injection and production wells needs to be selected with great care. In some cases only a low rate of

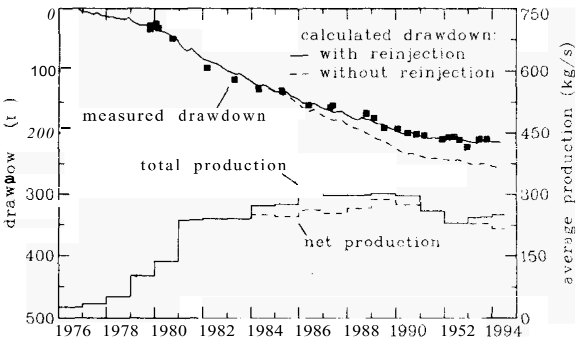

Figure 5. **Pressure** and production history of the Svartsengi reservoir. Model calculation for production with and without reinjection.

injection will improve characteristics of production wells, whereas **m** other cases, where the flow paths between injection and production are sufficiently long, injection of cold water will raise the production capacity considerably.

There **seems** to be no general rule regarding the applicability of injection **as** a production method in geothermal exploitation. The individual nature of each geothermal reservoir calls for specific investigations for each case in order to determine the most appropriate reinjection **scheme. A** generalized simulation study on the benefits of reinjection into high-temperatun:**fields** ***utilized*** for electricity generation has shown that reinjection causes surprisingly small gain in electrical production when two phase condition prevail in the reservoirs (Sigurðsson et al., **1995).** Reinjection strategy **is,** however, always favorable when the management emphasis is on the thermal sweep of the reservoir.

6. SCALING PREVENTION

Part of the geothermal utilization is to design the utilization scheme in such a way that **precipitation from** the fluid will cause minimal effect on the geothermal operation. In Iceland it is mainly precipitation of calcite, silica, and magnesium silicate that have influenced the utilization **as** well **as** the management of the geothermal resources.

Precipitation of calcite is a fast process taking place where the geothermal **fluid** flashes for the first time. Calcite scaling is of concern in **two** fields in Iceland, Svartsengi and Hveragerði. The wellbore ***scaling*** is removed regularly by mechanical cleaning of the wells while they **are** discharging. In that way the debris reaches the surface and the production is only disturbed for one or two days. By using wide production casings (13 **3/8** ") such **as in** Svartsengi, the wells may be operated for **4-5** ***years*** before the scaling starts to affect the production rate and cleaning is required. Calcite scaling has therefore a relatively minor effect on the operational cost.

Calcite scaling is sometimes observed in low-temperature fields **as** a result of hot and **cold** water *mixing* m the production wells. The scaling **is** affecting the down-hole pumps, and a yearly cleaning of the pumps are necessary in some cases **(Suðureyri,** Selfoss).

Silica scaling affects the design of the utilization process rather than being an operational problem. This is because silica deposition is a much slower process than the precipitation of calcite. It is therefore possible **to** select **a** suitable place in the utilization scheme where it is convenient to remove the **silica** scaling. Production wells are always operated at well-head pressure above the scaling point of amorphous silica because removal of ***scaling*** is easier m **surface** piping than in wells. Fluidized bed heat exchangers are for example used in the power plant at Nesjavellir such that the precipitation takes place where the deposition can be removed relatively easily (Gunnarsson et al, **1992).**

Magnesium silicate deposits have been of concern in all cases where heated groundwater is used for space heating (Svartsengi, Nesjavellir, Hveragerði, and Reykjahlfð). These deposit may **usually** be avoided if heated groundwater is not allowed to **mix** with natural geothemal water. Geothermal waters are saturated in silica but depleted in magnesium. Cold groundwater, on the other hand, contains some **magnesium** The mixing of such waters may cause magnesium silicate precipitation although deposits do not occur in each of these **types** of waters. when the Nesjavellir power plant was commissioned in **1990,** it was found ***necessary*** to separate the distribution system within Reykjavik m order **to** prevent mixing of the heated ground water from Nesjavellir with geothermal water from the low-temperature fields (Laugames, **Elliðaár** and Reykir).

7. IMPROVED PRODUCTION CHARACTERISTICS

One of the district heating services that started operation in the period of high oil prices is the one at Egilsstaðir in East Iceland. **A** low-temperature geothermal resource had been located below Lake Urriðavatn **some** *5.5* km from Egilsstaðir. **A** few wells were **drilled** yielding enough hot water for heating of the town. Operation started in **1979,** but during the first four years substantial cooling of the produced water was observed (Fig. ***6).*** It became obvious that the heating service could not continue to meet the demand of the heating market unless the production characteristics were improved. **A** comprehensive reinvestigation of the geothermal system was carried out and the up-flow zone of the system located. **A** new well (well 8) was targeted to intersect this channel at depth greater than the depth of production zones in the other wells.

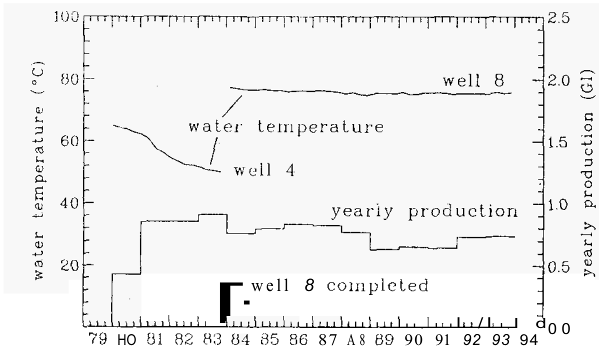

Figure 6. Production history from the Urriðavatn field. New well with improved production characteristics taken in **use i983** resulting m stable temperature delivery.

Well 8 turned out to be highly successful yielding more than 10°C hotter water than the older wells. The production capacity of this ***single*** well was, furthennore, several times greater than the capacity of each of the older wells. Figure ***6*** shows the production history from Urriðavatn. After **1984** well 8 has fulfilled completely the district heating demand. The temperature of the produced fluid from well 8 has changed very little during an operating period of ten years.

A similar situation arose in the Krafla high-temperature field in North Iceland. During the construction period of a 60 MW power plant **in this** field a volcanic eruption started within the caldera where the geothermal field is located (Stefánsson, **1981; Ármannsson** et al., **1987). The** geothermal reservoir became contaminated with magmatic gases **disturbing the** chemical equilibrium between **the** geothermal fluid and the reservoir rock (Ármannsson et al. **1989).** Complex precipitations started to clog **some** of the wells and acidic fluid was observed **in** others **(Ármannsson** and Gislason, **1992). As** a result a large part of the geothermal reservoir in Krafla **was** deemed un-exploitable. Considerable effort was therefore put into finding parts within the geothermal system where the reservoir fluid was not affected by the magmatic gases. Two such subsystems (Suðurhlíðar and Hvíthólar) were discovered and have delivered most of the steam used for the 15 years of power generation in Krafla. Both Suðurhlíðar and Hvíthólar are *small* compared to the main contaminated reservoir m Krafla. The. available steam has therefore only been enough for 30 MW production instead of the designed 60 MW.

The examples from Urriðavatn and Krafla show that a search for better production characteristics within a given geothermal system can be a viable management option when undesirable changes take place in the reservoir under exploitation.

8. NEW PRODUCTION FIELDS

The. demand for geothermal energy is increasing continuously in Iceland at the average rate of 6% annually during the last 30 years. This indicates that sooner or later the demand for geothermal energy will exceed the capacity of the reservoirs under exploitation. Most of the District Heating Services exploit one geothermal reservoir only. The District Heating Services in Reykjavik and Akureyri, however, utilize four reservoirs each. Up to the present only these two Utilities have been faced with the decision when the development of a new production field should take place. A prerequisite for this management option is of course that there are some unexploited geothermal resources in the neighborhood.

In the terms of investment, the largest management decision taken m Iceland was the decision to develop the Nesjavellir high-temperature field as additional energy source for the Reykjavik Municipal District Heating Service. The cost involved in the development of the Nesjavellir Co-Generation Power Plant is about 125 million US dollars (Gunnarsson et al., 1992). It is obvious that a long series of other management actions had preceded the decision to develop the field.

The. Reykjavik Municipal District Heating Service started operation in 1930 by distributing 2.5 MW from the Laugames field. In 1943 a new production field (Reykir) commenced operation and the power of the heating service increased to 45 MW. Production with down-hole pumps started in the Laugames field in 1962-1967 (see chapter 2). In the years 1967-1970 a new production field at Elliðaár was added to the distribution system. Redevelopment (by down-hole pumps) of the Reykir field increased the power from the field by a factor four. These different management actions had increased the power of the distribution system to more than 600 MW, used for space heating and as domestic hot water for 145,000 people (Zoega, 1987).

The timing of the development of a new production field is not a simple decision. Feasibility calculations can be carried out in an accurate way, but the assumptions behind the feasibility study may be subject to change. In the case of the development of Nesjavellir, the security of energy delivery was the major component in the timing of the development. Before Nesjavellir came in, three geothermal reservoirs, Laugames, Elliðaár, and Reykir, supplied the hot water. In all three reservoirs signs of "over-exploition" had been observed, mainly as invasion of cold water affecting some production wells. Although the cooling was not serious it raised some questions regarding the future evolution By developing Nesjavellir this uncertainty was removed and the overall security of energy delivery could be increased considerably.

The financial viability of the Nesjavellir Power Plant has never been questioned. The long term hot water price is estimated at 0.008 US$/kWh, which is lower than the pre-Nesjavellir consumer price of 0.013 US$/kWh. In addition the power plant is designed to generate some 80 MW of electrical energy m the future. The production cost of electricity from Nesjavellir is estimated to be 0.008 US$/kWh which is much lower than estimated for new hydro-power stations in Iceland (Gunnarsson et al., 1992). The timing was therefore mainly a comparison between the security of energy delivery and the long term minimum investment cost.

The. technical and economical conditions for developing the Thelamork reservoir for the Akureyri District Heating Service have recently been described by Bjomsson et al. (1994). The Thelamork reservoir is a relatively small geothermal resource located 11 km north of Akureyri. Its connection to the distribution system would add some 4 MW to the system. The energy price for this small geothermal resource is estimated 0.008-0.009 US$/kWh, which is much lower than the energy price of any other energy source available in Akureyri.

9. ECONOMICS

When geothermal energy is used as thermal energy, it is the cheapest energy source available in Iceland. Typical production prices (price at well-head) are m the range 0.001-0.005 US$/kWh, and consumer prices are usually m the range 0.010-0.020 US$/kWh. This is the main reason for the successful development of geothermal energy in Iceland. Geothermal energy has the largest share (44%) of the energy consumption m Iceland. No other country covers that large part of its energy demand by geothermal energy.

Electricity is mainly (95%) generated from hydropower in Iceland and geothermal energy contributes only 5% to the electricity generation. The cost of electricity generation in new power plants is estimated to be similar for hydro and for geothermal power plants. The production prices for both hydro and geothermal are estimated to be in the range 0.012-0.022 US$/kWh. In 1993 hydropower contributed 16.4% of the primary energy consumption m Iceland, geothermal energy 44.1%, and imported fossil fuels 40.5%. The total energy consumption in the year 1993 was 103,000 kWh/capita, which ranks among the highest in the world.

The geothermal potential of Iceland is great compared to the present level of energy utilization in the country. It is, however, the utilization methods and the management of the geothermal resources that have made geothermal energy the cheapest thermal energy in Iceland.

10. CONCLUSIONS

- The experience of commercial operation of geothermal resources m Iceland dates back to 1930. During this period, the production methods and the understanding of geothermal systems have improved considerably.
- Careful monitoring of the physical and chemical conditions m the reservoir is the basis for a proper reservoir evaluation at each time.
- New production techniques such as the use of down hole pumps and the co-generation of heat and electricity have been introduced and such management actions have increased the usable energy of the resources by a factor of more than four.
- Development of geothermal resources m Iceland has at all times been directed by the price of geothermal energy in comparison to other available energy sources. This has resulted m geothermal energy now being the cheapest source for heat energy in the country. Proper management of the geothermal resources maintains the low energy prices and secures the continuity of the produced energy.
- Effective use of the geothermal resources have contributed to low consumer prices and extended the longevity of the reservoirs in several locations.
- In Iceland, injection is primarily considered as a production method that can improve the long term exploitation of geothermal reservoirs. Several injection experiments have revealed that injection in each reservoir needs to be balanced in a careful way in order to obtain beneficial effect on the operational conditions in the different reservoirs.
- The search for improved production characteristics within a reservoir under exploitation has in many cases proved to be a viable management option when undesirable changes take place in the reservoir.

- Increasing demand for geothermal energy results in that new production fields have to be developed sooner or later. The timing of new development is not a simple decision. Technical and economical considerations have to be compared to political and sociological preferences. The timing of a new geothermal development depends on a comparison between the security of energy delivery and the long term minimum investment cost.
- Geothermal energy is the cheapest thermal energy source available in Iceland, and it contributes 44% of the gross energy consumption in the country. Typical well-head prices are in the range **0.001-0.005 US$/kWh,** and the consumer prices are usually in the range **0.010-0.020 US$/kWh.**

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