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GEOTHERMAL EXPLORATION AND DEVELOPMENT FROM A HOT SPRING TO UTILIZATION

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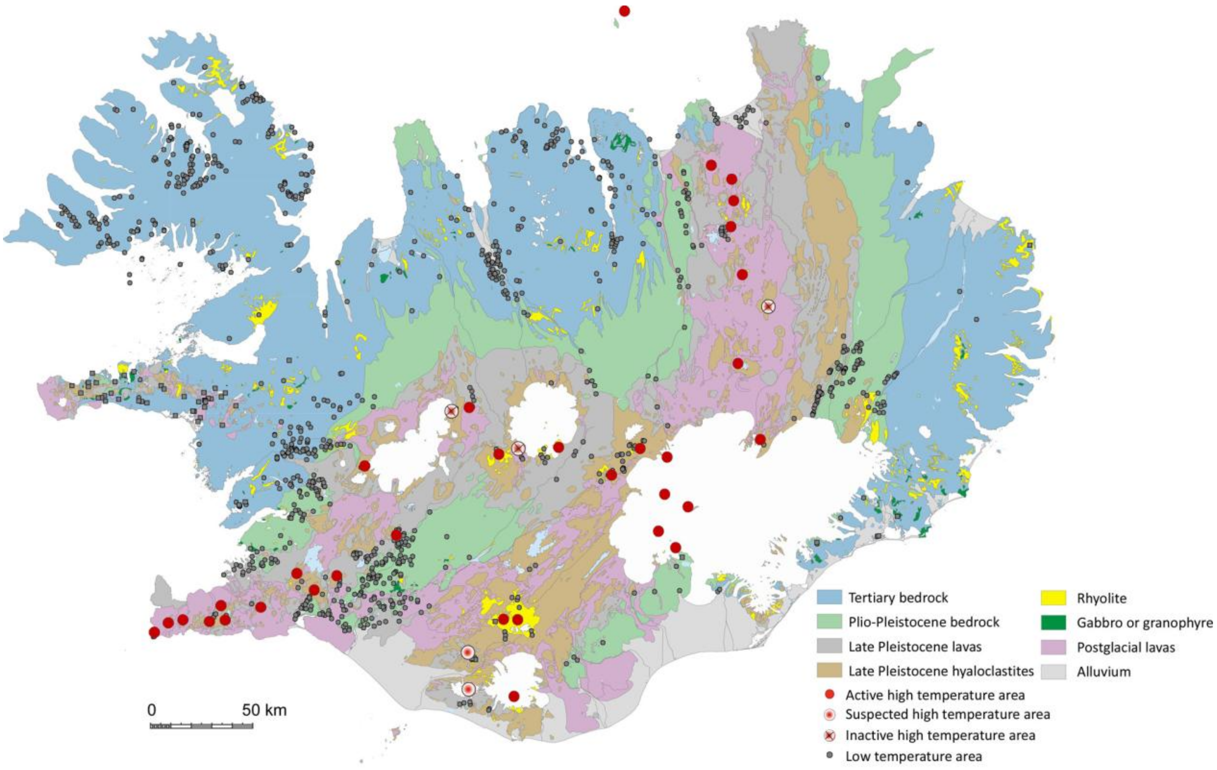
ABSTRACT

The use of geothermal energy in Iceland was very limited through the centuries and it was not until the beginning of the twentieth century that geothermal started to really contribute to the energy budget in Iceland. The usage has, however, increased dramatically during the last 100 years and today geothermal energy supplies over 65% of the primary energy used in Iceland. The most important use has been for space heating but geothermal power production has increased rapidly during the last few years. Exploration and the development of the geothermal fields are divided into several stages or phases starting with preliminary studies, and continuing with appraisal studies, project design, construction and operation of the geothermal plant, and the final phase of the life cycle of the development is the shutdown and the abandonment of the plant after operation for decades.

1. INTRODUCTION

Iceland is an island in the North Atlantic just south of the Arctic Circle. The island lies across the Mid Atlantic Ridge, the rift zone along the constructive boundary between the American and the Eurasian tectonic plates which move apart at an average rate of 2 cm per year. Iceland resides on a mantle plume and a hot spot in the rift zone and has been formed in frequent volcanic eruptions continually from Miocene time to present. This explains why this part of the ridge rises above sea level and forms an island with an area greater than 100.000 km^2. The presently active zone of rifting and volcanism crosses Iceland from southwest to northeast. Volcanic eruptions are very frequent in this zone and take place typically every few years. The Icelandic crust is therefore very young on the geological time scale and rocks on surface range in age from zero near recently active volcanoes to 15-16 million years in the coastal areas furthest away from the volcanic zone in the east and the west.

Iceland is rich in geothermal resources due to the volcanic activity, and heat flow through the crust is several times higher than the world average. Traditionally the geothermal fields are divided into high-temperature fields, where temperature above 200°C is found at 1 km depth, and low-temperature fields, in which temperature is lower than 150°C in the uppermost kilometre. Some 30 high temperature fields have been identified in Iceland, all within the active volcanic zone as shown in Figure 1. The low temperature activity is highest on the flanks of the volcanic zones but some low temperature resources are found in most parts of the country (Figure 1).



Basemap: Geological map of Iceland by Haukur Jóhannesson and Kristján Sæmundsson 1999. Iceland. 1:1.000.000. Icelandic Institute of Natural History.

FIGURE 1: Geothermal map of Iceland. High-temperature fields inside the active volcanic zone are shown as red circles, and hot and warm springs as yellow circles

The utilization of the geothermal resources of Iceland was very limited through the centuries. Hot water from warm springs was, however, used locally in some areas for bathing, cooking and washing, and sulphur was mined from a few of the high temperature areas and exported to Denmark. It was, however, not until at the beginning of the last century that utilization of the geothermal resources really started. Initially the geothermal development focused on the utilization of low temperature resources for space heating. Later utilization of the high temperature resources for electrical generation, space heating and some industrial uses followed.

Large scale utilization of geothermal resources in Iceland began in 1930 when a district heating system started operation in Reykjavik (capital of Iceland) supplying hot water to a hospital, a school, a swimming pool, and some 70 homes. The utilization grew gradually over the next decades (Figure 2). During the energy crises in the 1970s an effort was made to exclude use of oil for house heating and replace it with geothermal energy. This was a very successful development and today almost 90% of houses in Iceland are heated by geothermal energy and electricity (generated by hydro and geothermal) serves about 10% the heating market.

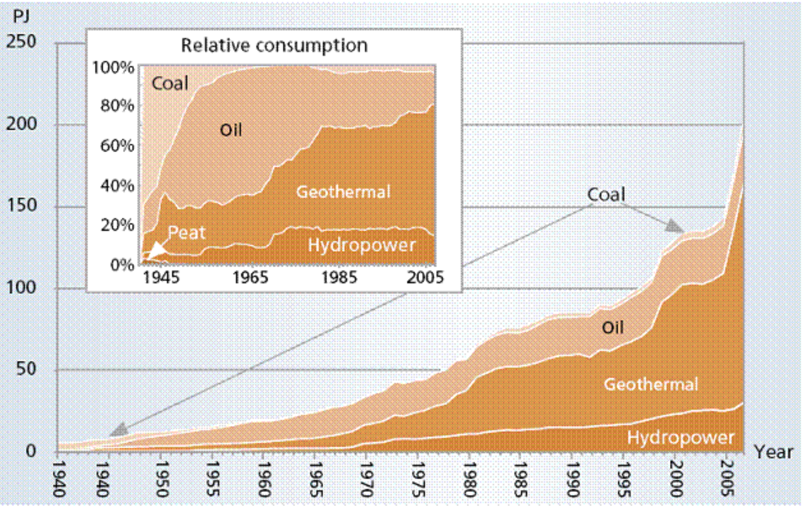


FIGURE 2: Primary energy consumption in Iceland 1940-2007. Source: National Energy Authority

During the last few decades the geothermal utilization has continued to grow as geothermal power production has increased. The installed geothermal power capacity is at the end of this year (2008) is 575 MWe. Geothermal energy has become the main source of energy in Iceland supplying over 65% of the primary energy used in the country (source.National Energy Authority).

The objective of this paper is to give a general overview of the methodology used in geothermal exploration and development in Iceland. We will do this with a step by step discussion leading through the exploration and the development and grouping the steps into project phases similar to what is done internationally, e.g. in the Philippines (Dolor, 2005), and in Kenya (Mwangi, 2005).

Before we start to describe the phases of geothermal exploration and development we should keep in mind that all human efforts are limited by factors which will determine the success of our endeavour. Some of these factors we can control, others not. For the successful development of geothermal fields the factors that first come into mind are the following: (1) *Market opportunity*: Initial geothermal field studies have the aim of understanding the basic properties of the geothermal fields and have therefore a general knowledge seeking purpose. Utilisation of the field will on the other hand depend on whether there are possible geothermal users for fluid or energy from the fields, i.e. is there a market for the geothermal fluid and the geothermal energy? Several geothermal fields are located close to populated areas and can easily be developed economically. Others are in remote areas, high up in mountains, and in Iceland some of the fields are underneath the ice cap of glaciers (Figure 1). Utilization of such fields is not possible for obvious technical and economical reasons. (2) *Knowledge and technical skills.* The exploration and development of a geothermal resource demands an experienced and skilled team of geothermal specialists, both various kinds of geoscientists and engineers. (3) *Time*: The development of a geothermal field takes several years. The construction of a geothermal power plant takes at least a couple of years and if we add the exploration and drilling period and the time needed for flow tests of wells, environmental impact studies and licensing, a time frame of 6 to 10 years is common. (4) *Financing:* Large geothermal projects are high cost projects. To develop a field for power generation the cost is of the order of 3-6 million US dollars per MW installed, depending on the properties (mainly temperature) of the field being developed. The geothermal developer must therefore have access to a mechanism to finance their projects. (5*) Luck*: Not all the parameters are known when you are evaluating the potential of a geothermal field and the feasibility of a geothermal project. One has therefore to take important decisions from limited information, especially early in the project. Unforeseen events will in addition of course happen during the life time of the project, and some of them can have serious influence on the project. In Iceland we ran into an eruptive period of the Krafla volcano only six months after the construction of the Krafla Geothermal Power Plant started. The eruptions had a serious effect on the geothermal system and changed at least temporally the production characteristics of the field. The eruptions delayed the development of the Krafla field but did not stop the project and power plant is in full operation today. The Krafla volcano had been dormant for 250 years.

2. STUDIES OF GEOTHERMAL SURFACE MANIFESTATIONS

The exploration and development of a geothermal field leads us through several steps. In the geothermal literature you will find various approaches in defining the steps. The first step in geothermal investigations is usually the studies of the geothermal activity found on the surface in the area under investigation. These manifestations are the first indication or evidence for the existence of a potentially exploitable geothermal resource. The manifestations can be of various types, ranging from active hot springs and fumaroles to hot and steaming grounds and cold but altered grounds indicating extinct geothermal activity on the surface.

The studies of surface manifestations include visual inspection of activity. Photographs are taken with conventional cameras or cameras that sense the infra red radiation of the hot manifestations. Maps are drawn to show the distribution of the manifestations and the soil temperature is measured and mapped.

The fluid temperature and flow rate of the hot springs is measured as well as the temperature of the steaming fumaroles. Measurement of the steam flow rate from fumaroles is not easy but indirect (or relative) estimation of the steam flow has been developed and applied in few high temperature areas in Iceland. Historical records of the geothermal activity in the area are collected to evaluate the stability of activity. Fluctuations in the activity are often related to earthquakes and volcanic activity.

The surface activity offers a window to the underlying geothermal system. Sampling of the geothermal fluids from the manifestations and analyses of the samples give indications on the fluid chemistry of the geothermal reservoir and through the application of geothermometers the reservoir temperatures can be estimated from the fluid chemistry. The distribution of the manifestations and the soil heat maps often indicate that the flow path for the upflow of the geothermal fluid to the surface is fracture controlled.

The studies of the surface manifestations and their results are gathered and described in a summary or reconnaissance report. The possibilities of utilizing the field are also described in the report and environmental aspects of utilization schemes are evaluated. The report concludes the first step of the geothermal exploration. Many geothermal fields in the world have only undergone exploration of the surface manifestation. Others have been explored further and several developed for utilization.

3. PHASES OF GEOTHERMALEXPLORATION AND DEVELOPMENT

The methodology and the strategy of the exploration and development of the Icelandic geothermal fields have been under critical discussion and review ever since their utilization started. The strategy adopted for early development was to estimate the power capacity of each field through exploration and drilling, and subsequently to design and construct a power plant with a view to fully utilize the estimated field capacity in a single power development. Later this strategy has been changed to stepwise development where the capacity of the field is tested with a relatively small power unit and later expanded in steps until the full potential of the field is developed.

A generic phase plan was proposed in 1982 for the systematic exploration and development of the Icelandic high-temperature fields (Stefansson et al., 1982). The plan, which is shown in Figure 3, divides the developments into the following five phases:

3.1 Preliminary study

The preliminary study starts with collection and critical review of existing geological, geophysical and geochemical data obtained for the area. On the basis of these a detailed multidisciplinary exploration program is defined and executed. The program usually includes various surface exploration methods, i.e. mapping of the geothermal manifestations and measurements of temperature and flow rate to compare with previous information, if available. The geothermal fluids are sampled for chemical analyses and chemical geothermometers are used to estimate reservoir temperatures. The geological studies would include lithological mapping, structural geology, volcanism, hydrogeology, geo-hazards and environmental geology. Geophysical surveys include gravity measurements to determine the density variations of the lithological units, and magnetic measurements to trace faults and dyes. The most important geophysical method in geothermal exploration is, however, the resistivity surveys. Various resistivity methods are applied including Sclumberger, TEM, CSAMT and MT. The resistivity anomalies are used to outline the probable extent of the geothermal field and define upflow and outflow zones.

The surface exploration concludes with a definition of potential drilling targets. Then a few (often 3–5) exploration wells, 1 to 3 km deep, are drilled at these strategic sites. The main objective with the exploratory drilling is to confirm the existence of a hot resource and prove the productivity of the drilling targets defined from the surface exploration. After successful completion of the exploration drilling, all the information obtained during the preliminary studies are incorporated into a conceptual model of the field and a comprehensive resource assessment carried out. The feasibility of further development of the resource is analysed and presented in a pre-feasibility report.

3.2 Appraisal study

The appraisal study is the next geothermal development phase after a positive conclusion of the preliminary study. It includes drilling of appraisal wells in order to determine production capacity and characteristics of wells and to obtain data to evaluate the reservoir characteristics and to confirm the existence of a productive resource for long-term operation of the planned power development. The reservoir evaluation includes detailed geological models showing the geological structures and main lithology units of the reservoir, delineation of the production zone and potential injection areas, distribution of productive aquifers, temperature and pressure distribution, reservoir fluid chemistry, reservoir permeability and porosity. The wells are flow tested and measurements carried out to determine the mass (steam and liquid) flow capacity of wells and the average fluid enthalpy. The production decline with time is evaluated at least on a short term basis. Scaling and corrosion potential of the geothermal fluid is also evaluated during the appraisal studies.

The conceptual model of the geothermal field is revised and updated according to the new reservoir data. Based on the conceptual model, a numerical natural state simulation model is developed and calibrated against available field data and production data from the wells. The final part of the appraisal phase is an economic feasibility study of the planned project to estimate the capital and operating cost of power plant.

3.3 Project design and construction

Project design and construction are the next two phases following the appraisal study completion. These phases include, as their names indicate, a detailed design of the project and thereupon the construction of the whole development and the installation of the plant equipment. Production and injection wells are drilled with the purpose of providing sufficient production and injection capacity for the project. The time is also used for testing of the wells, often several wells at the same time to observe and get quantitative measurements of the short term response of the reservoir to considerable production or production similar to what it will be when the power plant starts operation. The reservoir data obtained during these phases is used to revise existing conceptual and numerical models of the reservoir and make a prognosis for the future response of the reservoir to production. These models are imperial in deciding the production management of the reservoir during the operation of the plant.

3.4 Commissioning and operation

Commissioning and operation was the project’s final phase per the generic plan depicted in Figure 3. Successful operation of geothermal projects calls for a comprehensive monitoring and management plan for the utilized geothermal field in order to predict changes that may happen in the reservoir characteristics, well productivity/injectivity and fluid chemistry during long term operation. The management of geothermal resources is discussed in greater detail in Chapter 5.

3.5 Shutdown and abandonment

The sixth development phase, shutdown and abandonment, is often added to the generic plan to complete the life cycle of the development, though not shown in Figure 3. This is the final phase of any geothermal development (Dolor, 2005; Mwangi, 2005).

During exploitation of the geothermal reservoir, the reservoir pressure and the well output normally declines in the long term. The rates of decline depend on the rate of natural recharge of heat and fluid into the reservoir. They can also be controlled to some degree by the production and re-injection strategy and proper reservoir management. In addition to this "depletion" tendency of the reservoir the power plant components and other surface equipment get old and may start failing to an extent that makes it uneconomical in operation. There are a few examples of geothermal power plants that have been abandoned. A few geothermal power plants in the Geyser field in California have been shut down, however, because of the lack of steam due to over-exploitation of the field. This could have been avoided, if the generating capacity of the field had been adequately known prior to the construction of these plants, or realized in time. Other geothermal plants have been partially rebuilt to meet changes in steam characteristics (i.e. steam pressure and gas content), e.g. the Wairakei plant in New Zealand which celebrates its 50th anniversary of operation in November 2008. It is generally accepted that geothermal power plants can be operated for several decades if both the plant and the geothermal field are properly managed and operated.

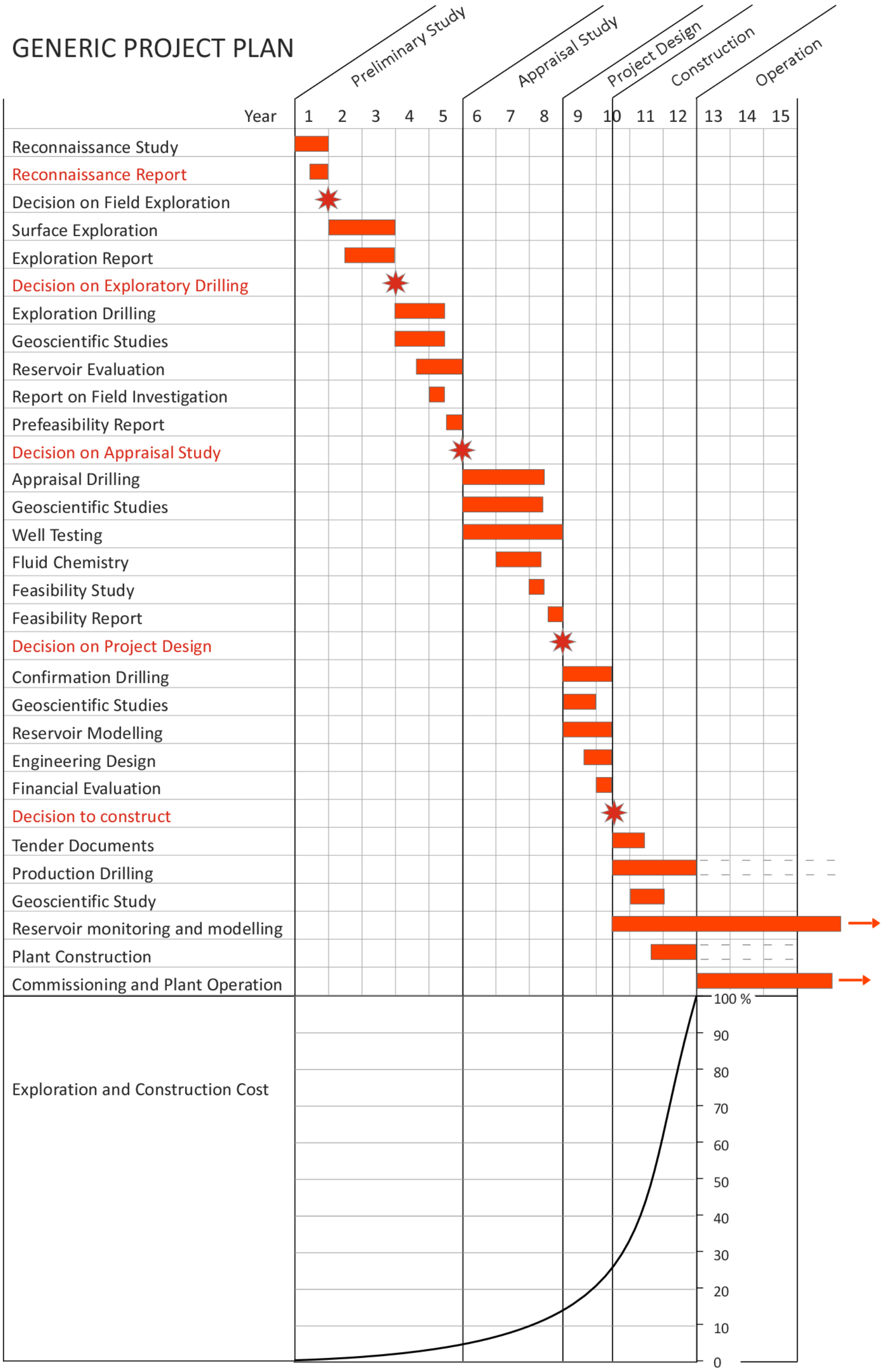


FIGURE 3: The Icelandic generic plan of 1982 for geothermal power development

The generic plan in Figure 3 illustrates the relevance of the main tasks required for each development phase discussed above. Also shown in the figure is a rough relative estimate of the associated exploration and development cost. It clearly indicates that the relative cost of the preliminary studies is small, but escalates when production drilling and construction of the project starts. Figure 3 also gives an estimate of the timeframe for the development. According to the figure, it takes ten years of exploration and drilling before a decision to construct the plant is taken and a total of 13 years from the start of the project until the plant is finally commissioned and starts operation.

The development strategy described above assumes the production potential of the geothermal field to be known prior to the decision on utilization. A generating capacity of the power plant is subsequently decided to fully match the field potential. The above described strategy is probably borrowed from hydropower development in Iceland, for which the determination of production capacity is rather easy and is known at a relatively early stage in the exploration phase. This does, however, not apply to geothermal areas where reliable knowledge on the maximum generating capacity can only be obtained through an extensive exploration and research as detailed above.

Stefansson (1992) discussed several examples of geothermal projects worldwide and pointed out that a stepwise development strategy for geothermal resources has considerable economical benefits compared to full utilization of the geothermal filed in one big step. By following the generic plan in Figure 3 but selecting a relatively small (20–50 MW) power unit as a first step, the time scale can be reduced and the first unit commissioned and put into operation much earlier than is possible for a "full" size plant. Monitoring of the field's response to the first development step is then used to determine if and when the next step can be undertaken, a new power unit (20-50 MW) installed and so on until the full potential of the reservoir is utilized. One can say that in the stepwise strategy the resource's sustainable generating capacity is first known when the field is fully utilized, whereas in the one step strategy the production capacity is determined (and not necessarily on basis of sustainability) before the power plant is built. A comparison of these two strategies is shown in Figures 3 and 4.

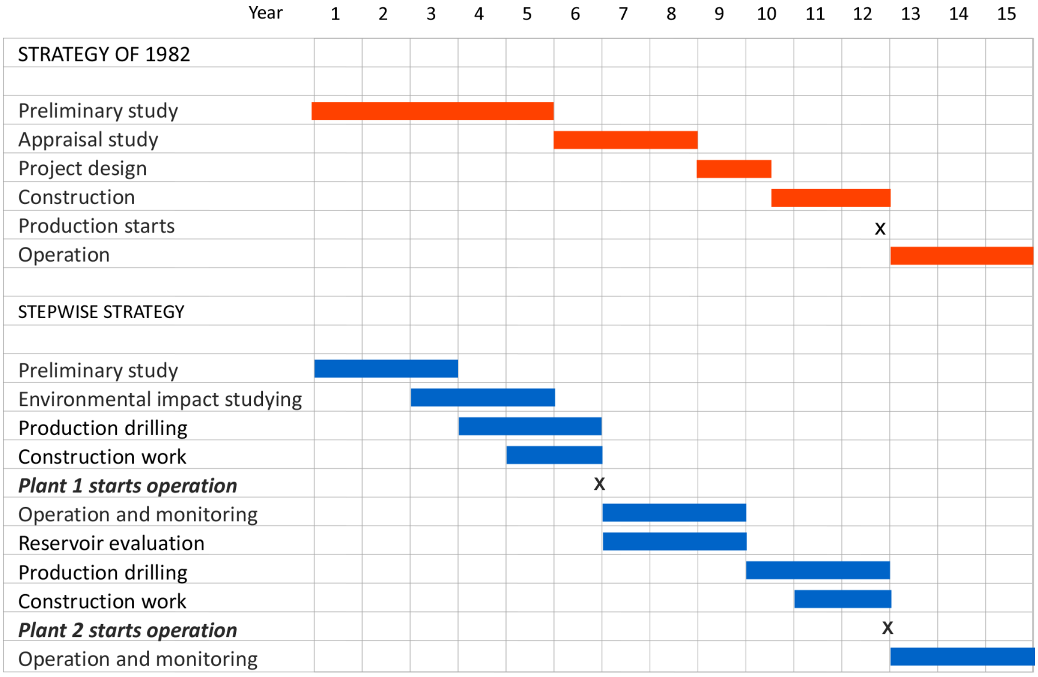


FIGURE 4: The stepwise development strategy (lower part of the figure) compared to the strategy of 1982 (upper part of the figure) where the full potential of the field is matched in one power plant

The Icelandic energy companies have been applying the stepwise development approach in their latest developments, but the current approach is more aggressive than initially assumed, i.e. when the stepwise plan was suggested ten years ago. An example of this is the power plant at Hellisheidi, which is in the south-western part of the Hengill geothermal area only 20 km from Reykjavík. Hellisheidi has been a candidate for utilization for decades. The first idea dates back to the 1940s when it was suggested that the field could be developed for space heating in Reykjavík. The preliminary studies customary at that time were carried out and one shallow exploration well drilled to about 100 m depth. The project was never realized, however, but geothermal studies were continued in the area as a part of the geothermal exploration undertaken for the Hengill area. The geology was mapped during 1965 to 1985 and the geophysical surveying was carried out between 1975 and 1985. Finally an 1800 m deep exploration well drilled in 1985 confirmed the existence of a 280°C resource.

The drilling of the exploration well in 1985 completed the preliminary studies of the Hellisheidi field at that time. Further development of the field was, however, delayed until 2001 when Reykjavík Energy decided to develop the field for power generation and hot water production for space heating in Reykjavík at a later stage. The appraisal phase was carried out during the following three years with the drilling of 8 deep wells, additional preliminary studies and an environmental assessment. Reykjavík Energy decided in 2004 to start production/injection drilling and construction of the power plant and to develop the field in the following stages:

Hellisheidi I	90 $\mathrm{MW_e}$ electric plant to be completed in 2006
Hellisheidi II	33 $\mathrm{MW_e}$ bottoming unit, completed in 2007
Hellisheidi III	90 $\mathrm{MW_e}$ electric plant completed in 2008
Hellisheidi IV.	400 $\mathrm{MW_{th}}$ hot water plant to be completed in 2009

Hellisheidi I to III were commissioned on time and the production drilling and construction work for Hellisheidi IV is on schedule.

Further development of the field has not been decided and will depend on the response of the field to this utilization. Reykjavík Energy is monitoring the field response and so far no signs of over-exploitation have been observed. The production history is, however, short and the fluid withdrawal from the field only a small fraction of what it will be when all four power plants are in operation.

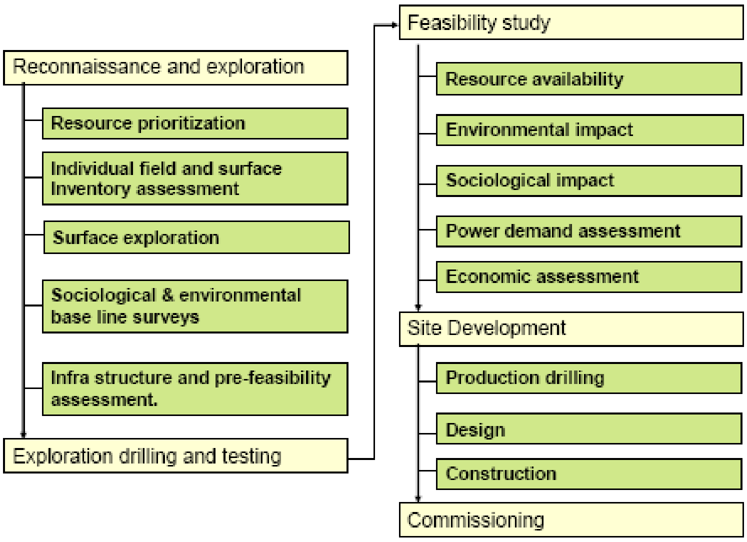


FIGURE 5: Schematic flow diagram for geothermal development

The discussion above has been focused on the geothermal developments in Iceland. A similar approach is being applied in other geothermal countries, and the World Bank has on its webpage (http://www.worldbank.org/) general information on geothermal development and a phase development scheme (Figure 5).

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