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Development of the 400 MW Northeast Iceland Geothermal Project

Bjarni Pálsson[1], Árni Gunnarsson[1], Kristinn Ingason[2], Ásgrimur Gudmundsson[1], Hreinn Hjartarson[3], Bjarni Már Júlíusson[4]

[1]Landsvirkjun Power Ltd, Háaleitisbraut 68, IS-103 Reykjavík, Iceland, [2]Mannvit Engineering Ltd, [3]Theistareykir Ltd, [4]Landsvirkjun, the National Power Company of Iceland

Corresponding author: BjarniP@LvP.is

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ABSTRACT

Since 2005, Landsvirkjun, the National Power Company of Iceland, and Theistareykir Ltd have joint forces to develop four high enthalpy geothermal fields within 30 km radius in Northeast Iceland to create a sufficiently power capacity to attract power intensive industry into the area, Landsvirkjun to develop Krafla, Bjarnarflag and Gjástykki and Theistareykir Ltd to develop Theistareykir. One alternative could be a 250,000 tonne aluminum smelter in the town of Husavik, requiring 400 MW_e that could potentially start operation in 2015. If the project goes through, it would be the first large aluminum smelter only powered by geothermal energy and at the same time, the geothermal development project would be one of world largest geothermal project. This project is referred to as the Northeast Iceland Geothermal Project

This paper presents an overview of the preparation phases for this extensive geothermal project, including surface exploration, exploration drilling, power plant design strategy, planning and environmental impact assessment.

1. INTRODUCTION

Geothermal conditions in Iceland are very favorable for energy utilization. Iceland is a so called “hot spot”, a highly volcanically active island on the boundary between the Eurasian Continental plate, moving east, and the American Continental plate, moving west. In addition, Iceland is on the path of warm ocean current, the Gulf Stream, and humid lows from the Caribbean Ocean, bringing relatively mild climate and high level of precipitation (Figure 1). Approximately 30 high temperature areas can be found on the spread zone, crossing the island from the southwest to the northeast. Several have been identified as favorable for electrical power generation, economically competitive with the most favorable hydropower potentials, with temperature at 2000 m depth 250-350°C (Figure 2).

For centuries, the main form of harnessing the high temperature fields was gathering dry sulphur for gun powder production but several unsuccessful attempts were made for other industrial applications.

In the 1960’s a cascaded use of high temperature geothermal fluid started in the Námafjall field. Steam produced from 300-2000 m deep wells has been utilised to produce electrical power in the 3 MW_e back pressure turbine Bjarnarflag power station, used directly for industrial applications in a diatomite plant (1963-2005) and in a brick factory and the separation water is used for district heating system and for the Mývatn Nature Baths, attracting up to 100 thousand visitors annually to the area.

Since the 1980’s, Landsvirkjun has focused its geothermal activity on the Northeast Iceland, Námafjall (Bjarnarflag), Krafla and Gjástykki areas. Landsvirkjun purchased the 30 MW Krafla geothermal power plant in 1986 and extended it to 60 MW in 1999.

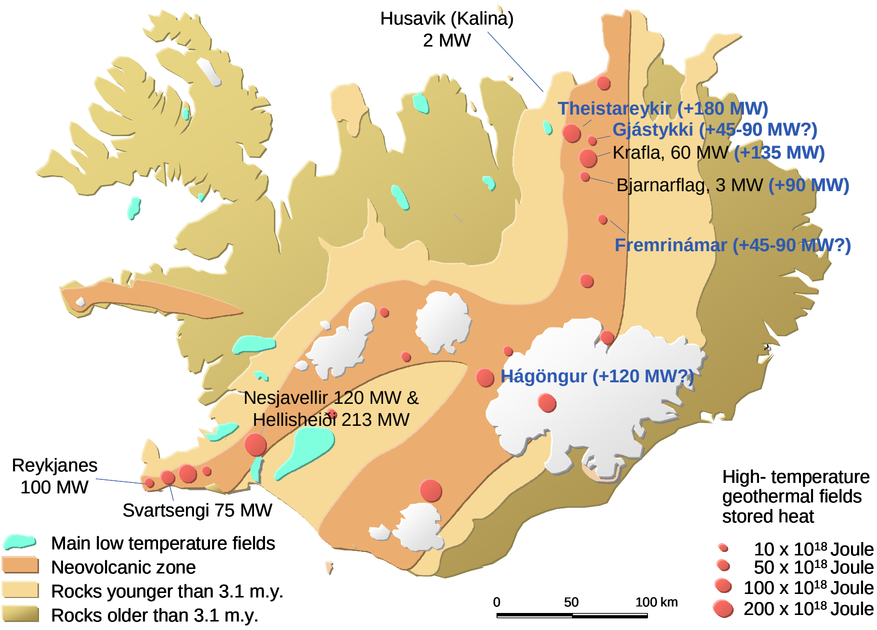

Figure 1: Current geothermal power capacity and future plans of Landsvirkjun and Theistareykir.

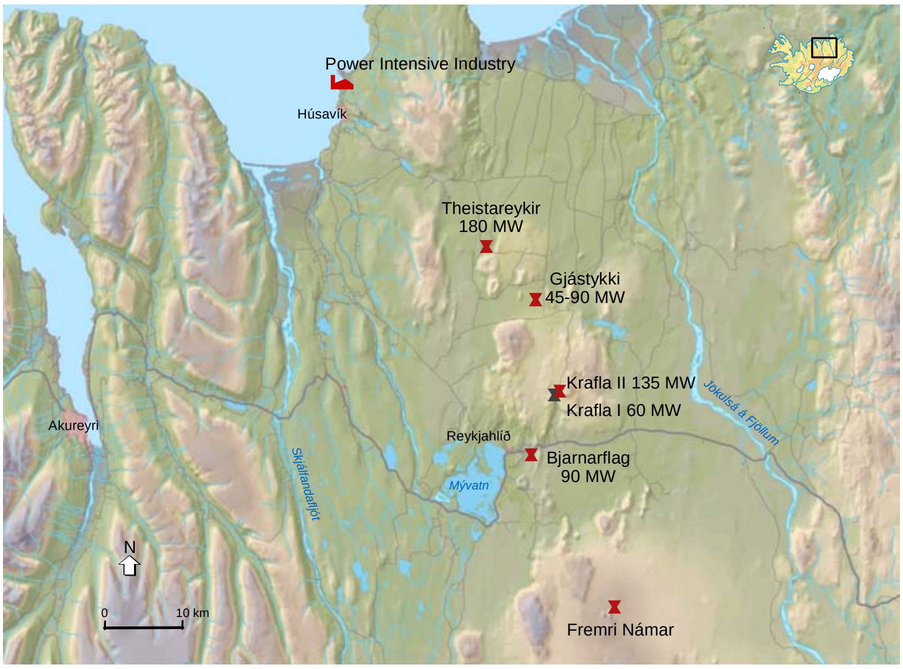

Figure 2: Geothermal power potential in Northeast Iceland.

In 2005, the diatomite plant in Bjarnarflag was shut down. The same year, Landsvirkjun purchased a 32% share in Theistareykir Ltd., a company founded few years earlier to develop the Theistareykir geothermal field. The two companies decided to join forces in an attempt to attract power intensive industry into the area. The ideal customer would require a long-term power purchase agreement for several hundred MW of power, built up in stages, and would recruit several hundred skilled employees in Northeast Iceland. After discussions with several interested companies, Landsvirkjun and Theistareykir started formal negotiation procedure with Alcoa in 2006, aiming at building an aluminium smelter requiring at least 400 MW, delivered over a 2-3 year period. Even for relatively well known fields, this would be a demanding task.

2. GEOTHERMAL DEVELOPMENT STRATEGY

A development strategy for such an extensive project is a complex interaction between the geothermal exploration programs, the power purchase agreements, the permission process and eventually, public acceptance.

Ideally, the geothermal exploration program starts with relatively low cost surface surveying, such as geological mapping, geochemical studies and geophysical measurements of the fields which aim at finding best locations for exploration wells. The first exploration wells are drilled with the purpose to localize the main up-flow zones, followed by more reliable strategy for production drilling. As a result, the financial risk is minimized at the same time as the value of information is optimized. However, the timeframe of other external factors, such as changing market conditions, rig availability and transportation cost and strict environmental restrictions can affect such optimization.

In general, the process of developing a geothermal site in Iceland is as follows:

2.1 Exploration License

The first step would be to apply for a 3-7 year exploration license from the National Energy Authority. The National Energy Authority seeks opinion from (i) the local municipality or municipalities which determine if the exploration plans are in line with land development strategy, determined within acting development plans, and (ii) from the Ministry for the Environment, which seeks information from several relevant organizations and agencies and possibly other stake holders. As a result it is more likely to succeed if support is received from owners of land and geothermal rights (if not the government) and the local municipality.

The exploration license has to span the period from first phase surface exploration, well location and acquiring of licenses for exploration drilling, the more detailed second phase exploration, project design and environmental impact assessment, until a power production permit is acquired, prior to start of construction. The Energy Authority has limited exploration licenses to 3-10 years to make sure the license holder is not dwelling too long with the exploration.

2.2 Geothermal Exploration

The process of geothermal exploration through first phase surface exploration, first phase exploration drilling and more detailed second phase surface exploration and second phase exploration drilling is described in further details later in the paper.

2.3 Planning Permits

According to the Icelandic Planning and Building Act No. 73/1997, geothermal power projects have to be included in two levels of planning. Most importantly in the *Municipal Plan* which expresses the policy of the local authority for land use, transportation, service systems, development of settlements and not least environmental matters for the duration of at least 12 years. A more detailed *Local Plan* has to be prepared for the land directly used for the power development, determining items such as sizes of building areas, drill sites, steam gathering system etc. In certain cases, e.g. if a geothermal project extends over more than one municipality or if it extends into the highlands of Iceland, a *Regional Plan* can be made, combining more than one municipality plans. All of these plans have to be evaluated and publicly presented for opinion according to the Strategic Environmental Assessment Act No. 105/2006.

2.4 Engineering Design

At various stages of the project´s development, the site is evaluated and reconsidered with regard of power potential and feasibility.

After the first phase surface exploration, the power potential of the site is estimated in a simple conceptual model (e.g. Monte Carlo method). Potential access routes, connection to transmission lines, likely location of cooling water, mines etc. is mapped. Maps with 10 m resolution accuracy in contour lines have been prepared at this stage. These results, along with rough estimates of quantities are presented in *Feasibility Study* report.

If a feasibility study appears to be positive and in line with the long term power development strategy of the power company, a decision may be made to continue with more expensive and comprehensive *Plan Design*. At this stage, further exploration drilling and more detailed surface exploration is required, resulting in a more advanced conceptual model of the geothermal reservoir, which will continue in natural state and numerical simulation. Furthermore, environmental issues are studied in further details, both with respect to environmental impact as well as utilization aspects, such as ambient temperature, humidity and dominating wind direction for conceptual design of cold end. The project plan reports is divided in two parts, first a draft report is prepared prior to Environmental Impact Assessment (EIA) and then the results of the EIA are included in the final report. iIt often has significant impact on important issues, such as layout of an impact on surface structures, drill pads, access roads, power line location etc. The project plan report also includes construction time schedule a list of main quantities and cost estimation with 10-15% accuracy sufficient to allow making a decision if to start construction. At project plan stage, the power project is presented in municipal and, if relevant, regional plans.

If a decision is made to build a power plant, the project proceeds into Tender Design stage, that includes detail design, as relevant, and making of tender documents. Landsvirkjun's policy is to tender power projects into several work packages, e.g. (i) Drilling Works, (ii) Steam supply system, civil and steal works, (iii) Powerhouse construction and (iv) turbine generating unit, with or without the cold end etc.

2.5 Permits for Power Projects

Prior to power plant construction, several permits have to be in place, most importantly:

Development Permit from the local municipality, subject to plans and EIA.

Power Development License from the National Energy Authority.

Operating Permit from the Environment Agency.

These permits and licenses will be acquired once a decision has been made to develop the power projects.

2.6 Environmental Impact Assessment (EIA)

Exploration drilling is not automatically subject to full EIA. However, deep high temperature wells are subject to *Notification* of project to the Planning Agency, which after seeking for the opinion of stakeholders will determine if the project is subject to full EIA. In Northeast Iceland this process has given mixed results. In 2002, drilling of up to 6 wells in western Krafla field was determined subject to full EIA as they were located on postglacial lavas whereas drilling in southern and eastern Krafla were not. The first 6 exploration wells in the Theistareykir area were not considered subject to full EIA but further drilling awaits full EIA of the 200 MW_e Theistareykir Power Plant. Drilling of the first three exploration wells in the Gjástykki area will take place on recent lava, erupted in the Krafla fires 1975-1984 and were subject to full EIA.

All geothermal power projects larger than 10 MW_e are by law automatically subject to EIA. The process may take from 6 months but the reality has been 18-24 months.

2.7 Public Acceptance

In Iceland, as in most western societies, debates on nature preservations and land use have increased significantly in recent years, in particular if large international corporations, such as aluminum corporations, are involved. In addition to the planning and EIA processes, the power companies Landsvirkjun and Theistareykir Ltd. have attempted to meet the increasing demand for public participation in several ways. Most important is open presentation of the project, directly in public meetings, through project web page and through public media.

An innovative approach has been the application of a so called sustainability initiative, aiming at having public participation in measuring the impact of the project on the local environment, society and economic development. This methodology was successfully implemented in a prior project of Landsvirkjun and Alcoa, involving the 700 MW_e hydro project Kárahnjúkar and the 340 kt/a aluminum smelter in the small town of Reydarfjordur in 2003-2009. The sustainability project for the Northeast Iceland project is in the initial phases establishing baseline conditions of environment, society and economy in the local communities, Northurthing, Thingeyjarsveit and Skutustadarhreppur.

Public surveys have indicated that the project has an overwhelming local public support despite significant impact in the relatively small community.

3. GEOTHERMAL EXPLORATION PROGRAM

When entering into project of the scale of magnitude and complexity as the Northeast Iceland project, it is vital to have a clear exploration strategy available for all parties involved. The exploration strategy for the Northest Iceland projects has to meet the requirement of the development companies to maximize knowledge at the same time as minimizing cost and risk of failure, as well as the expectations of the potential power purchaser and the provider of the exploration license, the National Energy Authority, within restrains from environmental regulations.

The exploration projects aims a trustworthy conceptual model of the resource, which can be referred to as *Geothermal Play* – equivalent to the petroleum play in the oil industry.

3.1 First Phase Surface Exploration

The first phase exploration stage, or surveying, starts with relatively low cost exploration methods that can be done without drilling. Generally they are divided into three categories:

(i) Geothermal and geological mapping, focusing on analysis of geothermal manifestations, geological formations, identification of faults and fractures, origin, orientation and history of volcanic activity. The geothermal map gives a strong indication about the size and nature of the geothermal field, as most Icelandic high temperature fields are inside active central volcanoes and both up-flow and recharge is associated with the main tectonic.

(ii) Geophysical surveying. Over the past two decades, Transient Electro Magnetic resistivity measurements (TEM) have been considered the most effective first phase surveying tool for Icelandic an environment, as basaltic formations conducts electrical currents better with temperature up to 230-240°C, reflecting progressive changes in alteration of clay minerals until stable chlorite is formed, which leads up to higher resistivity signals. This phenomenon shows up as a “low resistivity cap” covering a “high resistivity core”. Figure 4 shows a TEM survey covering the geothermal areas under discussion in Northeast Iceland. Other first phase geophysical studies include MT- (magnetic telluric), gravity- magnetic- and increasingly seismic surveys.

(iii) Geochemical surveying focusing on sampling and analyzing the geothermal natural outflows. It gives a good indication of temperature distribution in the reservoir (Armannsson, 2005). These surveys have the dual purpose of indicating the nature of the resource as well as providing baseline conditions to later monitor environmental impact of exploration and production.

None of the measurements listed above can stand alone but have to be interpreted in relation with each other. The best example is when TEM measurements show resistivity low cap outside active volcanic areas, it may be an old geothermal system that has cooled down. The parameters acquired at the first phase surface exploration, such as size of “TEM resistivity cap” and reservoir temperature, are used to prepare a volumetric estimate of the geothermal resource.

3.2 First Phase Exploration Drilling

If still uncertainty about reservoir temperature, following successful first phase surface exploration, e.g. if no steam vents are available, 500-1000 m deep slim or core-drilled holes can be drilled to confirm level of mineral alteration and correlate with actual temperature. Such wells may also give indication about reservoir pressure and fluid properties, for approximately 20-30% of the cost of full size exploration well and significantly less impact. The relatively small rigs could for example be transported on ice roads into lava fields or wetlands where conventional drilling operation would leave larger footprints.

Landsvirkjun’s safety policy is to drill the first deep well in a high temperature field (*wild cats*) with a large rig, equipped with two annular BOP valves and two sources of cooling/drilling water. The first wells are drilled near to the center of the field, typically from a location where permanent impact is minimized, if possible. During the first phase exploration drilling stage, 3-6 wells are drilled.

3.3 Second Phase Surface Exploration

Following successful first phase exploration drilling stage and during second phase exploration drilling and development drilling stages, the reservoir model is improved with further surface exploration, such as installation of distributed micro seismic sensors, MT survey and joint inversion interpretation. The more advanced exploration techniques may include leveling, tilt and GPS observations (Sturell et al., 2008), well interference tests with pressure and tracers etc.

During second phase surface exploration, a full environmental monitoring program starts to identify base-conditions; monitoring of groundwater chemistry, air quality, fauna, wildlife, geological features, impact on other land uses, such as tourism and farming etc.

3.4 Second Phase Exploration Drilling

Prior to a final decision on the power project, typically following an EIA and during power sales negotiations, the field is further explored by drilling deeper and stepping-out from the center of the field, extended flow-testing if possible, to allow further studies of pressure behavior and geothermal resource modeling (update of conceptual model and Monte Carlo and/or full scale reservoir simulation) to better determine the size and production capacity of the reservoir. Typically, half of the steam required for the first phase of the power project has been gathered at the end of second phase exploration drilling stage.

3.5 Appraisal and Operational Phase

Operation of geothermal power project requires constant re-evaluation of the geothermal resource to help decision on if and how to extend the power production, where to locate make-up and step-out wells and to make long term prediction on power capacity and sustainability of the power production, the last one being an ever more important issue. Therefore, geothermal exploration is an ongoing process throughout the lifetime of the power plant.

4. OVERIVEW OF THE GEOTHERMAL FIELDS

When the decision of Landsvirkjun and Theistareykir Ltd. for a joint development was made in late 2005 the four fields were at different exploration stage. Both Námafjall (Bjarnarflag) and Krafla fields had been partly developed for decades whereas the Gjástykki field was still in first phase surface exploration and exploration licence not yet been granted and only two deep exploration wells had been drilled in the Theistareykir field. At present, Table 1 gives a simple overview of the status of surface exploration. The table does not reflect the different level of exploration stages for the fields. Both Krafla and Bjarnarflag are in second stage exploration phase, Theistareykir field is in second phase surface exploration but Gjástykki is still in first phase exploration and no deep exploration well has been drilled.

An important aspect of the surface exploration survey was to make a common TEM survey covering all four fields. The survey illustrated clearly the extent of all fields, as well as confirming that no other high temperature fields exist within that area, eliminating speculations about a “hidden” field between Gjástykki and Theistareykir. Figure 3 presents the results of the TEM survey at 500 m below sea level, 800-1000 m below surface.

Table 1: A simple presentation of the status of surface exploration. 1) Not numerical.

	Geologic al/ geotherm	Resistivity survey	Ground-water	Exploratio n wells	Reservoir Simulation Model
Krafla	X	TEM/MT	X	8	X
Bjarnarflag	X	TEM/MT	X	3	X
Theistareyki r	X	TEM/MT	X	6	X 1)
Gjastykki	X	TEM	X	0	-

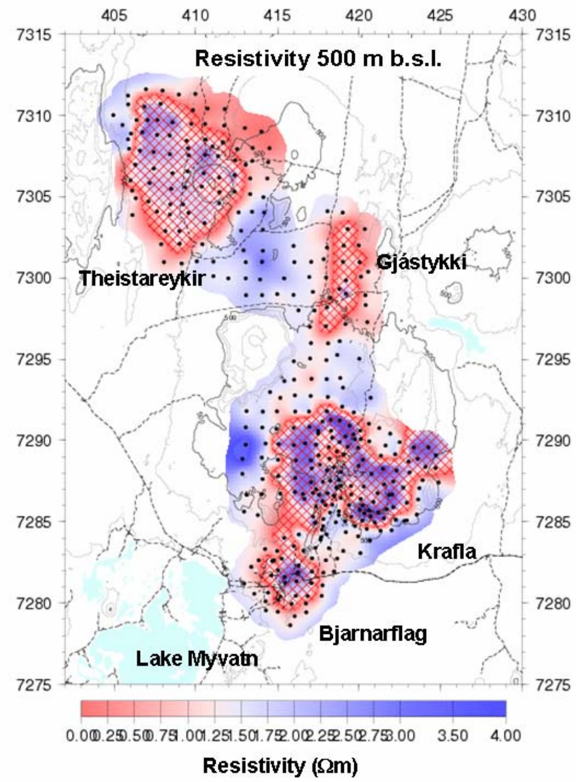

Figure 3: A TEM resistivity survey anomalies at 500 m b.s.l. (800-1100 m below surface) showing the geothermal areas in Northeast Iceland.

4.1 Krafla

The Krafla geothermal field is probably the most studied one in Iceland and its unique exploration experience has been presented in several publications (Gudmundur Pálmason, 2003; Halldór Ármannsson, 2005; Ásgrímur Gudmundsson, 2001; Gunnlaugur Nielsen et al., 2000; Bjarni Már Júliusson et al., 2005 etc.). It is a 45 km^2 area within the active Krafla central volcano, wherein three eruption periodes are known during the last 1000 years. The most resent one was Krafla fires 1975-1984.

Development of the Krafla field in the mid 1970's was the first large scale geothermal electrical power project in Iceland. Following sharp increase in oil prices, electricity was in demand for house heating. In the spring 1975, after drilling only 2 relatively shallow exploration wells the year before, a parliamentary committee (Kröflunefnd) decided to develop the field and purchase two 30 MW dual-flow double pressure Mitsubishi turbines.

The project was however affected by volcanic activities of Krafla fires that started in December 1975 and continued over the next 9 years, causing volcanic gases to contaminate the lower and hotter part of the geothermal reservoir. This caused the installation of turbine 2 to be postponed.

The Krafla geothermal system proved to be a very complex one and a long learning curve was met. The Krafla power station came online in January 1978 producing only 7 MW$_e$ and full 30 MW$_e$ capacity was not reached until the 10 MW well K-21 came online in 1984. The gas concentration in monitoring wells followed the volcanic episode closely. In the year 1981 a significant decline was observed in well K-7, which monitored the CO_2 concentration, see Figure 4. In 1996 the confidence in the Krafla area was sufficient to allow the decision to install the second 30 MW$_e$ turbine in 1996-1999.

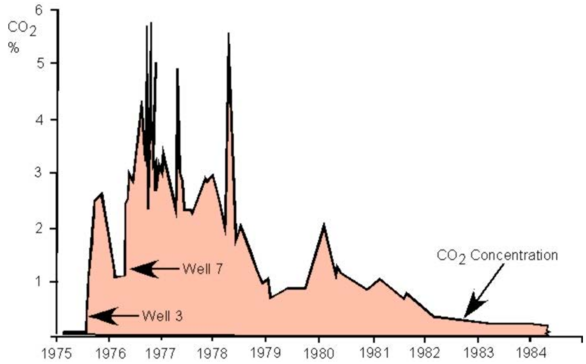

Figure 4: CO_2 concentration in two wells illustrating the increase in gas concentration in relation with volcanic eruptions 1975-1984.

Following the successful extension of the Krafla power plant, a 40 MW extension was designed and past through EIA process in 2001.

During and after the Krafla fires, scientists have been in particular interested in the Krafla field. During the fires, scientists located S-wave seismic shadow, which was interpreted as shallow magma chamber below the Krafla caldera, having two peaks reaching as high as 3-5 km from surface, one below the Leirhnjukur volcano, that erupted several times during the Krafla fires 1975-1984 and in the Mývatn fires in 1724-1729, the second being below the Viti explosion crater, which erupted in 1724. Later, scientists from University of North Carolina (Tang, 2005 and 2006) and Duke University (Steven Onacha, 2006) studied the micro seismic activity in the Krafla field. The studies showed the impact of geothermal fluid re-injection clearly and vast majority of events were around 1-2 km depth, at the same level as the main production zone, considered to represent heat mining. Onacha applied joint inversion method to more accurately interpret micro seismic and MT surveys, resulting in a map showing high gradient from the high resistivity core towards a deeper low resistivity core and very few seismic events were located below that level, see Figure 5.

Seismicity outside of the production zones was identified and drilled into. Wells KJ-35 is 2500 m long and deviates 1200 m towards the Leirhnjúkur volcano and well KJ-36 is also 2500 m long and deviates towards the Northern part of the field, 1000 m north of Viti. Both wells were initially very powerful, in particular well KJ-36 which was around 30 MW to start with but was very corrosive with Cl content 200-300 ppm, and a hole was created on the 10 mm thick flowline towards the well silencer within 5 days. Trials to influence the outflow (acidity) by changing wellhead pressure were unsuccessful. Therefore, a cement plug was placed at 1700 m depth. At present a feed zone at 1600 m provides 4 MW_e of neutral steam. In total some 10 wells in the Krafla field are believed to suffer from low pH fluid from fractures below 2000 m depth. Currently, a campaign is ongoing to develop method to handle such fluids (Kristján Einarsson et al., 2010). Some alternatives are under consideration:

(i) Barefoot completion (without slotted liner), depending on mixing high pH feed zones to neutralize the fluid before it enters the production casing. To test this, liner was pulled out of hole KJ-39.

(ii) Downhole injection of chemical inhibitors.

(iii) Deep casings, allowing superheated fluid to be produced to surface, hence no downhole corrosion.

(iv) Corrosion resistant casing and liner material.

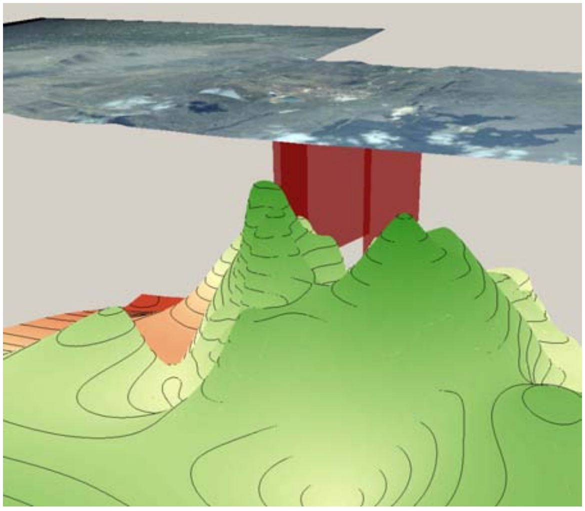

Figure 5: A 3D graph indicating gradient changes in resistivity from MT survey in Krafla.

Two last deep wells in Krafla were both drilled into magma. The ~2870 m (2500 m TVD) well KJ-39, directionally drilled through a 2000 year old erution fissure in the eastern part of the area, and the 2100 m deep vertical well IDDP-1 (Sveinbjörn Hólmgeirsson et al., 2010). These two discoveries have affected ideas about the Krafla area and its potential. Shallow heat source can allow alternatives like deep re-injection and shallower nearby production wells could be a potential way to tap vast amount of geothermal power out of the field. The wellhead of KJ-39 was not designed to handle the anticipated 160 bar wellhead pressure so cement plug was placed to cement of the bottom 200 m. However, well IDDP-1 is cased to 1950 m with ANSI Class 2500 wellhead and will be flow tested in 2010.

The future of power production in Krafla depends on if the development of utilizing low pH reservoir will be positively solved. Therefore it is uncertain although it clearly has great potential for significant extension of the Krafla power plant.

Opening access to the Krafla area for tourists has been hugely successful as annually, more than 100.000 tourists visit the site, mostly to see the Víti crater and the recent lava flows around the Leirhnjúkur. Popular stop is the Visitor center at the power plant where a video of the volcanic activities is demonstrated parallel to the generating renewable energy.

4.2 Bjarnarflag

The Bjarnarflag geothermal field is part of the Námafjall high temperature area, some 4 km west of Lake Mývatn and 6 km south of Krafla. TEM and MT resistivity measurements indicate the geothermal area is 20 km^2 in size, extending North and South along the rift zone. Surface manifestations are most comman at Mt. Námafjall and on its both sides. Good access is to the main target zones in the reservoir by by directional drilling. In the years 2006-2008 three wells have been directionally drilled, two successful and one step out (Ásgrímur Gudmundsson et al., 2009).

The area is exceptionally accessible with highway No 1 going through it and is in 320 above sea level (Figure 6).

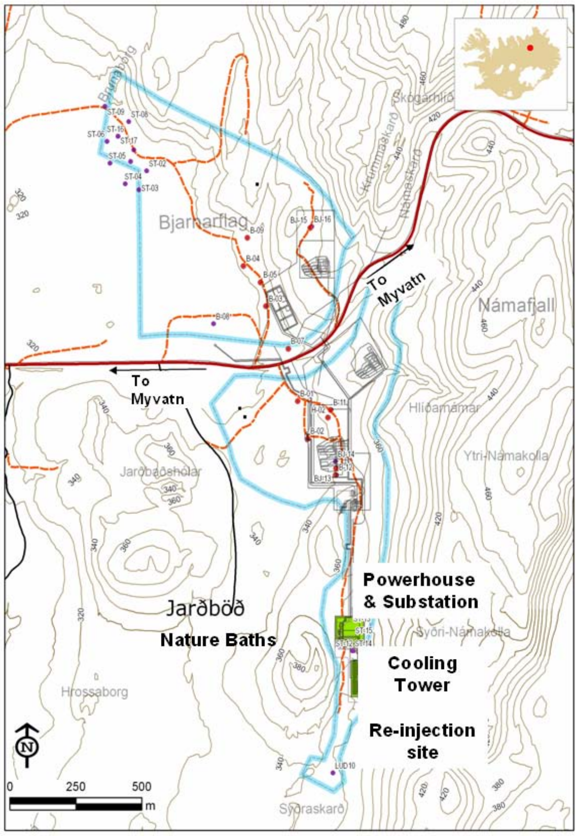

Figure 6: Schematic diagram for the Bjarnarflag power project.

The Bjarnarflag power plant passed EIA in 2003, was confirmed on municipal plan in 2004. As a conclusion the Bjarnarflag power project is currently the most developed of the NE-Iceland power projects.

4.3 Gjástykki

Gjástykki is the least known area of the four. It is a graben with a small lava dome volcano, Gjástykkisbunga, in middle but not believed to be a central volcano. In the latter part of the Krafla fires, activity moved north into Gjástykki and 25 year old lavas dominate the landscape. TEM resistivity measurements indicate the area is is around 10 km^2 or half the size of Bjarnarflag or and therefore power capacity could also be up to 60 MW. Geothermal manifestations are localized in a limited spots. Gas geotermometers indicate temperature of 280°C in the geothermal reservoir.

Landsvirkjun received exploration licence in 2007 and coredrilled a 600 m deep well in middle of the area later that year. The well had bottom-hole temperature of 200°C indicating a high temperature reservoir (Christian Lacasse, 2008). Landsvirkjun notified three deep exploration wells in early 2008 that were ruled to have a full EIA and results from that are expected before end of 2009.

4.4 Theistareykir Geothermal Field

Theistareykir area is located in a rift valley between Mt. Lambafjöll and Mt. Baejarfjall and Mt. Ketilfjall. Resistivity measurements indicate the field can be divided into west and east parts, in total 45 km^2. In the middle is a highly fractured zone, with significant thermal alteration (Bjarni Gautason et al., 2010; Gang Yu et al, 2010).

The eastern part is estimated to be half the size, where the geothermal surface manifestation are widespread at the northern and western foothill of Baejarfjall. The 6 exploration wells drilled from 2002 to 2008 were drilled from 3 drill sites in the eastern part. The wells drilled near to the mountains are hotter, with bottom-hole temperature 340-380°C were as the two wells drilled into the fracture zone in the middle of the valley are colder. The eastern part of the field alone is considered to have potential for up to 200 MW.

The west part is mostly under lava flows, the most recent 2500 years old, and therefore more difficult to access. In 2007, a 460 m deep slim core hole was drilled in the lava with a small rig. It has a constantly rising temperature gradient and bottom hole temperature of 180°C, equivalent to the mineral alteration expected from resistivity survey. The existence of the high temperature reservoir in the western part is therefore not proved but considered likely and if the area is as large as resisitvity measurements indicate, a conservative power potential could be 100 MW_e.

5. STATUS OF THE NE-ICELAND PROJECT

The current status of the exploration program as continuing demand for power in the area has lead to a potential construction schedule that could be realised if exploration drilling program is continued. If the exploration drilling program in 2010 is successful and a decision to construct the power plants by the end of 2010, the first turbines could be commissioned by the end of 2013 and all 400 MW online in early 2016, as presented in Figure 7.

5.1 Planning and EIA

Landsvirkjun has acquired exploration license for extension of Krafla and development of Gjastykki field but Theistareykir Ltd. holds exploration license for the Theistareykir field.

The four geothermal fields extend over three municipalities and a small part of the Gjastykki field is within the area falling under the *Regional Plan for the Central Highlands of Iceland*, see Figure 8. As a result, the three municipalities prepared an extensive regional plan for the high temperature geothermal fields in Suður-Þingeyjarsýsla, according to the act from 2006. Therefore, this plan presents a joint policy of the three municipalities and the state for land use and preservation policy of the area. The Regional Plan passed the Strategic Environmental Assessment and was signed by the Icelandic minister for the environment in February 2008. The regional plan for the high temperature fields was the first of its kind in Iceland. The power companies, Landsvirkjun and Theistareykir Ltd., were not involved in preparing the plan but provided information as requested by the municipalities.

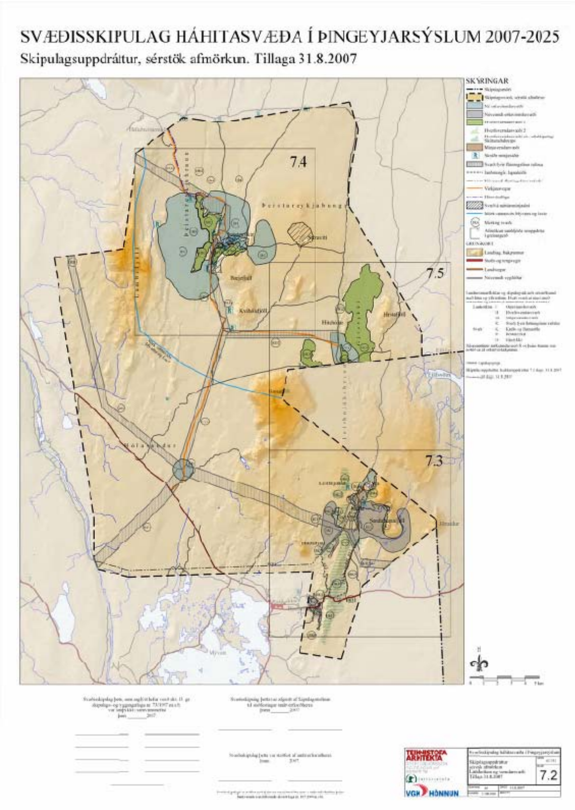

Figure 8: Regional plan for the geothermal sites in Northeast Iceland.

Based on the Regional Plan, the three municipalities are now altering their Municipal Plans to reflect the proposed project layout in Krafla, Gjastykki and Theistareykir whereas Bjarnarflag is already on municipal plan.

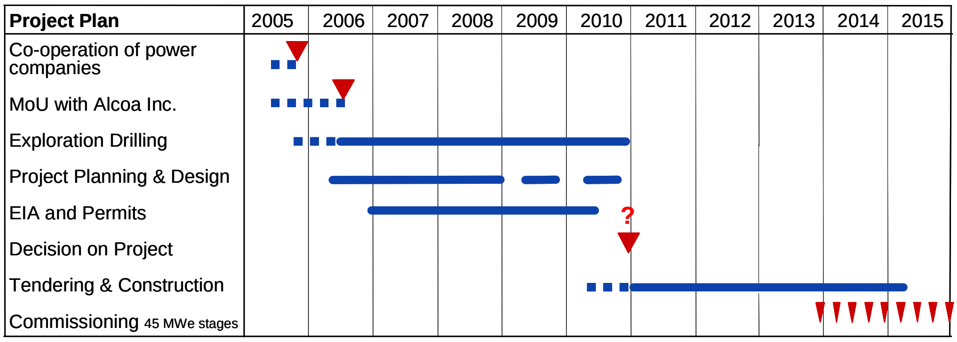

Figure 7: The fastest possible construction schedule for the 400 MW_e Northeast Iceland project.

Environmental impact assessment (EIA) has been quite demanding for the Northeast Iceland project. A part from the strategic environmental assessment for the regional, municipal and local plans, exploration drilling in Western Krafla and in Gjastykki have been ruled to have a full EIA. The EIA for Theistareykir and Krafla were ruled to be assessed in parallel with EIA for transmission lines and aluminium smelter at Husavik and all common impacts assessed and present especially in joint EIA. This is the first time such EIA process is practiced in Iceland. The EIAs for both Krafla and Theistareykir as the joint EIA are expected to be completed in spring 2010, allowing second phase exploration drilling to continue in summer of 2010.

5.2 Status of Exploration Drilling

Since spring 2006, 15 exploration wells have been drilled in the three fields, in addition to the two older exploration wells in Theistareykir and 3 old wells in Bjarnarflag that will be connected to the new plant. Table 2 presents the current statues of the exploration drilling program.

Table 2: Results from exploration drilling in NE-Iceland, 2006-2009.

	No wells	Output
Bjarnarflag	3+3	44 MW_e
Krafla	8	13 (36) MW_e
Gjastykki	0	0
Theistareykir	4+2	44 MW_e

As can be seen, the exploration drilling program has been very good in both Bjarnarflag and Theistareykir with producing more than 7 MW_e on average per well in both fields. Reservoir modelling, based on extended flow tests resulting in minimal pressure draw down, concludes that 90 MW_e production will be sustainable in both fields and it is likely that both fields can withstand more production, in particular the larger Theistareykir field. However, further drilling and flow testing is required to prove sustainable production of 180 MW_e.

The exploration drilling program in the Krafla field, with both step-out and deeper wells, has proven to be more challenging as the energy rich deep fluid has proven to be too sour for conventional production methods and will not be included until a solution will be proven.

5.3 Power Plant Design

The geothermal properties, such as enthalpy, pressure and gas content, of all three known fields have proved to be very similar and as the fields are all within 30 km diameter, 300-500 m a.s.l., the environmental conditions, such as weather is quite similar. The gas content is approximately 1% in Krafla, 0.5% in Bjarnarflag and 0.2% in Theistareykir This provides an opportunity to standardise the power plants quite significantly, e.g. steam supply system pressure, turbine generating units and even cooling towers, with minimal differences. Therefore, the plant design for Bjarnarflag, Krafla and Theistareykir in all cases assumes a single flash, single flow turbines with inlet pressure 8-10 bar. The separation water of 180°C has to be re-injected to maintain pressure support. The general plant layout is presented in Figure 9.

The three or four power plants are expected to be remotely operated from a dispatch center in Reykjavik and have a common service center, either in Mývatn or town of Husavik but be manned with maintenance crews on shifts, ready for manual operation during the first two years in operation.

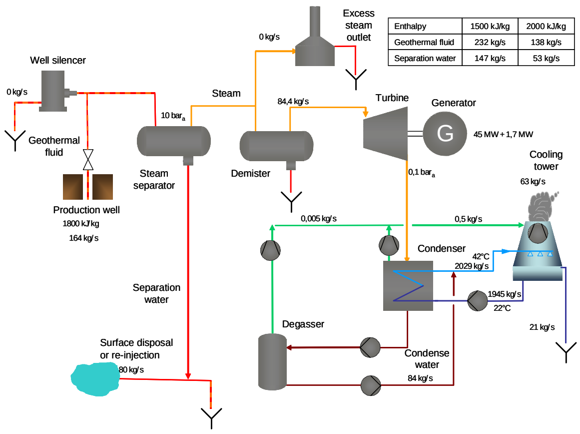

Figure 9: General plant layout for the NE-Iceland geothermal power plants.

6. CONCLUSIONS

The Process of exploring three to four geothermal fields within limited time and budget to sufficiently base a decision if to develop at least 400 MW_e within several years is an extremely challenging task.

This paper aims at presenting at the same time the scope and extension of the project, the exploration and development strategy drawn up and the actual project status.

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