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Sustainability evaluation of geothermal systems in Iceland

Indicators for sustainable production

Rut Bjarnadóttir

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30 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Sustainable Energy Engineering

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Abstract

There is an increasing demand from the society to utilize resources in a sustainable way. Utilization of geothermal resources are no exception from that and as the demand for renewable energy sources increase as does the stress on existing resources. This calls for a policy in the sustainable management for resources but no such policy exists for geothermal development in Iceland. Ruth Shortall, a master student at the University of Iceland has developed a Geothermal Sustainability Assessment Protocol (GSAP) which takes into consideration all aspects of geothermal development, the environment, the economy and the society. The GSAP is a set of sustainability indicators that measure sustainable development. In this thesis the indicators that have to do with the geothermal production and the influence it has on the resource itself are developed. Seven indicators were developed and they capture some of the most important properties affected during geothermal utilization. The indicators developed and the method used to evaluate them are: 1) Utilization efficiency, using exergy analysis 2) Productive lifetime, using existing reservoir models 3) Reserve capacity ratio, using definitions of probable and proven reserves 4) Reclamation time, using existing reservoir models 5) Change in dissolved chemicals, using geothermometers and relative changes 6) Ground subsidence, evaluating impacts on the surroundings and 7) Micro seismic activity, evaluating impacts on the surroundings. To test the effectiveness of these indicators they are applied to the Krafla geothermal field in Iceland. The grading of the indicators is in some cases based on relative comparison to other geothermal fields and in other cases a benchmark is set. The results for the Krafla field indicate the production is sustainable under current conditions. The overall result is that sustainability indicators are a good way to measure sustainability of geothermal production because they take into consideration many properties and can quantify the sustainability using grades. This enables comparison between existing fields and helps in decision making when new fields are being developed. The indicators are only at a developing stage and future work includes improving the methodology, the scoring and applying them to more fields for comparison.

Útdráttur

Aukinn þrýstingur er frá samfélaginu um að nýta náttúru auðlindir á sjálfbæran hátt. Vinnsla á jarðvarma er ekki undanskilin því og samfara aukinni eftirspurn á endurnýtanlegri orku eykst þrýstingur á núverandi auðlindir. Þetta kallar á stefnumörkun í sjálfbærri auðlindastjórnun en engin slík stefna er í notkun á Íslandi fyrir nýtingu á jarðvarma. Ruth Shortall, meistaranemi við Háskóla Íslands hefur þróað aðferð við að meta sjálfbærni jarðvarmavinnslu (GSAP) sem tekur tillit til allra þátta sjálfbærrar vinnslu, umhverfisins, hagkerfisins og samfélagsins. Þetta mat byggir á sjálfbærnivísum sem eiga að meta sjálfbæra þróun. Þessi ritgerð fjallar um þá vísa sem snúa að jarðvarmavinnslunni sjálfri og áhrifunum sem hún hefur á auðlindina. Sjö vísar voru þróaðir og þeir fanga nokkra af mikilvægustu þáttunum í jarðvarma nýtingu. Vísarnir sem voru þróaðir ásamt aðferðum til að meta þá eru eftirfarandi: 1) Nýtni, notast er við exergíu greiningu 2) Líftími, notast er við líkanreikninga 3) Forða hlutfall, notast er við skilgreiningar á líklegum og staðfestum forða 4) Afturkræfni, notast er við líkanreikninga 5) Breyting í uppleystum efnum, notast er við efnahitamæli og hlutfallslegar breytingar 6) Landsig, mat á áhrifum á nærliggjandi svæði og 7) Smáskjálftavirkni, mat á áhrifum á nærliggjandi svæði. Til þess að kanna virkni vísanna er þeim beitt á jarðhitasvæðið við Kröflu. Einkunnagjöf vísanna er í sumum tilfellum byggð á samanburði við önnur jarðvarmasvæði á Íslandi en í sumum tilfellum er ákveðið viðmið sett. Niðurstöðurnar fyrir Kröflu svæðið gefa til kynna að vinnslan þar sé sjálfbær miðað við núverandi ástand. Heildar niðurstaðan er að sjálfbærnivísar eru gott tól við mat á sjálfbærni því þeir geta tekið tillit til margar eiginleika og gefa sjálfbærninni tölulegt gildi með einkunnagjöf. Þetta gerir samanburð á vinnlu á jarðhitasvæðum mögulegan og hjálpar til við ákvarðantöku við þróun nýrra svæða til vinnslu. Þessir sjálfbærnivísar eru á þróunarstigi og næstu skref væru að beita þeim á fleiri jarðhitasvæði bæði til samanburðar og til þess að bæta aðferðafræðina og einkunnagjöfina sem hér hefur verið þróuð.

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Nomenclature

A	*area of reservoir (m^2)*
B	*exergietic power (MW)*
b	*specific exergy of a fluid(kJ/kg)*
b^{CH}	*chemical exergy (kJ/kg)*
b_i	*exergy of well i(kJ/kg)*
b^{KN}	*kinetic exergy (kJ/kg)*
b^{PH}	*physical exergy (kJ/kg)*
b^{PT}	*potential exery (kJ/kg)*
B_{TOTAL}	*total exergetic power (MW)*
C	*heat capacity, (J/ kg K)*
C_e	*conversion efficiency (%)*
C_r	*specific heat of rock at reservoir conditions (kJ/kgK)*
C_w	*specific heat of water at reservoir conditions (kJ/kgK)*
d	*average thickness of reservoir (m)*
E_0	*level of sustainable production (PJ)*
E_P	*primary energy extracted (PJ)*
g	*gravity acceleration (9.81 m/s^2)*
h	*enthalpy (kJ/kg)*
h_0	*enthalpy at T_0 and P_0 (kJ/kg)*
$h_{extracted}$	*enthalpy over 15°C of extracted fluid (kJ/kg)*
$h_{injected}$	*enthalpy over 15°C of injected fluid (kJ/kg)*
k	*permeability of the formation (mD)*
k_r	*relative permeability (mD)*
$\dot{m}_i$	*mass flow rate of well i (kg/s)*
$M_{extracted}$	*mass extracted from reservoir (kg)*
$M_{injected}$	*mass injected back into reservoir (kg)*
P	*pressure (Pa)*
P_0	*ambient pressure (Pa)*
P_f	*plant factor (-)*
Q_r	*heat in rock (kJ/kg)*

Q_T	*total thermal energy (kJ/kg)*
Q_w	*heat in water (kJ/kg)*
r	*reserve capacity ratio*
r_f	*recovery factor (-)*
$R_{capacity}$	*reserve capacity (MW)*
$R_{probable}$	*probable reserves (MW)*
R_{proven}	*proven reserves (MW)*
s	*entropy (kJ/kg°C)*
s_0	*entropy at T_0 and P_0 (kJ/kg°C)*
t	*time (economic life) (years)*
T	*temperature (°C)*
T_0	*ambient temperature (°C)*
T_a	*average temperature of reservoir (°C)*
T_f	*final or abandonment temperature (°C)*
V	*velocity (m/s)*
W	*power potential (MW_e)*
$W_{net,electricity}$	*net power output (electricity production) (MW_e)*
$W_{net,total}$	*net power output (electricity production + exergetic power of direct use) (MW)*
x	*mass fraction (-)*
z	*elevation relative to coordinates in the environment respectively (m)*
η_B	*utilization efficiency (%)*
η_P	*primary energy efficiency (%)*
λ	*thermal conductivity (W/mK)*
ρ_r	*rock density (kg/m^3)*
ρ_w	*water initial density (kg/m^3)*
Φ	*porosity, i.e. fraction void spaces in a material (-)*

Abbreviation

GSAP	*Geothermal Sustainability Assessment Protocol*
EIA	*Environmental Impact Assessment*
IHA	*International Hydropower Association*
IUCEN	*International Union for Conservation of Nature*
ÍSOR	*Íslenskar Orkurannsóknir (Icelandic Geosurvey)*
LV	*Landvirkjun*
LVP	*Landsvirkjun Power*
OECD	*Organization for Economic Co-Operation and Development*
OR	*Orkuveita Reykjavíkur (Reykjavík Energy)*
OS	*Orkustofnun (National Energy Authority)*
RU	*Reykjavík University*
SAP	*Sustainability Assessment Protocol*
SPE	*Society of Petroleum Engineers*
TEM	*Transient Electromagnetic Measurement*
UI	*University of Iceland*
UN	*United Nations*

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1 Introduction

It has been recognized that if today's energy path is continued, without any change in government policy, a rapid increase in the dependency on fossil fuels will become reality, with alarming consequences for climate change and energy security (IEA, 2009). The primary energy consumption has increased by 50% since 1980 and is predicted to increase further by 40% in the next two decades (IEA, 2009). This increase along with the tax on emissions of carbon dioxide stimulates the market in looking for other sources of energy. Therefore there is an increasing demand for renewable energy sources such as hydro, wind, wave, solar, biomass and geothermal.

Geothermal energy is a resource that has great potential and geothermal utilization is predicted to increase steadily in the years to come and can contribute to replacing fossil fuels with renewable energy sources. The technology in geothermal exploration and production is improving progressively and now it is possible to get more energy out of known geothermal systems than before and utilize systems that were not considered viable.

There is an increasing demand from the society to utilize resources in a sustainable way with respect to the environment, economy and the society. Geothermal energy is a renewable energy source (EU Directive 2009/28/EC) and can be utilized in a sustainable manner if managed properly (Axelsson & Stefánsson, 2003). Geothermal systems are complicated and there are many interconnected parameters that affect the productivity of such systems. Sustainable utilization of the geothermal resource involves monitoring how these system parameters react to the production and take actions accordingly. Currently there does not exist a protocol to evaluate the sustainability of all the aspects of a geothermal development. A set of sustainability indicators is a tool that can be used to measure and monitor these changes and demonstrate if the utilization of the resource is sustainable (Becker, 2004). By developing and applying this set of sustainability indicators for geothermal development, various geothermal fields can be compared and evaluated in terms of sustainability.

This thesis was done in cooperation with Ruth Shortall who is a master student in environmental and natural resources at the University of Iceland. Shortall has developed a Geothermal Sustainability Assessment Protocol (GSAP) (Shortall, 2010). The GSAP takes into consideration all the aspects of geothermal development, the environment, the economy and the society. Shortall has developed nearly 50 sustainability indicators. This thesis focuses on and develops further the indicators that have to do with the geothermal production and how it affects the geothermal resource.

The aim of this thesis is to evaluate sustainability of geothermal production by developing sustainability indicators and to apply them to a geothermal system under production to test their effectiveness. This thesis identifies some of the main parameters that are affected during geothermal production and uses them do develop the sustainability indicators. The indicators are developed with Icelandic conditions in mind and area applicable to both high- and low-temperature fields.

The thesis is constructed in the following way: The second chapter covers the background on sustainable development and geothermal utilization. In the third chapter the sustainability indicators are chosen and the methodology behind them is discussed. The forth chapter describes the indicators and how they are graded. The fifth chapter is a case study of the Krafla system where the indicators are applied and the sustainability of the geothermal production at Krafla is evaluated. The last chapter is the conclusion and future work and there the usefulness of the indicators is discussed and what can be done to improve and develop them further.

2 Background

2.1 Sustainable Development

The concept of sustainability dates back centuries. Experts trace it to practices by some Native American tribes and 13th century forestry laws. The industrial revolution of the 17th to the 19th century led to human population explosion and unpredicted industrial, technological and scientific growth that has continued to this day. By the 20th century the human consumption of resources was growing exponentially. Ecology as scientific discipline was gaining general acceptance and ideas of the interconnectedness of living systems were being explored (Worster, 1994). The term sustainability was introduced in the mandate adopted by the International Union for Conservation of Nature (IUCEN) in 1969. It was a key theme of the United Nations Conference on the Human Environment in Stockholm in 1972. The concept was coined explicitly to suggest that it was possible to achieve the economic growth and industrialization without environmental damage. In the following decades, mainstream sustainable development thinking was progressively developed through the World Conservative Strategy (1980), the Brundtland Report (1987) and the United Nations Conference on Environment and Development in Rio (1992), as well as in national government planning and wider engagement from business leaders and non-governmental organizations of all kinds (Adams, 2006).

Sustainability, in general terms, is the ability to maintain balance of a certain process or state in any system and sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only in the present, but also for future generations. The definitions that is most quoted is from the Brundtland Report from 1987, there it states that sustainable development is "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987)

Indicators have been used in biology to gauge the health of ecosystems for many years and now indicators have been seen by many as the way to evaluate sustainability. An indicator is something that points to an issue of conditions. Its purpose is to show how well a system is working. If there is a problem the indicator can help determine what direction to take to address the issue. Indicators are varied as the type of system they monitor. The main characteristics of effective indicators are that they are relevant, easy to understand, reliable and based on accessible data (Sustainable Measures, 2006).

The Bellagio principles for Assessment where developed November 1996 by an international group of measurement practitioners and researchers from five continents that came together at the Rockefeller Foundation's Study and Conference Center in Bellagio, Italy. The principles serve as guidelines for the whole sustainability assessment process including the choice of design of indicators, their interpretation and communication of the result. They are interrelated and should be applied as a complete set. They are intended for use in starting and improving assessment activities of community groups, non-government organizations, corporations, national governments, and international institutions (Hardi & Zdan, 1997).

Sustainable development can be strong or weak. Weak sustainability assumes the validity of growth and places equal importance on environment, social justice and economic prosperity. Strong sustainability on the other hand has the environment as a foundation to social justice and economic prosperity. In other words, strong sustainability focuses on the viability of health of a resource to sustain exploitation, whereas weak sustainability believes in economic forces and technological advances (Bosselmann, 2002). Figure 2-1 shows the visual representation of weak and strong sustainability.

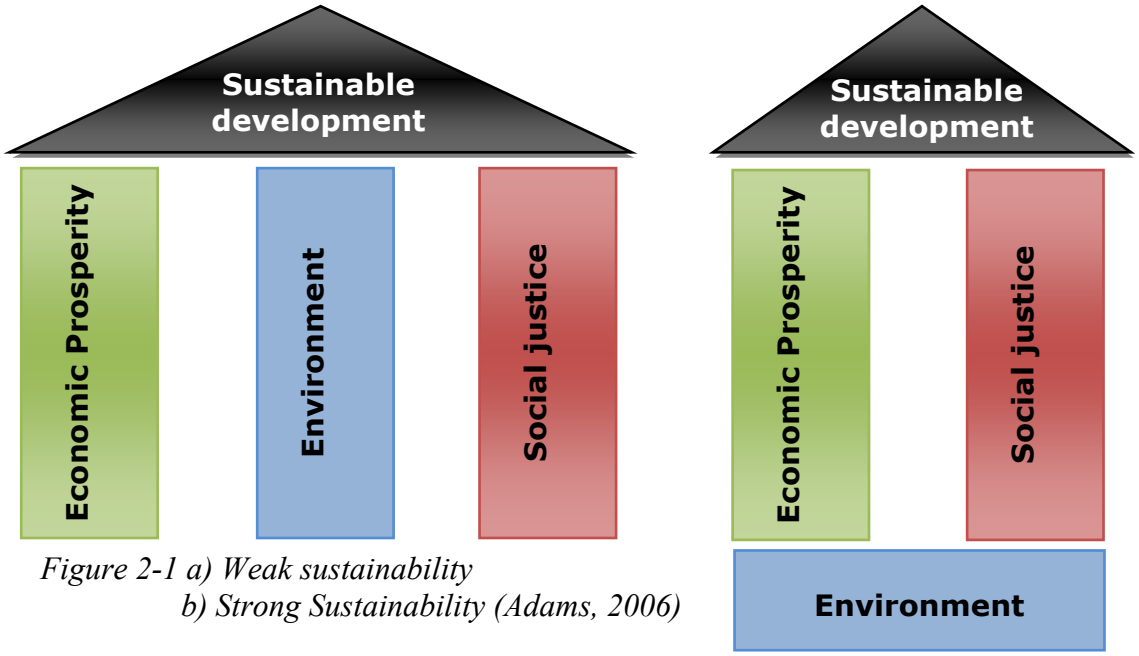

Figure 2-1 a) Weak sustainability
b) Strong Sustainability (Adams, 2006)

The thought behind the visual representation of sustainability is that when the sustainability is weak then all the aspects weigh equally but in strong sustainability the foundations is the environment (natural resources). Overexploitation of resources can thus in other words lead to e.g. economic depression and possibly lead to a decline in social welfare.

There exist methods to evaluate sustainability of energy projects and most of them are in the form of checklists. One such checklist is from the International Hydropower Association (IHA) and is referred to as a Sustainability Assessment Protocol (SAP). This protocol provides guidance on key sustainability aspects of new hydropower and other energy projects (International Hydropower Association , 2006).

2.2 Sustainable Geothermal Utilization

Geothermal energy has been regarded as a renewable energy source because it recharges at a similar timescale as the production from the resource. It depends on the type of resource and the production method if the geothermal utilization can be considered sustainable.

A working group at Orkustofnun, (Axelsson, et al., 2001) has proposed a definition for the sustainable production of geothermal energy:

"For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, ***E_0****, below which it will be possible to maintain a constant energy production for a very long time (100–300 years). If the production rate is greater than* ***E_0*** *it cannot be maintained for this length of time. Geothermal energy below or equal to* ***E_0****, is termed* ***sustainable production*** *while production greater than* ***E_0*** *is termed* ***excessive production****."*

This definition applies to the total extractable energy, and depends in principle on the nature of the system in question, but not on load factors or utilization efficiency. It also depends on the mode of production, which may involve spontaneous discharge, pumping, injection or periodic production. The value E_0 is not known in advance, but it may be estimated using available data by modeling. Figure 2-2 shows the different between sustainable and excessive production.

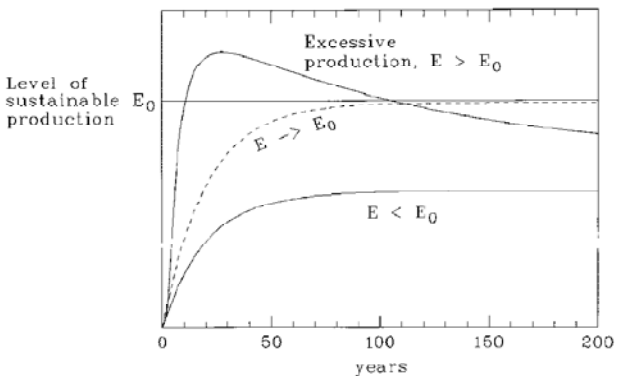

Figure 2-2 A schematic figure illustrating the difference between sustainable and excessive production (Axelsson & Stefánsson, 2003)

2.3 The Geothermal Resource

Geothermal energy consists of all the thermal energy stored in the earth's crust. Thermal energy in the earth is distributed between the constituent host rock and the natural fluid that is contained in its fractures and pores at temperatures above ambient levels. These fluids are usually water with various amounts of dissolved salts and are typically present as liquid or supercritical fluid phase but may sometimes consist of a saturated or superheated steam vapor phase. Most geothermal resources presently usable for electric power generation result from the intrusion of magma from great depths into the earth's crust. These intrusions usually reach depths of 0 to 10 km (Tester, Drake, Golay, Driscoll, & Peters, 2005).

The source and transport mechanisms of geothermal heat are unique to this energy source. Heat flows through the crust of the earth at an average rate of almost 60 mW. The intrusion of large masses of molten rock can increase this normal heat flow locally, but for most of the continental curst, the heat flow is due to upward convection and conduction of heat from the mantle and core of the earth and heat generated by the decay of radioactive elements in the crust. Local and regional geologic and tectonic phenomena play a major role in determining the location and quality (fluid chemistry and temperature) of a particular resource. Regions with higher-than-normal heat flow are associated with tectonic plate boundaries and with areas of geologically recent volcanic events (Tester, Drake, Golay, Driscoll, & Peters, 2005).

Clotworthy et al. have proposed a classification for the geothermal resource (Clotworthy, Ussher, Lawless, & Randel, 2004). The classification is based loosely on the McKelvey

diagram used within the Society of Petroleum Engineers (SPE) definition of proved, probable and possible reserves and contingent resources (Figure 2-3).

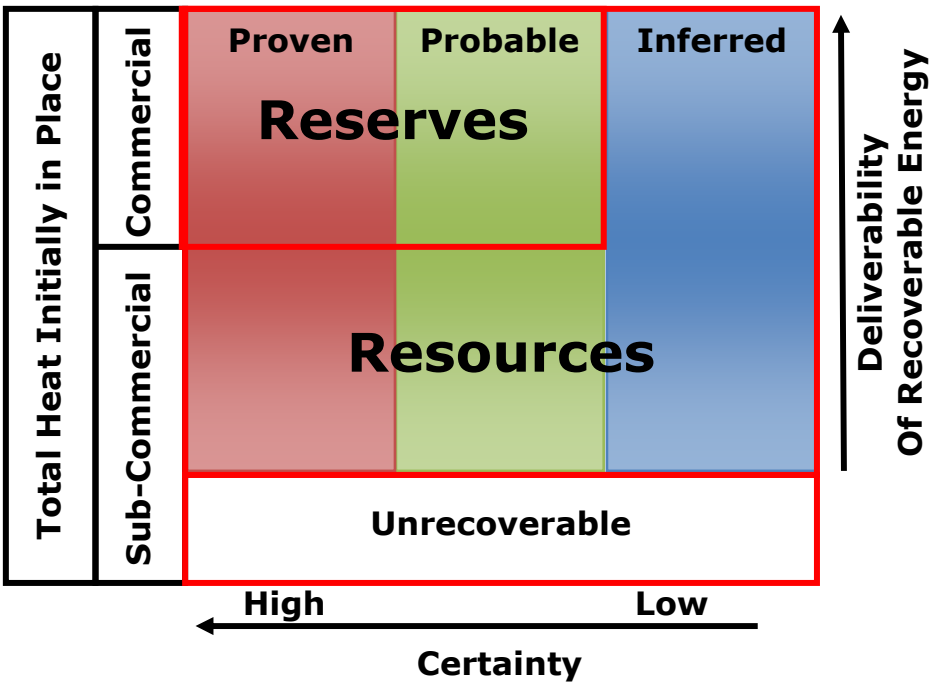

Figure 2-3 Proposed resource classification (Clotworthy, Ussher, Lawless, & Randel, 2004)

This classification is only to be applied to geothermal resources that are likely to be technically and commercially extractable now or in the foreseeable future. A three stage classification is suggested to define how reliable the resource is (Clotworthy, Ussher, Lawless, & Randel, 2004):

> ***PROVEN*** *means the portion of the resource that has been sufficiently sampled by wells that demonstrate reservoir conditions and deliverability of fluid over a volume of reservoir such that no substantive surprises can be expected by further drilling within that volume. Supplementary methods such as chemistry, pressure testing and geophysics may be used to demonstrate continuity of resource between and around the drilled area. The results of future drilling should have a very low probability of reducing the energy potential assessed within that volume or for the project as a whole (though that does not guarantee any individual well will necessarily be commercially successful).*
>
> ***PROBABLE*** *means the portion of the resource that is less reliably defined than the Proven area but with sufficient indicators of resource temperature from nearby wells or from geothermometry on natural surface discharges to characterize resource temperature and chemistry and with less direct measures such as geophysics or temperature gradient wells indicating the extent of resource. Probable resource will often surround proven resource.*

INFERRED *means the area/volume of resource that has less direct indicators of resource characteristic and extent, but still a sound basis for assuming that a reservoir exists, estimating resource temperature and having some indication of extent.*

The term ***RESERVES*** *is only to be used for those portions of proven or probable* ***RESOURCES*** *that are generally accepted to be commercially extractable with existing technology and prevailing market conditions. The differentiation between commercial and sub-commercial is not to be strictly interpreted as implying that commercial feasibility has been demonstrated. Rather it is intended to enable identification of the portion of heat that can be readily extracted using current commercial practices from that portion which still requires substantive improvements in technical or cost terms to be viable.*

Different levels of information are required about a geothermal field in order for a part or all of it to be classified as proven, probable or inferred.

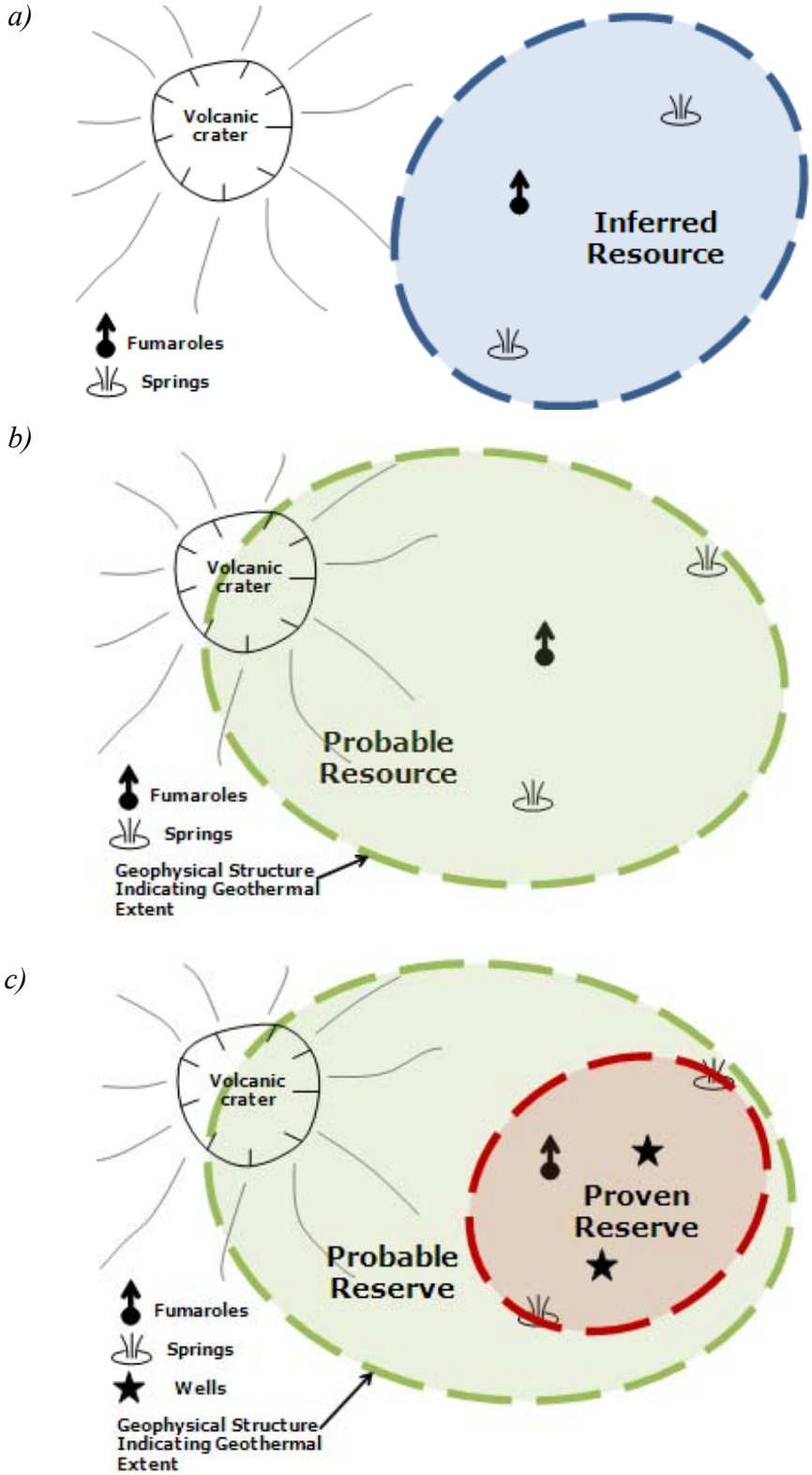

Figure 2-4 Examples of application of the proposed classifications.
a) Inferred Resource based on surface thermal features and geological setting.
b) Probable Resource based on (a) with additional comprehensive geophysical information that improves definition of depth and extent of geothermal system. c) Proven and Probable Reserves based on (b) after the drilling of successful exploration wells (adopted from (Clotworthy, Ussher, Lawless, & Randel, 2004))

A geothermal resource needs to have certain qualities to be considered a viable resource. The first is accessibility which is usually achieved by drilling to depths of interest. The second requirement is sufficient reservoir productivity, which depends on the type of geothermal system that is being exploited. To meet that, one needs to have sufficient quantities of hot, pressurized natural fluid contained in an aquifer with high rock permeability and porosity to insure long-term production at economically acceptable levels (Tester, Drake, Golay, Driscoll, & Peters, 2005).

Usually geothermal fields are categorized into low- and high-temperature fields. The general definition of a low-temperature field is that its temperature is less than 150°C at a depth of 1000 meters and for high-temperature fields the water temperature is 200°C or more at a depth of 1000 meters (Bödvarsson G. , 1964). High-temperature fields are located on active volcanic belts or along their periphery. Water in high-temperature fields heats up when it comes into contact with hot bedrock, which is heated by its proximity to magma. Because of the high-temperature, more minerals and gases are dissolved in the water in high-temperature fields than in low-temperature fields where the water can be used directly for hot water supply, and is generally deemed safe to drink. (Reykjavík Energy, 2009).

Geothermal systems are complicated systems and can be unpredictable. The process of mapping and modeling the system is a long and never ending. There is a lot of information that need to be available to construct an accurate model and the most important are the physical characteristics of the reservoir and the production history. It is possible to attain some of the information in the early stages of development but some of the information will not be available until after a few years of production.

2.3.1 Geothermal Resources in Iceland

There are two studies that have been done to estimate the total geothermal potential in Iceland. These studies estimate the potential differently, which reflects the dual nature of geothermal reserves. In 1982 Bödvarsson estimated the size of the total steady state energy current through the crust (Bödvarsson, 1982) and in 1985 Pálmason et al. estimated the amount of thermal energy stored in the crust (Pálmason, et al., 1985). The results of these two studies where then combined by Stefánsson in 2000 in a unified presentation, see Figure 2-5. Bödvarsson estimated that the energy current from below Iceland is about 30 GW (GW = $1 \cdot 10^9$ W) on average, and that at the surface the energy current is split between 7 GW by volcanic activity, 8 GW by water- and steam-flow in geothermal areas and 15 GW by heat conduction. The principal result of Pálmason et al. is that the total energy stored in the crust of Iceland, from surface down to 10 km, amounts to about 1.2 YJ (YJ = $1 \cdot 10^{24}$ J). Above 3 km depth the energy stored is about 0.1 YJ (termed accessible energy).

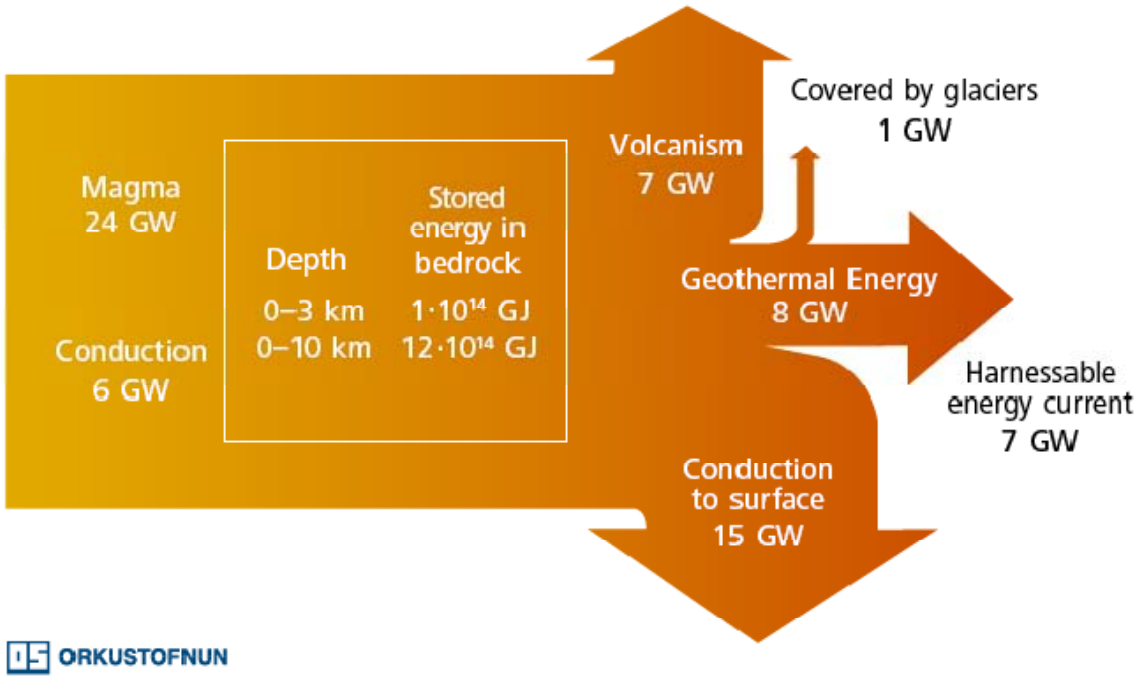

Figure 2-5 Terrestrial energy current through the crust of Iceland and stored heat (Ketilsson, Björnsson, Halldórsdóttir, & Axelsson, 2009)

2.3.2 Physical Characteristics

A geothermal resource is characterized by both physical conditions and physical properties. The physical conditions are pressure P (Pa) and temperature T (°C) for a reservoir that has a single phase. For a two phase reservoir the pressure and temperature are dependent on the enthalpy h (kJ/kg) or the mass fraction x (-). The physical properties are (1) permeability of the formation k, i.e. the ability of a material to transmit fluids (mD), (2) porosity Φ, i.e. fraction void spaces in a material, (3) relative permeability k_r, ratio of the phase permeability over the permeability of the porous medium, (4) thermal conductivity λ, controls heat transfer by conductions (W m^{-1} K^{-1}) and (5) heat capacity C, which determines the amount of stored energy (J kg^{-1} K^{-1}) (Bödvarsson & Witherspoon, 1989).

The physical characteristics are used to idealize the geothermal system and construct a conceptual model. To approximate the physical characteristics of the reservoir various information need to be gathered. This information is gathered at different phases of a geothermal development either exploration phase or exploitation phase.

2.3.3 Exploration Phase

The first step in geothermal development is exploration. The goal of geothermal exploration is to locate sites which can be used consistently into the future for the purpose of energy generation, and to evaluate the suitability of such sites for geothermal development. In this phase geophysical surveys and collected geochemical and geological data are analyzed and temperature gradient drilling provides an overview of where the geothermal potential lies for further development. Here are mentioned some of the method used during exploration:

Mapping of visible geysers, strata and faults

The first step in geothermal exploration is mapping the area that is under consideration. The emphasis is on mapping fractures, faults and strata that can give ideas about geothermal fluid in the ground. All natural geothermal surface activity is mapped and so are all volcanic formations and the type of strata in the area. When a surface map has been completed it is easier to make a decision on where to drill exploratory wells (Pálmason, 2005).

Thermal gradient drilling

One of the most direct ways in geothermal exploration is to map the thermal gradient using shallow boreholes. The thermal gradient can give indications about geothermal heat at greater depths. When using this method many shallow boreholes are drilled, usually 50-100 m deep. The thermal gradient is estimated by finding the temperature at different depths in a hole. When the thermal gradient in an area is considerably higher than the average value it can indicate the existence of a geothermal system. The thermal gradient drilling is mostly used in geothermal exploration in low-temperature fields and where the strata are compressed (Pálmason, 2005).

Resistivity measurements

Resistivity measurements are indirect geophysical measurements that explore the characteristics of the strata and draw indirect conclusions on the geothermal system. Resistivity measurements are synonym of different methods that measure the resistivity of strata. The resistivity is a material quality that is dependent on a few natural factors. The main factors are; the resistivity of the rock, porosity, type of liquid in the pores (air, water, or steam), temperature, amount of ions in the liquid in the pores (salt) and the type and amount of metamorphic rock formations. One of the most widely used resistivity measurement today in Iceland is the *Transient Electromagnetic Measurement (TEM)*. The TEM uses an electromagnetic impulse excitation to investigate the subsurface (Pálmason, 2005).

Conceptual model

A conceptual model is the representation of the most significant physical characteristics of a geothermal reservoir. The conceptual model is constructed out of the data acquired in the exploration phase. Plan views and vertical sections of the conceptual model show the temperature and pressure distribution as well as surface manifestations, flow boundaries, faults zones of high and low permeability and location of deep inflows and boiling zones. The conceptual model is the basis for a more complex numerical model which can be constructed in the exploitation phase when the geothermal fields has responded to the production.

2.3.4 Exploitation Phase

Production

The aim of a geothermal production should be to get the most energy out of a resource by extracting as little as possible of geothermal fluid. This will encourages efficient use of the resource and that is one of the main goals of sustainable development.

Geothermal production involves extracting warm fluid from underground reservoirs. To get to the fluid wells need to be drilled into the reservoir. In high temperature geothermal fields these wells are usually 1000-2500 m deep. The production technique is still developing and the experience that has been gained throughout the years is becoming very valuable.

Monitoring

Monitoring the responses of geothermal systems during long-term production provides important data on the nature and properties of the system. Monitoring involves physical as well as chemical aspects, such as the observation of surface subsidence, permanent reservoir pressure drop and reduction in fluid temperature.

The fluid extraction from the reservoir can have various influences on the resource. First of all these influences will depend on the resource type; high- or low-temperature field, open or closed reservoir, permeability and porosity.

Pressure and temperature changes

Pressure drop (drawdown) and temperature changes are the most important changes that will be in the reservoir because it will affect the productive lifetime of the resource. The pressure drop will usually be higher in the first few years of production and then it will decrease and sometimes the pressure will reach a steady state, especially in low-temperature fields. Temperature decrease in a reservoir is usually associated with excessive fluid withdrawal an inflow of cold water into the reservoir because of pressure drop in the reservoir.

Other conditions will change with pressure drop and change in temperature such as the enthalpy or the steam fraction.

In some cases long term production can cause the formation of a steam cap in the reservoir. Then a drawdown in the reservoir will cause a pressure drop and eventually boiling of the geothermal fluid and a steam layer will form on top of the liquid layer. The pressure in the steam cap can be very high and wells that are drilled into the steam cap are very productive for some time. In the long run the activity in the geothermal system will decrease because of a pressure drop in the steam cap.

Changes in dissolved chemicals

The concentration of dissolved solids and gases in geothermal fluids are determined by their source of supply to the fluid and by the formations of hydrothermal minerals, which remove dissolved components from the fluid. The source of dissolved solids and gases include (Arnórsson, 2004):

1. The rock through which the fluid percolates
2. Magma
3. Dissolved matter in the recharging water

In high-temperature fields the chemical changes are often very complex and dramatic. The fluid is very concentrated and the discharge and production characteristics may change drastically due to a change in the reservoir or even the well itself. A drawdown in the field

will create a growing steam zone, steam cap, at the upper levels and degassing of the lower reservoir into the steam phase. Early indicators of these changes may be seen in chemical changes of the discharged fluid. Cooling effects will also be reflected in chemical changes, but usually in high-temperature fields these are an indication of overexploitation and not necessarily caused by inflow from a different source (Kristmannsdóttir & Ármannson, 1996).

There are various chemicals that are dissolved in the geothermal fluid. All the major ions found normally in groundwater are in geothermal waters such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, SO_4^{2-} and Cl^{-}, but their concentration in geothermal water is generally much higher (Chandrasekharam & Bundschuh, 2008). The amount of dissolved chemicals is usually measured in mg/kg or mg/l. Chemical ratios are also used to monitor changes and so are chemical geothermometers which estimates temperatures at a depth using chemical concentration in the fluid.

Isotope measurements can provide information on the characteristics on the geothermal field, e.g. on the mixing between waters of different temperatures and origin, on the underground flow patterns of the hot fluids, on the degree of interaction with the reservoir rocks and on the origin of the various fluid components and on the estimation of deep temperature using isotopic geothermometers. Isotopes are not monitored regularly in all geothermal fields so using them as a monitoring tool is difficult.

For a well that gives water or both water and steam it is possible to monitor the following chemicals/chemical ratios: SiO_2, Na/K or/and K/Mg. These chemicals/chemical ratios are all very temperature dependent and take place in temperature dependent chemical reactions and are monitored to follow temperature changes in the reservoir. Cl is monitored to try to detect if there is mixing of cold groundwater into the geothermal reservoir.

If the well is a pure steam well then it is better to use gas ratios to monitor mixing and boiling. The following gases can be monitored CO_2, H_2, CH_4, N_2, NH_3 and H_2S.

In low temperature fields it is easier to follow the chemical changes because there is no steam phase present and boiling and enthalpy changes are not complicating the interpretation of the changes. In low temperature fields the same chemicals can be monitored as for the two phase high temperature fields.

Subsidence

Long term withdrawal of liquid from a geothermal reservoir can in many instances bring about sufficient pressure reduction for the formations above the reservoir to compress and the surface to subside. This has not been a problem in Iceland but in New Zealand in the Wairakei field the ground localized subsidence levels of 1.5-2 m have been measured.

Subsidence may have harmful effects on surface structures, particularly long fluid transmission pipelines. Subsidence has also been found to affect the well casing.

Reinjection of the effluent fluid back into the reservoir has proved to be a good method in counteracting the subsidence effect.

Micro seismic activity

Micro seismic activity has been associated with high-temperature geothermal fields for a long time. Researches have shown that in some high-temperature fields this activity is persistent. The cause of this is believed to be because of divergence of faults. The small quakes are produced when hot rock cools, contracts and fractures. The geothermal fluid forces itself into the fractures and expands them. This happens so fast that it causes seismic waves. The hypocenter of the quakes indicates where heat exchange between the cooling intrusion and the geothermal system is happening (Pálmason, 2005).

Seismic activity has also been associated with reinjection of waste water back into the geothermal system.

Micro seismic activity has positive impacts on a geothermal system. The small quakes help keep the geothermal reservoir permeable by re-fracturing faults that might have been clogged up with precipitations.

The micro seismic activity can also have negative impacts; this is when the seismic events damage above ground constructions in the area. This is not a known problem in Iceland.

Advanced modeling

Simulation studies or modeling are important tools in reservoir engineering. When a conceptual model has been constructed and a production history has been documented it is possible to make a numerical model that can predict the response of the geothermal reservoir to future production. These models can predict the productive lifetime of the reservoir and a possible reclamation time after the production has ceased.

Numerical models are mathematical models that use numerical time-stepping procedure to obtain the models behavior over time. The mathematical solution is represented by a generated table and/or graph. Detailed and complex numerical models (finite element or finite difference) can accurately simulate most aspects of a geothermal systems structure, conditions and response to production. Numerical modeling can take a long time and requires powerful computers as well as complex and detailed data on the geothermal system in question (Axelsson, Björnsson, Steingrímsson, & Stefánsson, 1996).

2.3.5 Geothermal Energy Utilization in Iceland

There are seven geothermal power plants in Iceland that produce electricity and the largest ones are Hellisheidi 213MW_e (MW = $1 \cdot 10^6$ W), and Nesjavellir, 120MW_e. In total the electricity generated by the geothermal power plants in 2008 was 4 TWh (TWh = $1 \cdot 10^{12}$ Wh) and that was 25% of the total electricity generation. Geothermal energy accounts for almost two thirds of primary energy consumption in Iceland (National Energy Authority, 2009).

The most important aspect of geothermal utilization in Iceland is district heating. Today around 89% of all households in Iceland are heated using geothermal heat. The water used for the district heating comes either from low temperature areas that are located all over the country or from the high temperature areas where the separation water is used to heat up fresh water which is then used for district heating. Figure 2-6 shows geothermal utilization in Iceland in 2008. The total use of geothermal energy in 2008 was 39 PJ (PJ = $1 \cdot 10^{15}$ J)

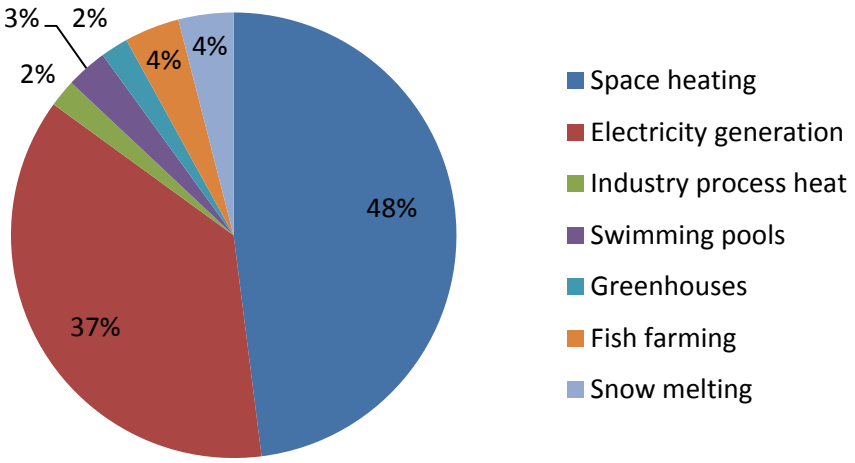

Figure 2-6 Geothermal utilization in Iceland in 2008 (National Energy Authority, 2009)

3 Methodology

3.1 Selection of Indicators

The task of selection a set of indicators requires knowledge of the system that the indicators will be applied to. The indicators are usually applied as a complete set like the GSAP that Ruth Shortall has developed. This thesis, as mentioned before, is only considering a part of this GSAP and focusing on the geothermal production and the influences on the resource. Shortall discusses in more detail how the GSAP is developed and the methodology behind the protocol (Shortall, 2010).

There are certain guidelines that must be taken into consideration when selecting indicators. The United Nations (UN) have published a report called "Indicators of Sustainable Development: Guidelines and Methodologies" (United Nations, 2007) that provides, as the title implies, guidelines on indicator selection and development. Organization for Economic Co-Operation and Development (OECD) also published a report about indicator development in 1993 called "Environmental indicators for environmental performance reviews" (OECD, 1993) where criteria for selecting environmental indicators are discussed.

The UN report and the OECD reports have a few common guidelines and by combining the two reports the following criteria can be used when selecting the indicators:

A sustainability indicator should:

- Be **responsive** to changes in the environment and related human activities
- Be **relevant** to assessing sustainable development progress
- Use **data** which is readily **available** or made available at a reasonable cost/benefit ratio and which is **updated** regularly or adequately documented of know quality
- Be **clear and unambiguous** and able to show trends over time
- Provide basis for **international comparisons** and based on **international standards** and international consensus about its validity to the extent possible
- Have a **threshold** or **reference** value against which to compare it so that users are able to assess the significance of the value associated with it
- Be **theoretically** well founded in technical and scientific terms

These criteria describe the "ideal" indicator for sustainable development and cannot all be met in practice.

When considering geothermal production it is not easy to find a threshold or a reference value for some of the indicators because the geothermal systems are all different and therefore comparison methods will have to be used to find an average value to assess the significance of the value associated with it.

After looking closely at the geothermal system the following indicators were chosen in cooperation with the committee for sustainable utilization of geothermal resources:

1. Utilization efficiency
2. Productive lifetime
3. Reserve capacity ratio
4. Reclamation time
5. Change in dissolved chemicals
6. Ground subsidence
7. Micro seismic activity

Detailed description and further development of the indicators is in chapter 4.
Some of the indicators are more complex than others and a special methodology has to be defined before they are evaluated. The following chapters explain the methodology behind the indicators.

3.2 Efficiency

3.2.1 Exergy Analysis

Efficient use of natural resources is very important in sustainable development and one way to assess the performance of the entire plant is to use the second law of thermodynamics by comparing the actual power output to the maximum theoretical power that could be produced from the given geothermal fluid. This involves determining the rate of exergy carried into the plant with the incoming geofluid. The specific exergy b of a fluid that has pressure P and temperature T in the presence of an ambient pressure P_0 and ambient temperature T_0 is given by (DiPippo, 2008):

$$b = b^{PH} + b^{KN} + b^{PT} + b^{CH} \tag{3.1}$$

Where:

b^{PH} = *physical exergy, kJ/kg*
b^{KN} = *kinetic exergy, kJ/kg*
b^{PT} = *potential exergy, kJ/kg*
b^{CH} = *chemical exergy, kJ/kg*

The physical exergy is given by

$$b^{PH} = (h - h_0) - T_0(s - s_0) \tag{3.2}$$

Where:

b^{PH} = *exergy per unit mass of substance at the given conditions, kJ/kg*
h = *enthalpy of the fluid, kJ/kg*
h_0 = *enthalpy of the fluid at T_0 and P_0, kJ/kg*
T_0 = *temperature of the fluid at the reference state, °C*
s = *entropy of the fluid, kJ/kg°C*
s_0 = *entropy of the fluid at T_0 and P_0, kJ/kg°C*

When evaluated relative to the environment, the kinetic and potential energies of a system are in principle fully convertible to work as the system is brought to rest relative to the

environment, and so they correspond to the kinetic and potential exergies, respectively. Accordingly,

$$b^{KN} = \frac{1}{2}V^2 \tag{3.3}$$

$$b^{PT} = gz \tag{3.4}$$

Where:

V = velocity, m/s
z = elevation relative to coordinates in the environment respectively, m
g = acceleration of gravity, 9.81 m/s^2

Beforehand it is expect that the kinetic and potential exergy will not contribute much to the total exergy and therefore it might be omitted from the exergy calculations. This was verified with calculations and the outcome was that these factors are insignificant.

The chemical exergy is the component associated with the departure of the chemical compositions of a system from that of the environment. The chemical exergy analysis is beyond the scope of this thesis because it is not considered to contribute to the results.

Thus the formula used to calculate the exergy will be as in (Bödvarsson & Eggers, 1972):

$$b = b^{PH} = (h - h_0) - T_0(s - s_0) \tag{3.5}$$

When this is multiplied by the geofluid mass flow rate, $\dot{m}$ (kg/s), the maximum theoretical thermodynamic power of the exergetic power is obtained:

$$B = b * \dot{m} \tag{3.6}$$

The exergetic power is calculated for each well and then the total exergetic power input to a power plant will then be:

$$B_{Total} = \sum_{n=1}^{i} b_i * \dot{m}_i \tag{3.7}$$

Where:

B_{TOTAL} = Total exergy extracted, W
b_i = exergy of well i, kJ/kg
m_i = mass flow rate of well i, kg/s

3.2.2 Reference State

A reference state has to be chosen when assessing the exergy. The reference state is not a predetermined state, it can be selected based on circumstances. In this paper the reference state is chosen when the temperature is 5.5°C (278.65 K) and pressure is 1 atm (1.013 bar). The temperature 5.5°C is the average temperature in Iceland (Iceland Statistics, 2008).

3.2.3 Utilization Efficiency

The ratio of the actual net power to the exergetic power is defined as the utilization efficiency or the second laws (exergetic) efficiency of the plant:

$$\eta_B = \frac{W_{net,total}}{B_{Total}} \tag{3.8}$$

Where:

η_B = utilization efficiency
$W_{net,total}$ = net power output (electricity production plus exergetic power of direct use), MW
B_{Total} = exergetic power for the all the wells, MW

It is expected that the utilization efficiency of a power plant that only produce electricity will be lower than for the combined heat and power geothermal power plants.

The Lindal diagram in Figure 3-1, shows the wide range of possible uses of the geothermal fluid at different temperatures. The Lindal diagram emphasizes two important aspects: 1) possible to enhance the feasibility of the geothermal projects with cascading and combining uses, 2) The resource temperature limits the possible uses.

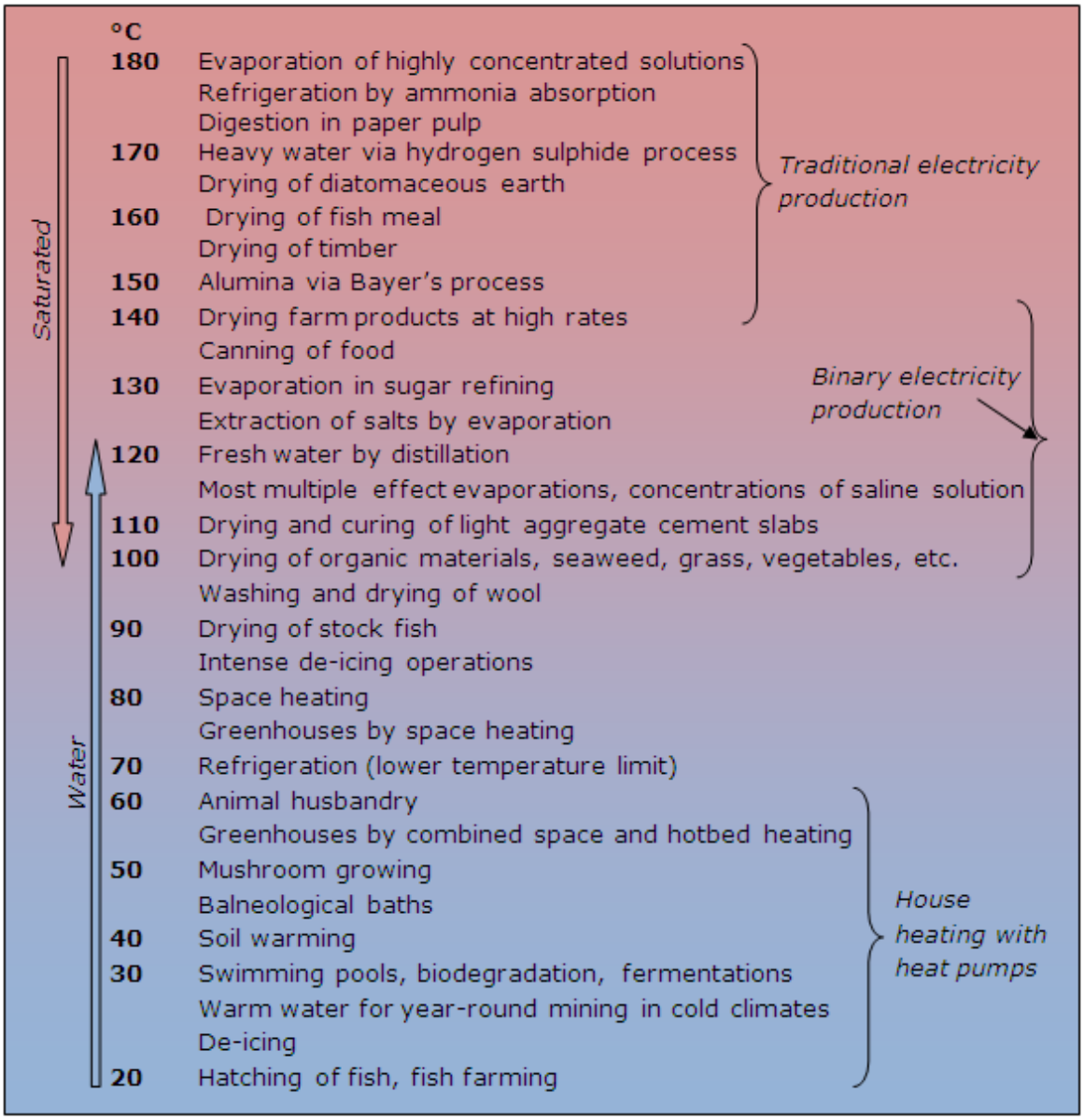

Figure 3-1 Lindal Diagram, derived from (Líndal, 1973) and (Pálmason , 2005)

3.2.4 Primary Energy Efficiency

Primary energy efficiency is also a useful ratio to estimate efficiency geothermal utilization. The primary energy efficiency measure how much of the primary energy extracted is used to generate electricity. This efficiency is only calculated for high-temperature fields.

The primary energy consumption is defined as the amount of fluid from the geothermal reservoir with enthalpy over 15°C minus the amount of liquid re-injected back into the reservoir with enthalpy over 15°C:

$$E_P = M_{extracted} * h_{extracted} - M_{injected} * h_{injected} \tag{3.9}$$

Where:

$M_{extracted}$ = *mass extracted from reservoir, kg*
$h_{extracted}$ = *enthalpy over 15°C of extracted fluid, kJ/kg*
$M_{injected}$ = *mass injected back into reservoir, kg*
$h_{injected}$ = *enthalpy over 15°C of injected fluid, kJ/kg*

Primary energy efficiency is defined as the ratio of energy generated and energy extracted:

$$\eta_P = \frac{W_{net,electricity}}{E_P} \tag{3.10}$$

Where:

η_P = *primary energy efficiency*
$W_{net,electricity}$ = *net power output (electricity production), MW_e*
E_P = *primary energy extracted, MW*

3.3 Reserve Capacity

The reserve capacity in a geothermal resource and the reserve capacity ratio are defined in the following way:

The reserve capacity is defined as:

$$R_{Capacity} = R_{Probable} - R_{Proven} \tag{3.11}$$

The reserve capacity ratio can be defined as:

$$r = \frac{R_{Capacity}}{R_{Probable}} \tag{3.12}$$

Where *R* represents reserve.

Figure 2-4c shows how proven and probable reserves are defined. To find the reserve capacity the proven and probable reserves have to be known. The proven reserves in a geothermal field are taken to be the installed capacity and available capacity from existing wells, exploratory and production wells, which are not being utilized. The probable reserve can be estimated using the volumetric method or using areal production values and resistivity measurements.

3.3.1 Volumetric Method

The volumetric method is used to estimate the amount of energy in a geothermal resource. This method involves calculating the amount of thermal energy contained in a given volume of rock and water and then estimating how much of this energy maybe recoverable given a reference temperature. The volumetric method uses the volume of the rock, the specific heat and temperature of rock to calculate the energy (Pálmason, 2005). The essential weakness of the method lies in the assumption of a fixed recovery factor, while energy recovery strongly depends on the physical conditions and properties of the reservoir (Parini, 2000). Because the method does not account for any inflowing heat to the system

the result of the method gives the minimum amount of energy stored. The volumetric method has been used for national estimates of geothermal resources in several countries and was used in Iceland in 1985 (Pálmason, et al., 1985).

The reference temperature can be chosen as ambient temperature following the exhaust pressures of the turbines or the reference temperature can be equivalent to the minimum or abandonment temperature of the geothermal fluids for the intended utilization of the geothermal reservoir. For electricity generation the abandonment temperature is usually around 180°C for conventional power plants.

The equations used in calculation the thermal energy for a liquid dominated reservoir is as follows as described in (Sarmiento & Steingrimsson, 2007):

$$Q_T = Q_r + Q_w \tag{3.13}$$

Where:

$$Q_w = A \cdot d \cdot \left[\rho_r \cdot C_r \cdot (1 - \emptyset) \cdot \left(T_a - T_f\right)\right] \tag{3.14}$$

$$Q_r = A \cdot d \cdot \left[\rho_w \cdot C_w \cdot \emptyset \cdot \left(T_a - T_f\right)\right] \tag{3.15}$$

Where:

Q_T = total thermal energy, kJ/kg
Q_r = heat in rock, kJ/kg
Q_w = heat in water, kJ/kg
A = area of the reservoir, m^2
d = average thickness of the reservoir, m
C_r = specific heat of rock at reservoir conditions, kJ/kgK
C_w = specific heat of water at reservoir conditions, kJ/kgK
$\emptyset$ = porosity
T_a = average temperature of the reservoir, °C
T_f = final or abandonment temperature, °C
ρ_r = rock density, kg/m^3
ρ_w = water initial density, kg/m^3

Equation 3.11 only gives the thermal energy in place in the reservoir. To size the power plant that could be supported by the resource, the following equation is used:

$$W = \frac{Q_T \cdot r_f \cdot C_e}{P_f \cdot t} \tag{3.16}$$

Where:

W = power potential, MW_e
r_f = recovery factor
C_e = conversion efficiency
P_f = plant factor
t = time in years

Recovery factor refers to the fraction of the stored heat in the reservoir that could be extracted to the surface. It is dependent on the fraction of the reservoir that is considered

permeable and on the efficiency by which heat could be swept from these permeable channels.

Conversion efficiency takes into account the conversion of the recoverable thermal energy into electricity.

Economic life of the project is the period it takes the whole investment to be recovered within its target internal rate of return.

Plant factor refers to the plant availability throughout the year taking into consideration the period when the plant is scheduled for maintenance, or whether the plant is operated as a base-load or peaking plant.

The reserve estimation is done using commercial software that provides for a probabilistic approach of calculating uncertainty in the occurrence of events or unknown variables. @Risk is popular software used for this purpose. @Risk uses Monte Carlo simulation to assess the resource and evaluate the risk. (Sarmiento & Steingrimsson, 2007).

3.3.2 Size of Geothermal Fields

The size of a geothermal field *A,* needs to be known when using the volumetric method.

Area of proven reserve

One approach in estimating the production area of an existing production field is to draw circles with a 1200 m radius around the drill pads in the area and the area that is formed is then defined as the size of the production area (Björnsson, 2007).

To evaluate this, the mathematical software Matlab is used. A program was written that takes in the x- and y-coordinates of the wells. It plots them up on a graph and draws circles with a 1200 m radius around each well. The circles are then joined into one area and the size of it calculated.

Using the resource classification discussed in the beginning of chapter 2.3 the production area would be referred to as the area of a proven reserve.

Area of probable reserve

When the geothermal activity is being mapped using resistivity measurements it is common to estimate the size of the geothermal reservoir using the total area of the high-resistivity core that is at 800 m depth (Arnason & Karlsdottir, 2006). This core can be found by indentifying a low-resistivity coat that is lies over the high-resistivity core. The low-resistivity coat has minerals like smecite that thrive in lower temperatures than 240°C. Those minerals have resistivity lower than 10 Ωm. When the temperature in the rock goes above 240°C these minerals are replaced by others that have higher resistivity. The core under the low-resistivity coat has steam and water with higher temperatures than 240°C as is desirable for electricity production (Björnsson, 2006).

Using the resource classification discussed in the beginning of chapter 2.3 the area determined by the high-resistivity core would be referred to as the area of a probable resource.

3.3.3 Areal Production

It is possible to use areal production (MW_e/km^2) values to estimate the probable reserves of new geothermal fields. The area of the probable field must be known and then an average value for the areal production can be used to estimate the probable reserve capacity. This is not a very accurate method but can be used at the early stages in estimating the probable reserves (Björnsson, 2007).

This method is used when little information about the field is available and it is not possible to use the volumetric method.

The average areal production worldwide for high-temperature fields is estimated to be 10-20 MW_e/km^2 (Björnsson, 2007). Recent report from OS estimates that the areal production for Icelandic high-temperature fields is 5 MW_e/km_2 within the area of the high-resistivity core (Ketilsson, Björnsson, Halldórsdóttir, & Axelsson, 2009).

3.4 Dissolved Chemicals

It is possible to use chemical analysis on water in the natural outflow from geothermal fields to estimate the temperature of the water deep down in the system. The method is based on that the chemical reactions that are between the water and the rock are dependent on the temperature that is present. After the chemical reactions have taken place they are not easily reversible as the water cools, e.g. when it emerges to the surface. The concentration of dissolved chemicals in the water can then be used to estimate the temperature in the geothermal system. The method used to estimate the temperature at a depth below the geothermal field without drilling is called geothermometer measurement (Pálmason, 2005).

3.4.1 Quartz Geothermometer

One of the most used geothermometers in Iceland is the quartz geothermometer. It is based on the chemical balance between the silica minerals quartz or chalcedony and dissolved silica in water. The chemical balance can be descried using the following equations:

$$SiO_2(quartz) + 2H_2O \Leftrightarrow H_4SiO_4(dissolved\ silica) \tag{3.17}$$

$$SiO_2(chalcedony) + 2H_2O \Leftrightarrow H_4SiO_4(dissolved\ silica) \tag{3.18}$$

The chalcedony geothermometer has proven to give better results water in low-temperature fields but the quartz geothermometer has proven to work better in high temperatures and in older geothermal systems. Quartz is a crystallization of silica but chalcedony is thought to be a mixture of moganite and quartz where the moganite will transform with time into quartz. The quartz geothermometer is represented by the amorphous silica solubility line in Figure 3-2.

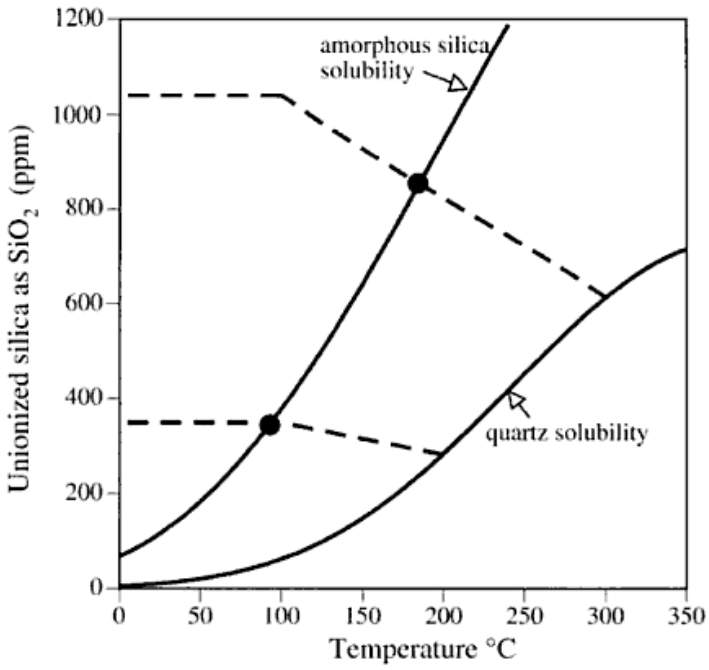

Figure 3-2 Quartz and amorphous silica solubility vs. temperature along the vapor saturation curve. (Arnórsson, 2004).

The dashed lines show the silica concentration in water initially in equilibrium with quartz during adiabatic boiling to 100°C and subsequent cooling. The increase in aqueous silica concentration during boiling is the consequence of steam formation. Amorphous silica saturation (shown by the dots) is attainted at 188°C in the case of the 300°C aquifer water, but at 94°C in the case of the 200°C aquifer water. It is assumed that the pH of the water is not raised sufficiently during boiling to cause significant ionization of the aqueous silica. If some ionization had occurred, amorphous silica saturation would be reached at lower temperatures than indicated in the figure (Arnórsson, 2004).

A silica (quartz) geothermometer equation given by Fournier and Potter that is useful through the temperature range 20-330°C at the vapor pressure of the solution is

$$t°C = -4.2198 \times 10^{1} + 2.8831 \times 10^{-1}S - 3.6686 \times 10^{-4}S^{2} + 3.1665 \times 10^{-7}S^{3} + 7.7034 \times 10^{1} \log S \quad (3.19)$$

Where S is the amount if silica in mg/kg (ppm) (Fournier, 1989, pp. 21-41).

3.5 Grading the Indicators

To be able to compare the sustainability of production for different geothermal fields a grading system for the indicators needs to be developed. That involves assigning each indicator a benchmark that will enable the grading, e.g. if the field that is being assessed is doing worse than the benchmark it gets a worse grade than a field that is exceeding the expectations of the benchmark. It is not an easy task to decide on the benchmarks because the fields that are being assessed are all unique and may have different physical properties. Because of this uniqueness it is not possible to assign a benchmark to all the indicators and a more simplified approach has to be taken when evaluating the sustainability.

All the indicators are graded on a scale from 1-5, 1 being the worst score an indicator can get and 5 being the best score.

The indicators are either measured out from relative standings or impacts. Example of a scoring chart is shown in Table 3-1 and Table 3-2.

Table 3-1 Grading of indicators - standings

Grade	Standings
1	Unacceptable
2	Below average
3	Average
4	Above average
5	Outstanding

Table 3-2 Grading of indicators - impacts

Grade	Impacts
1	Negative impacts
2	Some negative impacts
3	No impacts
4	Some positive impacts
5	Positive impacts

All the indicators will have equal weight because in this evaluation no property is considered more important than another.

4 Indicators for Geothermal Production

This chapter defines the indicator and explains how they work and what they measure. The indicators are set up in the following way:

Description: Short description on what the indicator is measuring and why it is important.

Units: Units for the indicator.

How the production influences the indicator: How is the production from the geothermal resource changing the indicator?

How to measure the indicator: What methods are used to measure or estimate the indicator?

How to evaluate the sustainability using the indicator: What determines if the indicator is going towards or away from sustainability?

Benchmark/grading: Is it possible to define a benchmark for the indicator for comparison or will it be best to do a relative comparison to find an average value and base the grading on that?

These indicators were developed with Icelandic geothermal fields in mind.

4.1 Utilization Efficiency

Description: Efficiency of geothermal utilization is measuring how well the extracted fluid is being utilized. Utilization efficiency is the ratio of the actual net power to the exergetic power. The exergetic power is the power extracted from the reservoir and the net power is the produced electricity plus the exergetic power of the direct uses (district heating, lagoons, industrial use etc.).

Units: [%]

How production influences the indicator: Production might change the physical properties and mass flow of the fluid in the long run and therefore change the amount of exergetic power extracted from the reservoir. The efficiency will also change if the fluid that is extracted is better matched with the spectrum of use (see Lindal diagram Figure 3-1). The efficiency can also change if the capacity of the power plant is changed.

How to measure the indicator: It is possible to use exergy analysis to measure the efficiency of the utilization. To calculate the exergetic power extracted from the reservoir the wellhead pressure, the enthalpy and the mass flow from each well needs to be known.

The exergy analysis is explained in chapter 3.2.1. The primary energy efficiency can also be calculated to see how it compares to the utilization efficiency. The primary energy efficiency takes into account reinjection of waste fluid back into the reservoir. To calculate the primary energy efficiency the net primary energy extraction from the field needs to be known as well as the net electricity output of the power plant.

How to evaluate sustainability: Efficient use of natural resources is important for sustainable development. High utilization efficiency as well as high primary energy efficiency is desirable because it is better in terms of sustainable use. To achieve high utilization efficiency the characteristics of the source should be matched with the spectrum of use (Lindal diagram Figure 3-1).

Grading: The grading is decided by comparing all the utilized geothermal fields in Iceland. This was done because there does not exist a benchmark or a reference value to base the grading on. The utilization efficiency is calculated for all the fields and the results are plotted up on a graph. The plot shows the average value and the standard deviation of the efficiency. The grading is then decided by using the standard deviation and the average see, Figure 4-1 and Table 4-1.

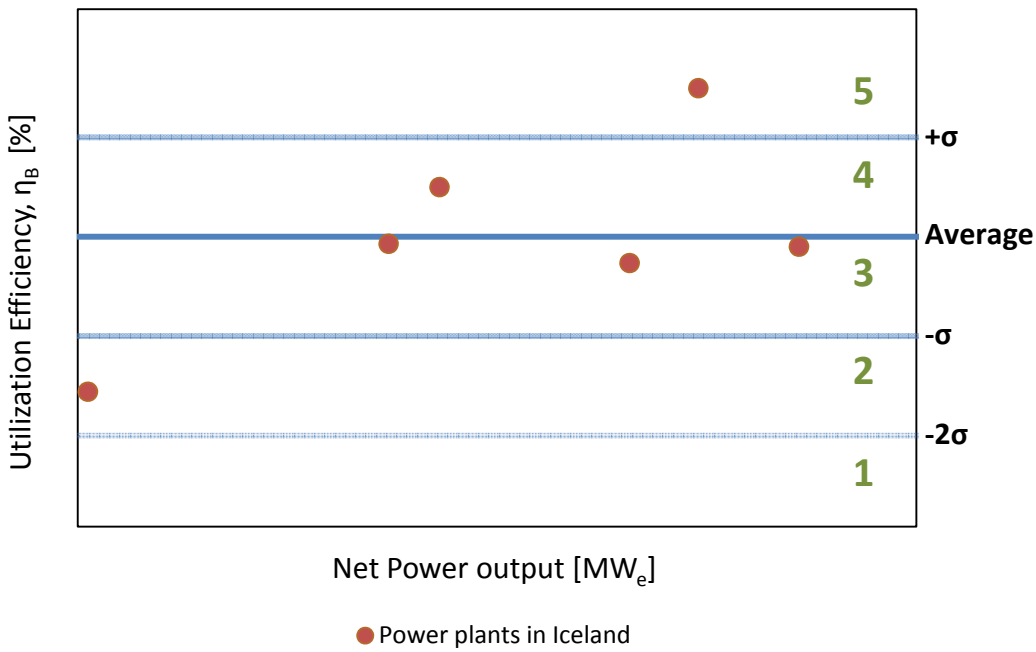

Figure 4-1 Grading the utilization efficiency indicator - All geothermal power plants in Iceland

Table 4-1 Efficiency utilization, η_B – Grading

Grade	Standings	Description
1	$\eta_B < -2\sigma$	Very poor utilization efficiency. Unacceptable.
2	$-2\sigma \leq \eta_B < -\sigma$	Poor utilization efficiency
3	$-\sigma \leq \eta_B <$ average	Average utilization efficiency.
4	Average $\leq \eta_B < +\sigma$	Good utilization efficiency..
5	$+\sigma \leq \eta_B$	Very good utilization efficiency. Co-generation plant.

4.2 Productive Lifetime

Description: Productive lifetime is the time that the resource can sustain a certain level of production. This indicator is dependent on the change in physical conditions of the fluid in the resource, mainly pressure drawdown and temperature changes.

Units: [years]

How production influences the indicator: Production can cause changes in the physical conditions of the fluid in the resource. The pressure can drop, the temperature can change and the enthalpy can change. A drastic chance in these factors may indicate overexploitation of the resource and shorten the productive lifetime.

How to measure the indicator: The productive lifetime cannot be measured directly, but it can be estimated using advanced reservoir modeling. To construct a model the main physical conditions and characteristics of the system need to be known. The production history needs to be available and data on measurements of the main physical properties that have been affected by the production.

Models are complex and expensive to make and not all geothermal fields have been modeled in detail. If no model exist it is possible to use pressure drawdown measurements in monitoring wells. The extent of drawdown can indicate whether the reservoir is experiencing a steep pressure drop or has obtained a steady pressure state.

How to evaluate sustainability: Production has been identified sustainable if the resource can sustain a certain level of production for at least 100 years (Axelsson, et al., 2001). That indicates that the reservoir is not being overexploited i.e. recharging at a similar rate as the extraction.

Benchmark/grading: The benchmark is 100 years.

Table 4-2 Productive lifetime – Grading

Grade	Productive lifetime	Description
1	Under 25 years	Very short productive lifetime. Great indication of pressure drawdown and/or cooling in the reservoir.
2	25-49 years	Short productive lifetime. Some indication of pressure drawdown and cooling in the reservoir.
3	50-74 years	Average productive lifetime. Indication of pressure drawdown and cooling in the reservoir.
4	75-99 years	Long productive lifetime. Little indication of pressure drawdown or cooling in the reservoir.
5	100 years and above	Very long productive lifetime. Very little or no indication of pressure drawdown or cooling in the reservoir.

4.3 Reserve Capacity Ratio

Description: Reserve capacity is the amount of available energy reserves in a geothermal system that is not being utilized or can be utilized from existing wells in the field. A single geothermal system that usually is associated with a central volcanic system can have a few geothermal fields that can be utilized. The reserve capacity ratio measures how much of the probable reserve is not being utilized

Units: [%]

How production influences the indicator: If the proven reserve capacity in the geothermal field is higher than the total reserve capacity then there is a risk of overexploitation of the entire system. Then it will not be possible to rest one field and utilize another and maintain the same level of production from the system for 100 years (sustainable).

How to measure the indicator: Difficult to measure and can only be based on conservative estimates using e.g. the volumetric method. The volumetric method estimates the probable reserves in a system, $R_{Probable}$ given the area of the high resistivity core. The volumetric method is described in chapter 3.3.1.

How to evaluate sustainability: The reserve capacity should have at least as much energy as the proven reserves, therefore the reserve capacity ratio should be 0.5 or higher:

$$r = \frac{R_{Capacity}}{R_{Probable}} \geq 0.5$$

This will allow for the resting of a geothermal field that has been under exploitation and needs to be rested possibly due to overexploitation. Then, another field in the same system can be utilized and the same amount of energy can be utilized. This is considered sustainable use of the system. E.g. if a system has probable reserves for 50 years of production and has a reserve capacity ratio of 0.5 or higher then after the first 50 years

another part of the same system can be exploited and the system can maintain the same production for the next 50 years which makes the production sustainable for 100 years.

Benchmark/grading: The reserve capacity ratio should be higher than 0.5.

Table 4-3 Reserve capacity ratio – Grading

Grade	Reserve capacity ratio	Description
1	Below 0	Massive overexploitation of the system. More is being utilized than the probable reserve is assumed to hold.
2	0-0.24	Overexploitation of the system. Almost all of the probable reserve is being utilized.
3	0.25-0.49	Some overexploitation of the system. More than half of the probable reserve is being utilized.
4	0.50-0.74	Sustainable use of the system. Less than half of the probable reserve is being utilized.
5	0.75-1.0	Sustainable us of the system. Very low proportion of the total system is being utilized. .

4.4 Reclamation Time

Description: Reclamation time is the time it takes the resource, in terms of pressure and heat, to recover from exploitation. It is not expected that the pressure and temperature will recover at similar timescales. The reclamation time indicator takes into account the time it takes the pressure to recover because the temperature will usually take a lot longer time to recover.

Units: [years]

How production influences the indicator: Excessive production for a long time will increase the reclamation time.

How to measure the indicator: This cannot be measured directly, only estimated using models. The same model can be used to estimate the productive lifetime and the reclamation time, given there is a production history available.

How to evaluate sustainability: If the reclamation time is longer than the production time of the resource then the utilization is not considered sustainable. Overexploitation of the resource can increase the recovery time to unacceptable levels.

Benchmark/grading: The reclamation time should not be longer than the production time of the resource.

Table 4-4 Reclamation time – Grading

Grade	Reclamation time	Description
1	Not possible to reclaim	The resource has been depleted and cannot be reclaimed.
2	Longer than productive lifetime	A lot to reclaim. The resource is not being utilized in a sustainable manner and there is great indication of a pressure drawdown or temperature decrease.
3	Close to productive lifetime	Something to reclaim. The resource is being utilized in a fairly sustainable manner and there is some indication of pressure drawdown or temperature decrease.
4	Shorter than productive lifetime	Little to reclaim. The resource is being utilized in a sustainable manner and there is little indication of a pressure drawdown or temperature decrease.
5	No reclamation time needed	Nothing to reclaim. The resource is being utilized in a very sustainable manner and there is no or very little indication of a pressure drawdown or temperature decrease.

4.5 Change in Dissolved Chemicals

Description: The concentration of dissolved chemicals in the geothermal fluid. The indicator monitors the concentration of two chemicals: chloride and quartz. From the changes in chemical concentration the cooling trends in the reservoir can be observed.

SiO_2

The concentration of dissolved quartz (Silicon Dioxide, SiO_2) in the geothermal fluid is very temperature dependent and changes may indicate cooling because of inflow of cold water, boiling or cooling of the host rock.

SiO_2 dissolves very fast and its concentration increases with increased temperature but it precipitates fairly slowly upon conductive cooling. SiO_2 also responds quickly to mixing but if the surrounding rock remains hot and heats up the water after mixing more SiO_2 will dissolve and the mixing can go undetected. The concentration of SiO_2 increases with boiling (increase in enthalpy) but may decrease again upon reaction with the rock although the latter is a fairly slow process.

Cl

Chloride (Cl^-) is the major anion of many geothermal waters and the principal conservative constituent.

If the geothermal fluid is rich in Cl and the ground water is not the mixing will easily be detected and the hot surrounding rock will not affect the concentration. The same will happen if the geothermal fluid is low in dissolved chemicals and mixes with seawater. The concentration of Cl increases with boiling (increase in enthalpy).

Units: Analytical results in [mg/kg]

How production influences the indicator: Some fields react to long term production by forming a steam cap. An indication of a steam cap formation is changes in the chemical composition of the extracted fluid because the concentrations of SiO_2 and Cl increase with boiling. Production can also cause drawdown in the system and that can cause inflow of cold water which can cause the Cl concentration to decrease. Excessive production can cause the host rock to cool and that changes the SiO_2 concentration.

How to measure the indicator parameters: Sampling wells, usually special monitoring wells in the geothermal field. The samples are analyzed and the changes in SiO_2 are monitored by using the quartz geothermometer and the changes in Cl are monitored by observing the relative changes in its concentration.

How to evaluate sustainability: Great decreases in dissolved SiO_2 and Cl concentrations in the field indicate cooling in the reservoir. Too much cooling is not desirable in terms of sustainable utilization. Long term increases in the SiO_2 and Cl concentrations can lead to oversaturation and that can result in scaling in equipment and wellbores.

Benchmark/grading: No specific benchmark is defined. To grade this indicator the data has to be obtained from wells from different parts of the same field. This is done to get an idea about the trend in chemical changes in the field as a whole. The data is analyzed and conceptualized to try to understand the changes that are occurring in the reservoir. Indications of cooling are not desirable.

Table 4-5 Change in dissolved chemicals– Grading

Grade	Impacts	Description
1	Major negative impacts	Chemical changes indicate great cooling in the resource
2	Moderate negative impacts	Chemical changes indicate some cooling of the resource
3	Minor negative impacts	Chemical changes indicate little cooling in the resource
4	Insignificant negative impacts	Chemical changes indicate very little cooling in the resource
5	No impacts	Chemical changes indicate no cooling in the resource.

4.6 Ground Subsidence

Description: Ground subsidence may be a result of geothermal fluid withdrawal during energy production. Subsidence is dependent on pressure drawdown in the reservoir and geological rock formations above the reservoir.

Units: Negative impacts and [cm]

How production influences the indicator: If the rock formation above the reservoir is week the production might cause drawdown in the ground above to subside.

How to measure the indicator: Can be measured by using gravity surveying in the geothermal field.

How to evaluate sustainability: If the ground subsidence has negative influence on communities or constructions in the area then the utilization of the field is considered to have unwanted impacts and can therefore not be considered positive with respect to sustainability.

Benchmark/grading: The benchmark is that there should not be any negative impacts on the communities and constructions in the area. The grading is based on how much negative influence the ground subsidence has.

Table 4-6 Ground subsidence – Grading

Grade	Impacts	Description
1	Major negative impacts	The ground subsidence has major negative impacts on the surrounding area, e.g. major damages on constructions.
2	Moderate negative impacts	The ground subsidence has moderate negative impacts on the surrounding area, e.g. medium damages on constructions.
3	Minor negative impacts	The ground subsidence has some impacts on the surrounding area, e.g. minor damages on constructions.
4	Insignificant impacts	The ground subsidence has insignificant impacts on the surrounding area.
5	No impacts	The ground subsidence has no impacts on the surrounding area.

4.7 Micro Seismic Activity

Description: Micro seismic events are usually associated with geothermal systems, such activity usually has good influence on the geothermal system. The movement in the ground helps keep the system permeable by reopening cracks that have been clogged up because of chemical precipitation. The seismicity mainly originates around fractures in a geothermal system. Micro seismic events are less than 2.0 on the Richter scale.

Units: Measured data [Richter]

How production influences the indicator: Pressure changes and mass removal due to production can induce micro seismic events in the geothermal field. Reinjection of geothermal brine can also increase the number and magnitude of micro seismic events in a geothermal field.

How to measure the indicator: Micro seismic activity is measured using monitoring instruments e.g. seismographs.

How to evaluate sustainability: Micro seismic activity has good influence on the geothermal system especially if the geothermal fluid is rich in chemicals. If the seismicity

will increase and become a threat to the surrounding area and have unwanted impacts then the utilization cannot be considered positive with respect to sustainability.

Benchmark/grading: The benchmark is that there should be some magnitude of micro seismicity in a geothermal field to keep it field active. It should not be that great that it has negative impacts on the communities and constructions in the area. The grading is based on the extent of impacts the micro seismic activity has.

Table 4-7 Micro seismic activity – Grading

Grade	Impacts	Description
1	Negative impacts	The micro seismic events have negative impacts on the surrounding area and/or on the geothermal resource. E.g. cooling events.
2	Some negative impacts	The micro seismic events have some negative impacts on the surrounding area and/or on the geothermal resource.
3	Neutral impacts	The micro seismic events have no impacts on geothermal system or the surrounding area.
4	Some positive impacts	The micro seismic events have some positive impacts on the geothermal system; enhances permeability to some extent.
5	Positive impacts	The micro seismic events have positive impacts on the geothermal system; enhances permeability considerably.

5 Case Study – Krafla Geothermal System

To test the effectiveness of the indicators that have been developed it is necessary to apply them to a geothermal field. Krafla geothermal field in Iceland was chosen because Ruth Shortall was testing her GSAP using that field (Shortall, 2010).

Krafla power plant is owned by Landsvirkjun and is located in Northern Iceland in the Mývatn area. The construction of the power plant took longer time than expected because of a series of nine volcanic eruptions that lasted 9 years (1975-1984). The plant was not running on the originally planned capacity until 1999 because of problems related to the eruption. The problems were changed behavior of the reservoir, changed chemical content of the fluid and problems related to drilling. The eruptions caused corrosive magma vapors to enter the geothermal system, destroying the borehole linings. Since 1984, seismic and volcanic impacts on operations have greatly diminished. The currently installed capacity in the power plant is 60 MW_e (Pálmason, 2005).

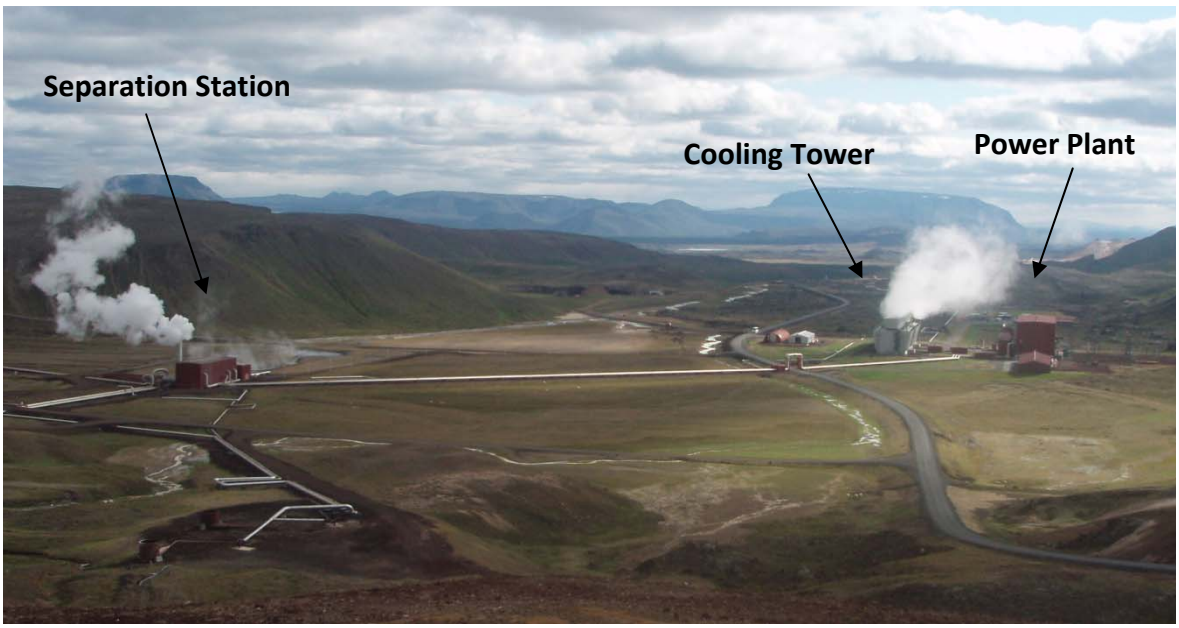

Figure 5-1 Krafla geothermal field in Iceland

The Krafla high temperature system is located within a central volcanic system which is named after a mountain consisting of hyaloclastite called Krafla. Evidence of geothermal activity can be seen on the surface over an area of 15 km^2. The Krafla system has four production areas; Hvíthólar, Sudurhlídar, Vesturhlídar and Leirbotnar which is the main production area, see production areas in Figure 5-2. Leirbotnar has been divided into two water systems; the lower system that is associated with warm intrusions has a temperature of 300-350°C and the other system which is above the lower system has temperatures around or below 210°C. The lower system is boiling and is a two phase system, so a

mixture of water and steam is in the rock. A low permeability between the systems causes the two systems to maintain their characteristics. The lower system had 10-100 times more of non-condensable gases than the system above (Pálmason, 2005)

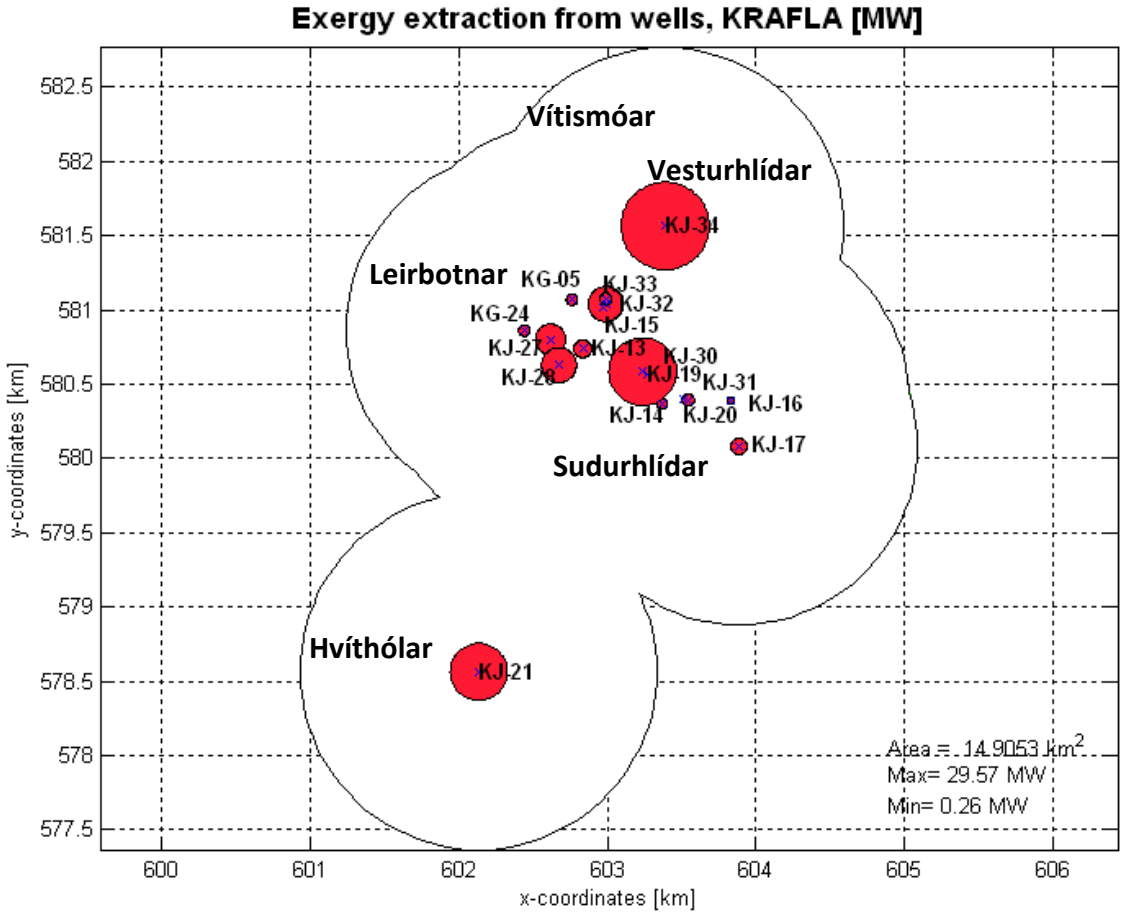

Figure 5-2 Production wells in Krafla. Exergy extraction in 2008.

Currently a new conceptual model of the Krafla system is being developed because of a proposed expansion of the plant and new power plants in the vicinity (Mortensen, et al., 2010). The numerical model that exists for Krafla is also being revised using new information obtained from new measurements.

The last well drilled at Krafla gave almost 16 MW_e and that made the well one of the most powerful well in the world. It is possible that the power in the well will decrease with time but this helped prove that the Krafla field is very suitable for electricity generation. In the near future the plan is to increase the production by 150 MW_e and build a new 90 MW_e power plant at Námafjall.

The data on Krafla used to evaluate the indicators are from LV and the reports used were the latest production report (Hauksson & Benjamínsson, 2009) and an unpublished report on a new conceptual model (Mortensen, et al., 2010).

Data on other power plants was attained from OR (Gunnlaugsson & Oddsdóttir, 2009) and OS with permission from LV and HS-Orka.

Table 5-1 Key figures for Krafla power plant (Pálmason G. , 2005)

Installed capacity	*60 MW_e (2x30 MW_e)*
Average energy production	*480 GWh*
Mass use at full capacity:	
-7.7 bar saturated high-pressure steam	*110 kg/s*
-2.2 bar saturated low pressure steam	*36kg/s*
Number of wells drilled	*34*
Number of production wells (2002)	*16 high-pressure and 5 low-pressure*
Deepest well	*2.222 m*

5.1 Utilization Efficiency

The power plant at Krafla produces only electricity and the installed capacity is 60 MW_e and the net power production in 2008 was 487 GWh.
To evaluate this indicator the utilization efficiency was computed for all the geothermal power plants in Iceland. This was done because there were no reference values available for Icelandic geothermal power plants. Figure 5-3 compares all the geothermal power plants in Iceland. The utilization efficiency for 5 foreign power plants only producing electricity is also plotted for comparison, case studies from DiPippo (2008). As expected Nesjavellir and Svartsengi show the best result and the reason is that these plants are co-generation plants and provide district heating water to neighboring communities. Bjarnarflag has very low utilization efficiency and the reason for that is that the plant is currently being used to test new wells that are supposed to be used for a new power plant that is to be constructed in the area. Bjarnarflag is also the oldest power plant in Iceland and the turbines have low efficiency. Krafla, Hellisheidi and Reykjanes are power plants that currently only produce electricity and the utilization efficiency for these power plants turns out to be very similar, or around 37%.

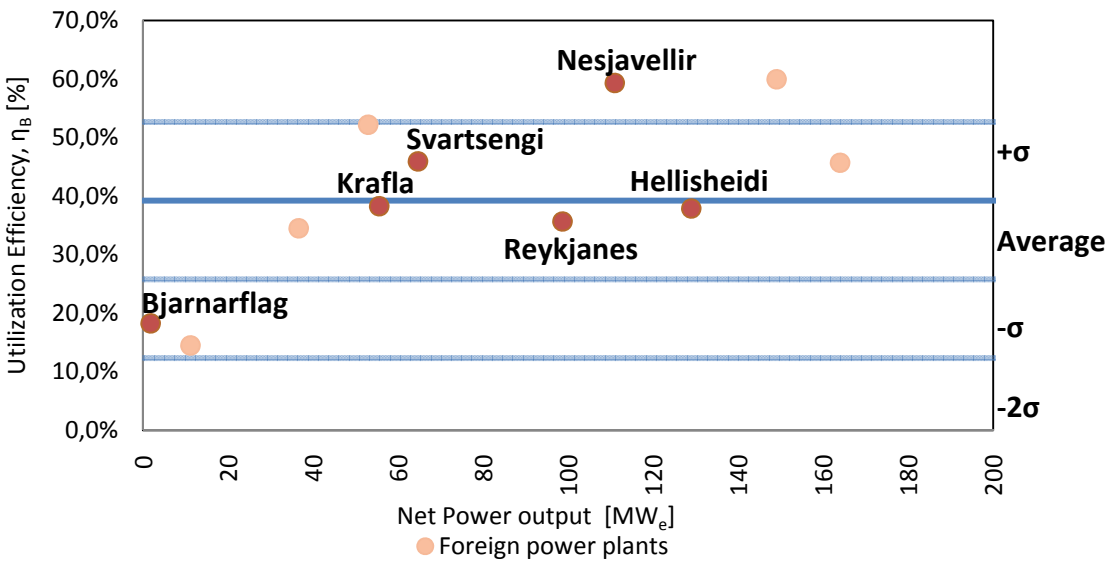

Figure 5-3 Utilization efficiency for geothermal power plants in Iceland 2008 and known values for five foreign power plant plotted for comparison

The primary energy efficiency was also calculated for the same field for comparison to the utilization efficiency and the results are shown in Figure 5-4.

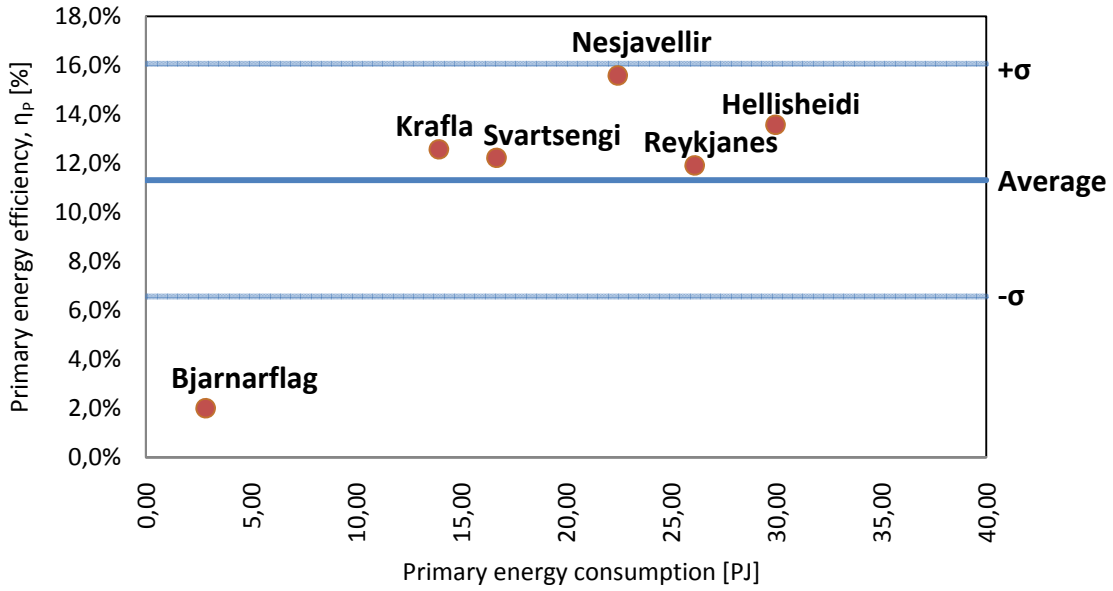

Figure 5-4 Primary energy efficiency for Icelandic power plants in 2008

The primary energy efficiency is very similar for all the power plants except for Bjarnarflag which has very low efficiency. The reason for this low efficiency is as mentioned earlier that the power plant is being used to test future production wells for a new power plant and in that process energy is wasted. The other power plants all have primary energy efficiency between 12%-15,6%.

The overall result for Krafla is that it places third both in utilization efficiency (η_B=38%) and primary energy efficiency (η_P=13%). The grading for this indicator is only based on the utilization efficiency.

Table 5-2 Efficiency of energy utilization – Results for Krafla field

Grade	Standings	Description
3	$-\sigma \leq \eta_B <$ average	Average utilization efficiency.

5.2 Productive Lifetime

Numerical modeling for the Krafla geothermal system has been developing throughout the years with more frequent measurements, increased knowledge on the geothermal system and increased computing power. The earlier models are mostly outdated but show how radical changes have to be made to be able to model the system correctly and trust possible results of a new model. The development of a new model is in process that uses the program iTOUGH2, but modeling measured data is not going as desired (Mortensen, et al., 2010).

Determining the productive lifetime without a model requires analyzing of measured data. The most important are drawdown in wells and temperature changes. In the Krafla field these changes are monitored in special monitoring wells in different productions areas in the field. Summary of observed changes is listed in Table 5-3.

Table 5-3 Temperature and pressure changes in the Krafla geothermal field (Mortensen, et al., 2010)

Field (well)	Temperature changes	Pressure changes
Leirbotnar – lower system (KJ-6)	Temperature has increased and is now almost 15°C higher than in the beginning of monitoring 30 years ago	Pressure increased steadily about 7 bar until the plant was expanded in 1997 then pressure dropped rapidly about 17 bar and has been increasing since then and is now 8 bar under original pressure
Vítismóar (KG-10) (Figure 5-5)	Temperature has decreased consistently for 30 years by 15°C	Pressure increased 2.5 bar until the expansion in 1997, then the pressure dropped 5 bar and has since then stayed fairly stable
Sudurhlídar (KJ-18)	Temperature has decreased consistently for 20 years by 10°C	Pressure dropped 7.5 bar in 1982-1987 and since then the pressure has decreased by additional 5 bar
Hvíthólar (KJ-21)	Temperature has decreased consistently for 20 year by 20°C	Pressure has dropped consistently for the last 10 year about 10 bar and before that the pressure had dropped 15 bar

The pressure change in well KG-10 is shown in
Figure 5-5 and the pressure drop in 1997 when the plant was expanded is noticeable.

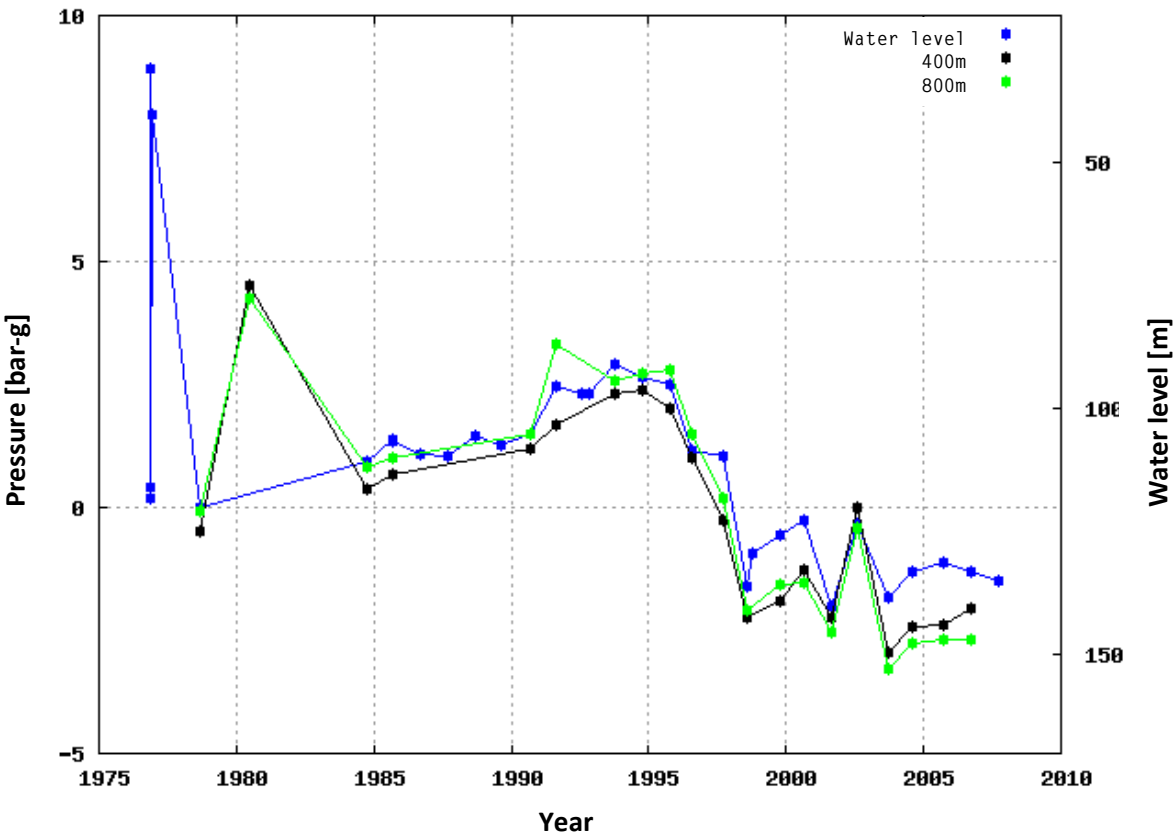

Figure 5-5Pressure change and water level changes in well KG-10 (Mortensen, et al., 2010)

There have been recorded some enthalpy changes in the Krafla field. Enthalpy has kept constant in the shallow wells in the Leirbotnar field while the enthalpy in the deep wells in Leirbotnar and Hvíthólaklif has decreases since the production was doubled in 1997-1999. The enthalpy has increased in Sudurhlídar but decreased in Vesturhlídar. Figure 5-6 shows how the enthalpy has changed.

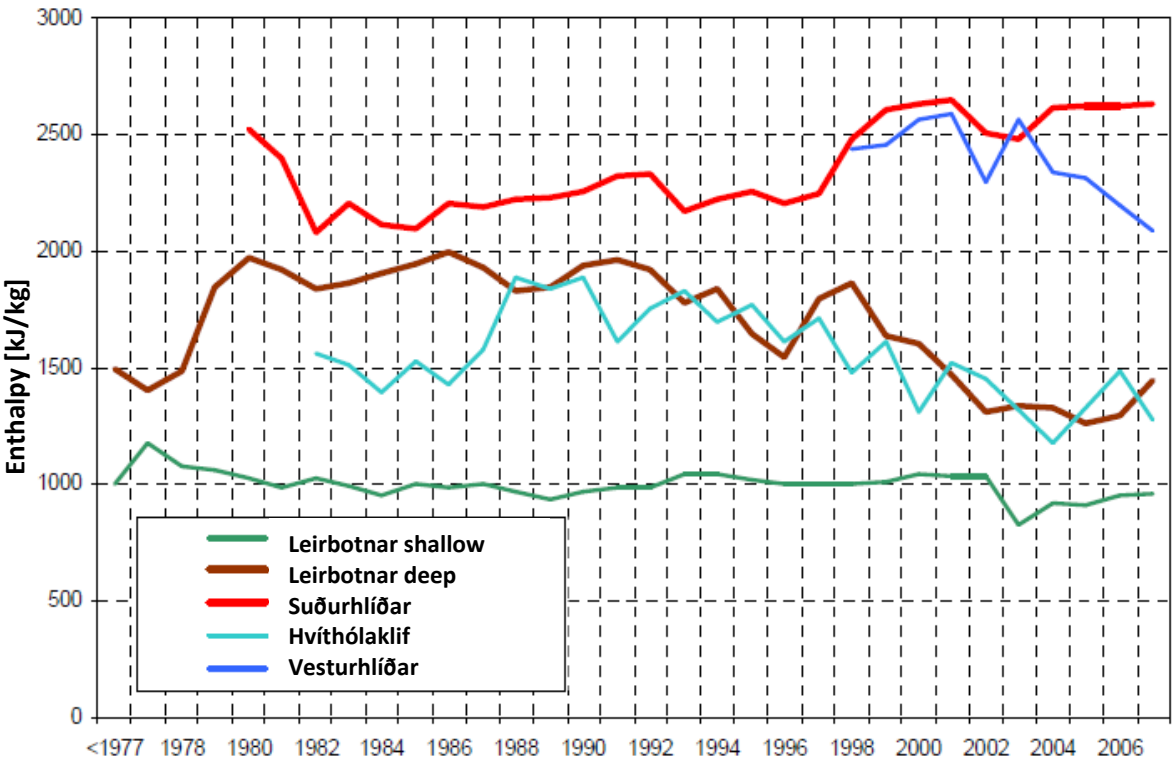

Figure 5-6 Change in enthalpy in the Krafla field (Mortensen, et al., 2010)

By combining these results for change in temperature, pressure and enthalpy it can be concluded that the system is responding to the production but the changes are very little. The production from the field has been going on for over 30 years and there is an indication that the field can withstand production for many years to come.

Table 5-4 Productive lifetime – Results for Krafla field

Grade	Productive lifetime	Description
4	75-99 years	Long productive lifetime. Little indication of pressure drawdown or cooling in the reservoir.

5.3 Reserve Capacity Ratio

There are two high-temperature geothermal fields associated with the Krafla volcanic system. These fields are the Krafla geothermal field and the field around Námafjall (Mannvit Engineering, 2008). Recent TEM indicate that the high resistivity core for the entire system is 62 km^2, Krafla 42 km^2 (Mortensen, et al., 2010) and Námafjall 20 km^2 (Karlsdóttir, 2002) . The probable reserve for just the Krafla system is estimated applying the volumetric method and using A=42 km^2 as the most likely area, 29 km^2 as the minimum and 55 km^2 as the maximum. The time was taken to be 50 years. The physical characteristics that were used are based on the report on the revised conceptual model of Krafla (Mortensen, et al., 2010).

The results of the volumetric method by using Monte Carlo simulation is a relative frequency plot where the mean value for the probable reserve is 322 MW_e and the 90% confidence interval is from 217 to 441 MW_e. See detailed calculations in appendix 2.
The installed capacity in the Krafla field is 60 MW_e. The estimated available unused reserves are 30 MW_e, this is from wells that have been drilled but are not connected to the power plant. This gives total proven reserves of 90 MW_e. In the near future the plan is to expand the Krafla power plant by 150 MW_e.

The reserve capacity ratio, for only the Krafla field, not taking into account planned power plants will be:

$$r = \frac{R_{Capacity}}{R_{Probable}} = \frac{(322 - 90)}{322} = 0.7$$

Taking into account the planned power operations it is assumed that the unused capacity will be utilized as well as power from the reserve capacity by drilling new wells. The reserve capacity ratio will be:

$$r = \frac{R_{Capacity}}{R_{Probable}} = \frac{(322 - 210)}{322} = 0.35$$

In Námafjall there are 35 MWe available as unused proven reserves. This is from research wells that have been drilled in the field. It is planned to build new plant in Námafjall that will be 90 MW_e. Both the expansion at Krafla and the new plant at Námafjall have already gone through an Environmental Impact Assessment (EIA) and combined they will increase the production in the entire system by 240 MW_e.

The reserve capacity ratio computed using the volumetric method will not be used to compare different fields. Instead the comparison will be based on probable reserve calculations using an average areal production from a recent report from OS (Ketilsson, Björnsson, Halldórsdóttir, & Axelsson, 2009). In this report the probable reserves are estimated by finding an average areal production value for Iceland using volumetric estimations. The result is that on average the areal production within the high-resistivity core in Iceland is 5 MW_e/km^2 (most likely value and the upper limit on the 90% confidence interval is 9 MW_e/km^2 and the lower limit is 3 MW_e/km^2). By using this estimate and the area of the high resistivity core the probable reserves for the fields in Iceland are found. In this estimate Krafla and Námafjall are estimated together. The probable reserves and the amount of proven reserves are shown in Figure 5-7.

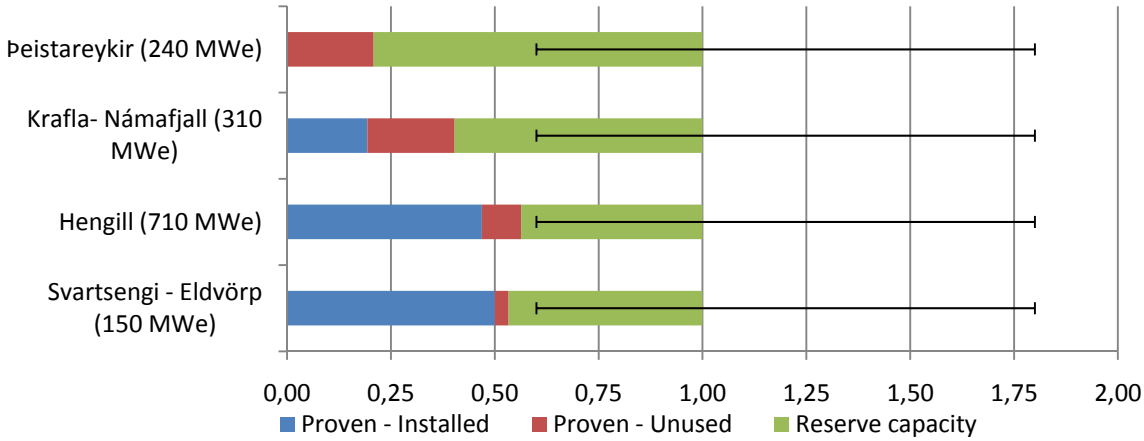

Figure 5-7 Probable reserves for geothermal systems in Iceland, $MW_{e,50}$. The reserve capacity ratio benchmark is 0.5. The error bars show the max and min values for the probable reserve.

Figure 5-7 indicates that for the Krafla-Námafjall system the most likely value for the total probable reserve is 310 MW_e and of that the proven reserve is 125 MW_e (0.4*310) and of that the installed capacity is 60 MW_e (0.19*310 MW_e), unused capacity is 65 MW_e (0.21*310). The reserve capacity accounts for the rest or 186 MW_e (0.6*310). The reserve capacity ratio for Krafla-Námafjall using these values is 0.6, which means that of the total probable reserve 60% are not being utilized. If the ratio remains above 0.5 and the fields currently being utilized would at some point need to be rested then the reserve capacity would be able to supply energy so that the system as a whole could maintain the same level of production.

If the planned expansions are taken into account then the unused reserves will be exploited and the reserve capacity will decrease. The results are shown in Figure 5-8.

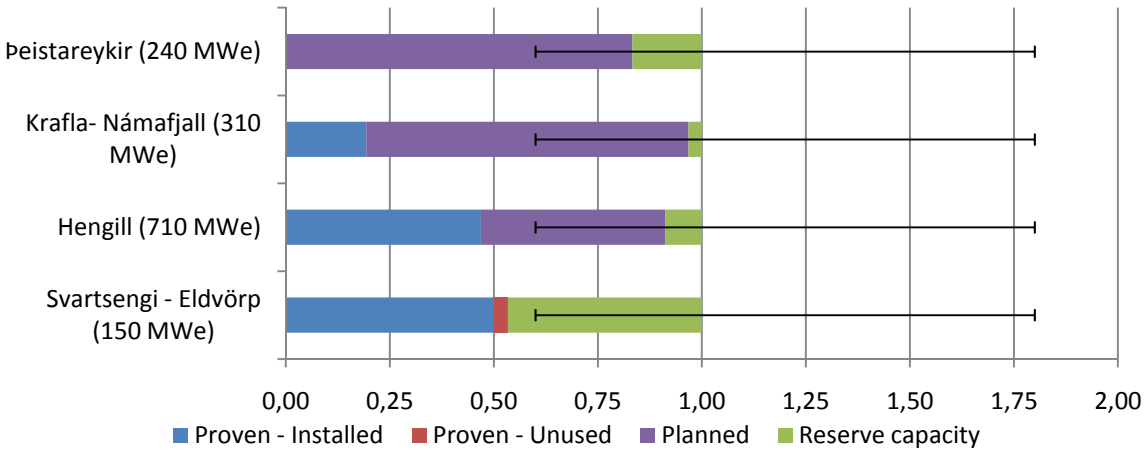

Figure 5-8 Probable reserves for geothermal systems in Iceland, $MW_{e,50}$ after planned power projects have been constructed. The reserve capacity ratio benchmark is 0.5. The error bars show the max and min values for the probable reserve.

After the planned expansion at Krafla and Námafjall the reserve capacity ratio for the entire system will be 0.03. This means that only 3% of the total probable reserves are not being utilized. If this expansion will become real the production from the system ceases to be sustainable according to the definitions of sustainable production (100 years).

The volumetric method for just the Krafla field gives 322 $MW_{e,50}$ and the estimate using areal production for the entire system, Krafla and Námafjall, gives only 310 $MW_{e,50}$. There is a rather large difference in this considering that the value for Krafla alone is higher than for both fields.

To grade this indicator the reserve capacity ratio obtained by using the volumetric method for the Krafla field is used. But both methods will result in the same grade.

Table 5-5 Reserve capacity ratio – Results for Krafla field

Grade	Standings	Description
4	0.50-0.74	Sustainable use of the system. Less than half of the probable reserve is being utilized.

5.4 Reclamation Time

As mentioned earlier there is a numerical model for the Krafla field being constructed and currently there are no available model calculations to estimate the reclamation time. By using the data from the productive lifetime indicator it is apparent that the production in the Krafla field is not causing great temperature decrease or drawdown.
The result for the reclamation time is that there is currently little to reclaim in the Krafla field and it is not estimated to take a long time for the pressure to recover.

Table 5-6 Reclamation time – Results for Krafla field

Grade	Reclamation time	Description
4	Shorter than productive lifetime	Little to reclaim. The resource is being utilized in a sustainable manner and there is little indication of a pressure drawdown or temperature decrease.

5.5 Change in Dissolved Chemicals

Because the Krafla field has four different production areas the data used for this indicator was from wells in all these areas. This was done to obtain a good result that described the field as a whole. Two wells from the Leirbotnar area; one drawing fluid from the upper reservoir and one from the lower reservoir were chosen. Two wells from the Sudurhlídar were chosen too because the wells there showed opposite trends. The data used was both SiO_2 and Cl concentrations in mg/kg (data acquired from LV). The SiO_2 concentration was interpreted in terms of the quartz geothermometer ($tSiO_2$) and the changes in Cl were interpreted using relative concentration changes. Table 5-1 shows which wells were chosen for chemical analysis of fluids and the results for the chemical changes. The average annual changes were found by using linear regression to fit to the data. The slope of the trend line is taken as the average annual change. The trend can be increasing or decreasing.

Table 5-1 Chemical changes in the Krafla geothermal field

Well	Average annual changes		Trend	
	Cl	$tSiO_2$ (°C)	Cl	tSiO2
Vesturhlídar - KJ-34	2.2%	2.40	Increase	Increase
Sudurhlídar - KJ-20	1.8%	-0.56	Increase	Decrease
Leirbotnar - KG-05	0.6%	-0.87	Increase	Decrease
Sudurhlídar - KJ-19	-0.3%	-4.45	Decrease	Decrease
Hvíthólaklif - KJ-21	-1.2%	-1.22	Decrease	Decrease
Leirbotnar - KJ-13	-1.3%	-3.66	Decrease	Decrease
Average	*0.3%*	*-1.39*	*Increase*	*Decrease*

The Cl changes and $tSiO_2$ area plotted with time in Figure 5-9 and Figure 5-10.

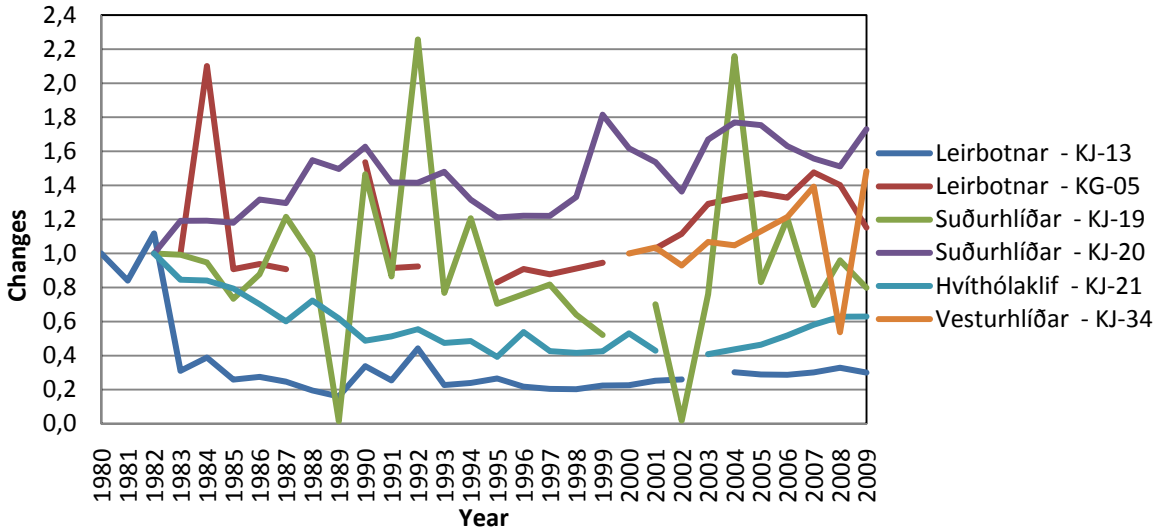

Figure 5-9 Krafla field, relative changes in Cl

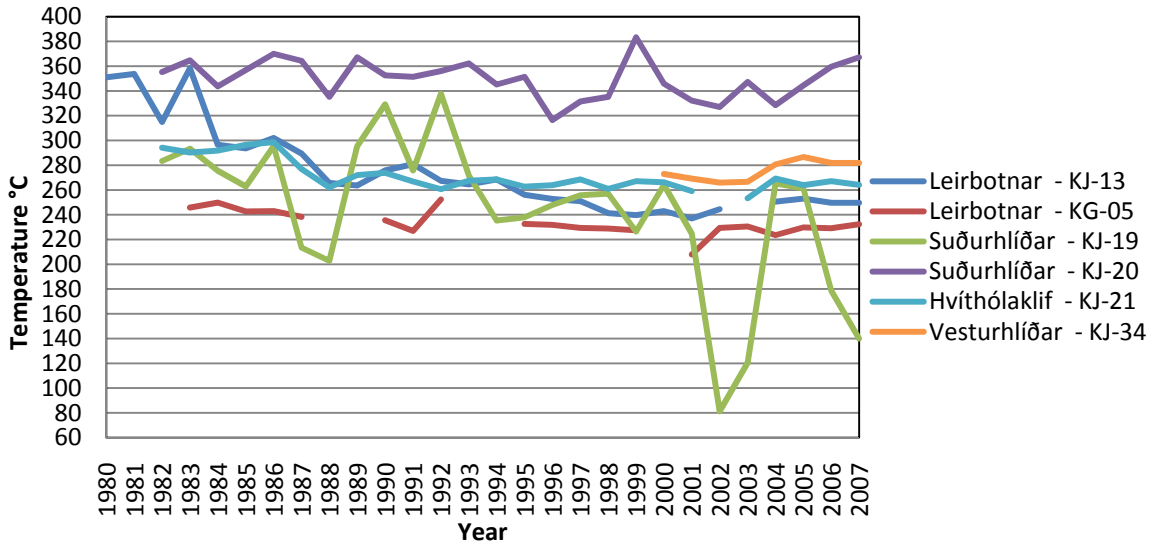

Figure 5-10 Krafla field, quartz geothermometer ($tSiO_2$) with time

The results for the Cl concentrations show that in three wells the concentration has increased and in three wells it has decreased. For the quartz geothermometer there is a decrease in all wells except for one, well KJ-34 where there is an increase. The average changes in all the wells indicate that the Cl concentration is increasing by 0.3% annually and the tSiO2 is decreasing by 1.4°C annually.
In the Krafla field the change in dissolved Cl is associated with a change in enthalpy; increase in dissolved Cl indicates that the enthalpy is increasing. The increase in Cl concentration has also been associated with an inflow of acidic fluid into the wells and a decrease when the acidic veins close up because of precipitation in the wells. The origin of this acidic fluid is from volcanic gases. The average overall changes in the Cl are very small, 0.3%, and can be considered as insignificant.
The decrease in $tSiO_2$ indicates that the host rock in the reservoir is cooling because of the fluid extraction, but this cooling is very small and can be considered as insignificant.

It is concluded that the geothermal production in the Krafla field has insignificant impacts on the chemical composition and there is very little indication of cooling in the reservoir.

Table 5-7 Change in dissolved chemicals – Results for Krafla field

Grade	Impacts	Description
4	Insignificant negative impacts	Chemical changes indicate very little cooling in the resource

5.6 Ground Subsidence

During the Krafla fires that lasted from 1975-1984 there were a lot of movement in the Krafla system. In between eruptions the ground was rising because of inflow of magma into the magma chamber and then it subsided again during an eruption. After the Krafla fires the ground movements in the field closest to Krafla have been monitored closely. From 1989 there has mostly been ground subsidence in the field. At first the rate of subsidence was 5 cm/year but is now around 1 cm/year. The subsidence center seems to moving from above the center of the magma chamber over to the center of the production area. According to this the pressure in the magma chamber under Krafla field seems to be stabilizing and ground subsidence because of pressure drop in the geothermal reservoir may be dominant in the coming years. (Mortensen, et al., 2010).

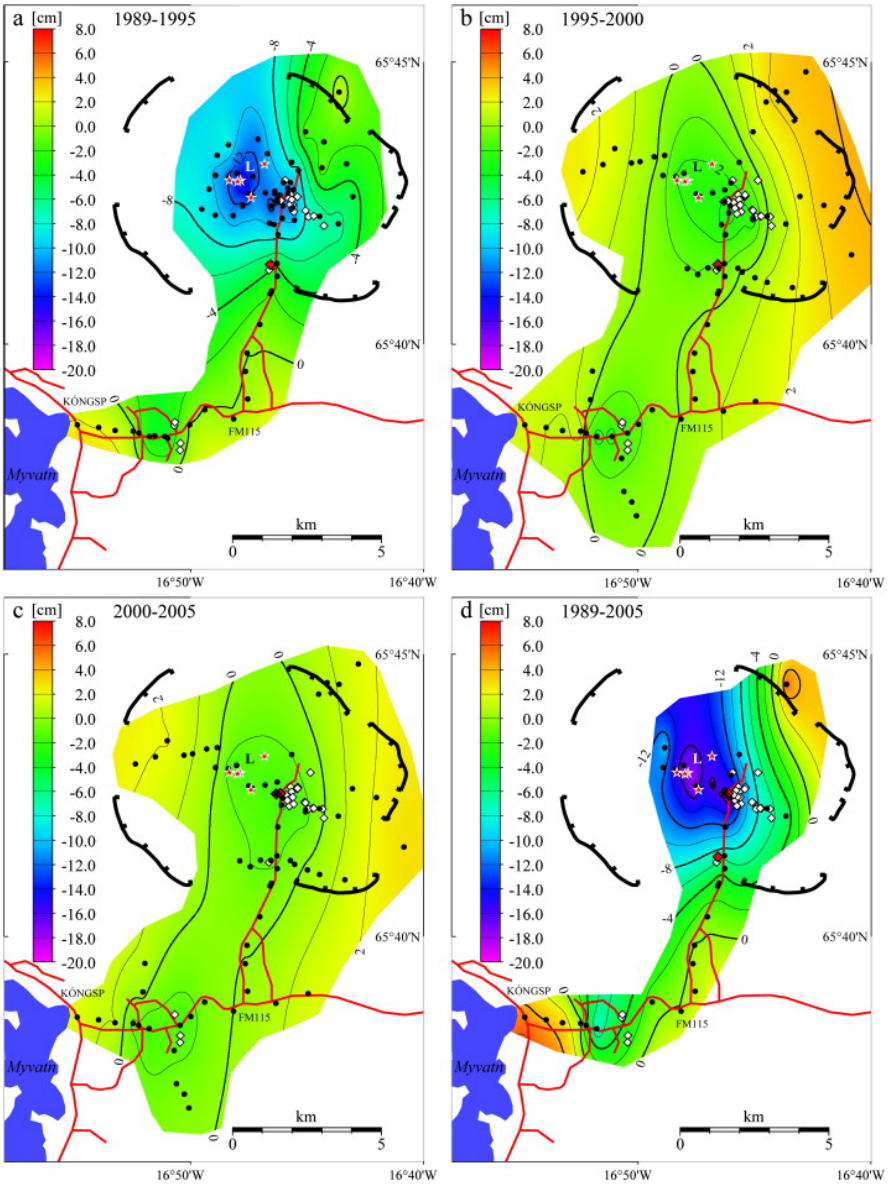

Figure 5-11 Vertical displacements inferred from levelling in the Krafla area 1989–2005 (Sturkell, Sigmundsson, Geirsson, Ólafsson, & Theodórsson, 2008)

There have not been any negative impacts due to the ground subsidence in the Krafla field.

Table 5-8 Ground subsidence – Results for Krafla field

Grade	Impacts	Description
4	Insignificant impacts	The ground subsidence has insignificant impacts on the surrounding area.

5.7 Micro Seismic Activity

The micro seismicity at Krafla from 2004-2007 is mostly concentrated around a 2 km wide and 4 km long area with a northwest direction, see Figure 5-12. The activity is mainly at 500-1500 m below sea level in the Leirbotnar and Sudurhlídar fields. In these fields the

production is at this depth which indicates that the seismic activity is associated with it. On the other hand the seismic activity is fairly little south and east of Víti, where the most powerful wells are located. Palagonite is more common around Víti than in Leirbotnar and Sudurhlídar where intrusions are dominating. It is possible that this difference in lithology has more influence on the seismic activity than the fluid extraction. Furth research might answer that (Mortensen, et al., 2010).

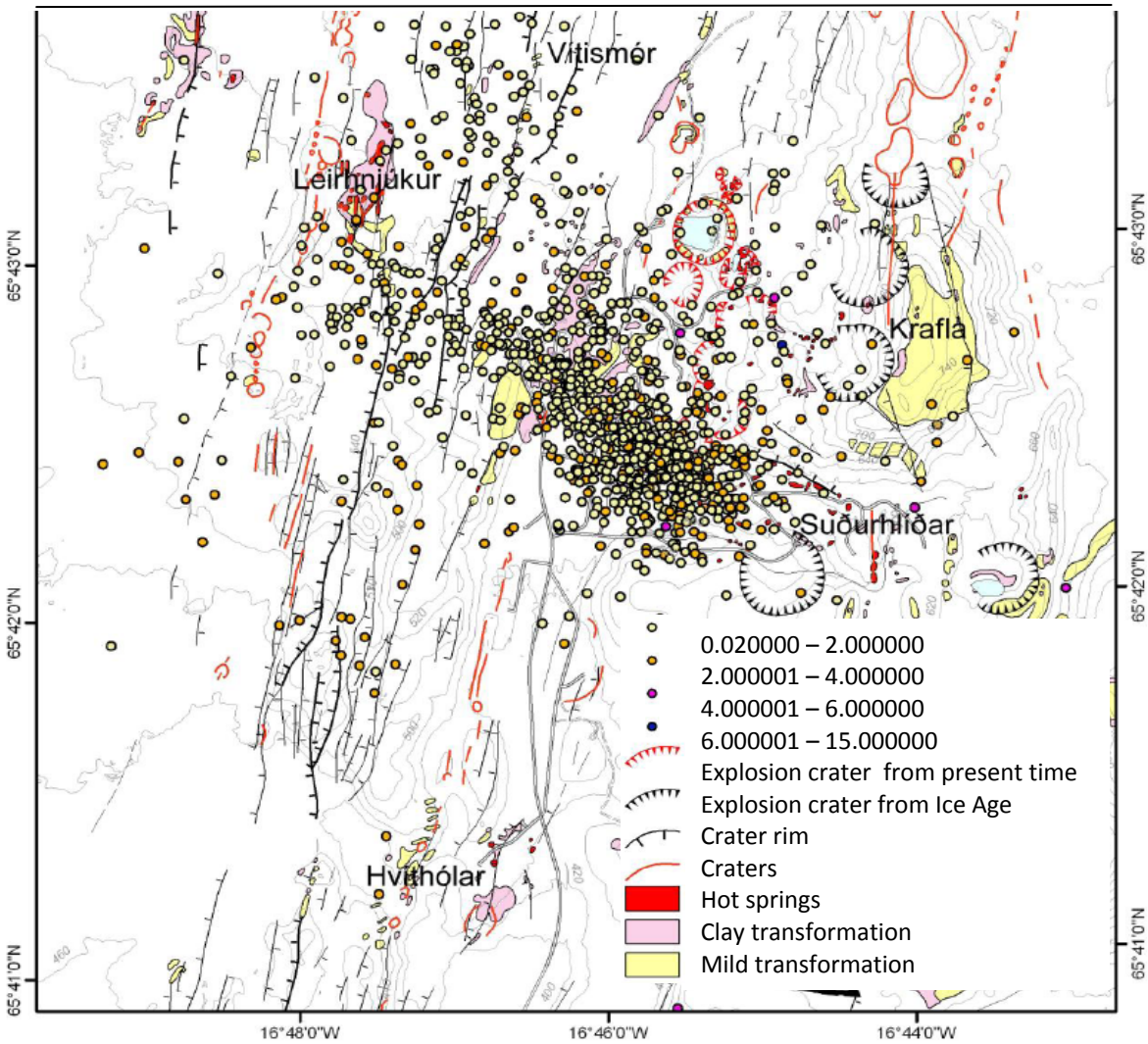

Figure 5-12 Micro seismic activity in Krafla field from 2004-2007 with accurate location (Mortensen, et al., 2010)

From the data available it is concluded that the micro seismic activity in Krafla has no negative effects on the surrounding constructions. It is also concluded that the activity has positive effects on the system by help maintain permeability.

Table 5-9 Micro seismic activity – Results for Krafla field

Grade	Impacts	Description
4	Some positive impacts	The micro seismic events have some positive impacts the geothermal system; enhances permeability to some extent.

5.8 Summary and Discussion

The results for all the indicators are combined in Table 5-10 and plotted graphically in Figure 5-13.

Table 5-10 Krafla geothermal field – Sustainability indicators for geothermal production

	Indicator	Score	Comments
1	Utilization efficiency	3 of 5	Average utilization efficiency.
2	Productive lifetime	4 of 5	Long productive lifetime. Little indication of pressure drawdown or cooling in the reservoir.
3	Reserve capacity ratio	4 of 5	Sustainable use of the system. Less than half of the probable reserve is being utilized.
4	Reclamation time	4 of 5	Little to reclaim. The resource is being utilized in a sustainable manner and there is little indication of a pressure drawdown or temperature decrease.
5	Change in dissolved chemicals	4 of 5	Chemical changes indicate very little cooling in the resource.
6	Ground subsidence	4 of 5	The ground subsidence has insignificant impacts on the surrounding area.
7	Micro seismic activity	4 of 5	The micro seismic events have some positive impacts the geothermal system; enhances permeability to some extent..
	Total Score:	*27 of 35*	*Overall score is 77%*

The Krafla geothermal field scores fairly high in this sustainability evaluation for geothermal production. The field is very powerful and will be providing energy for many years to come. The planned expansion might increase the stress on the system and with this addition the sustainability score might decrease. If the indicators are monitored over the next years, before and after the expansion, they should detect if there system is not being managed in sustainable way.

These results for Krafla should be taken provisionally because this is the first time the indicators are applied and therefore no comparison exists. It is expected that the indicators will develop when more experience has been obtained in using them and more experts give their input.

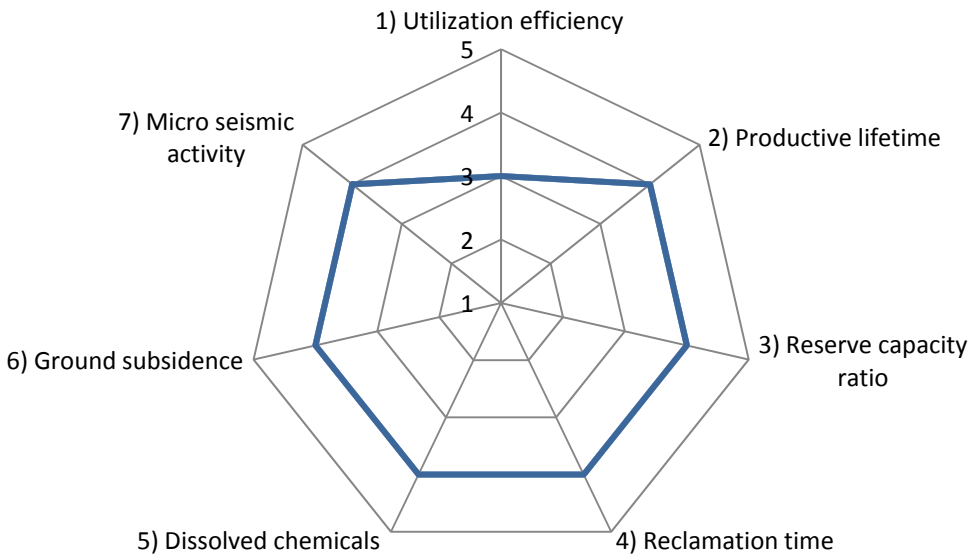

Figure 5-13 Results for the sustainability evaluation for geothermal production at Krafla

This conclusion for the Krafla field also shows where there is room for improvement. The utilization efficiency indicator scores the lowest out of all seven indicators and efficiency is therefore something that could be improved to increase the overall score.

6 Conclusion and Future work

Seven sustainability indicators for geothermal production have been developed by identifying some of the most important parameters in a geothermal resource that are affected during production. The indicators cover the main aspects of a geothermal resource that are affected during geothermal production and efficiency. A methodology to evaluate each indicator was developed and what data is required to compile them. A scoring chart was assigned to each indicator to enable the grading. The effectiveness of the indicators was tested and they were applied to Krafla geothermal field in Iceland. The indicators gave good results for the Krafla field in terms of sustainable production.

The indicators were developed to capture the important aspects in sustainable geothermal production. The indicators measure and monitor the changes in the resource itself and how it is being used. Some of the earlier definitions on sustainable production only take into consideration the level of extraction that can be considered sustainable. Certainly the pressure drawdown is of the main aspects to be concerned over in a geothermal production but other factors have to be taken into account when evaluating the whole production process and assessing the sustainability of the production.

Sustainability indicators as a tool to evaluate sustainability are effective. It is necessary to be able to quantify the sustainability of the production to compare different fields and evaluate future fields and the indicators make that possible. It is recognized that the indicators developed here are just a preliminary version and they will be developed further as the experience in applying them increases.

The future work will involve applying the indicators to other fields for further testing and as the application of the indicators has only been limited to high-temperature field they should be tested for low-temperature fields. They are expected to work for low-temperature fields as well but might require minor modifications or grading adjustments.

The indicators were developed as a part of the GSAP and the next step would be to integrate these seven indicators into the GSAP and test their effectiveness as a part of a complete set.

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Appendix A-1: Exergy Calculations

Reference state:

Reference state		
T_0	5,5	°C
T_0	278,65	K
P_0	1,013	bara
h_0	23,22	kJ/kg
s_0	0,08	kJ/(kg°C)

Results for exergy calculations for Krafla:

Well name	Total flow, m*	Enthalpy, h_1*	Separation pressure, P_1 *	Specific entropy, s_1	Exergy, e	Exergy, e
	kg/s	*KJ/kg*	*bar*	*kJ/kg°C*	*kJ/kg*	*MW*
KG-05	16,7	922	7	2,51	224,02	3,74
KJ-13	13,3	1546	7	3,93	451,13	6,00
KJ-14	4,3	2671	7	6,50	860,58	3,70
KJ-15	7,7	1719	7	4,32	514,09	3,96
KJ-16	2,6	2668	7	6,49	859,49	2,23
KJ-17	12,6	1490	7	3,80	430,75	5,43
KJ-19	2,9	2668	7	6,49	859,49	2,49
KJ-20	4,9	2584	7	6,30	828,92	4,06
KJ-21	56,7	1239	7	3,23	339,39	19,24
KG-24	20,4	928	1,2	2,65	188,64	3,85
KJ-27	30,4	1232	7	3,21	336,85	10,24
KJ-28	50,5	1095	1,2	3,10	232,51	11,74
KJ-30	26,5	2675	7	6,51	862,04	22,84
KJ-31	0,3	2667	7	6,49	859,13	0,26
KJ-32	34,9	1239	7	3,23	339,39	11,84
KJ-33	4,7	2675	7	6,51	862,04	4,05
KJ-34	34,3	2675	7	6,51	862,04	29,57
					Total:	**145,3**

*Production report Krafla and Bjarnarflag 2008 (Hauksson & Benjamínsson, 2009)

Results for all power plants:

Power plant	Net generated [MWe]	Exergy of DH+other [MW]	Exergy extracted, [MW]	Utilization efficiency	Utilization
Nesjavellir	111	35,64	247,9	59,3%	Electricity+DH
Svartsengi	64,7	27,7	201,3	45,9%	Electricity+DH+lagoon
Krafla	55,6	0,00	145,3	38,3%	Electricity
Hellisheidi	129	0,00	340,5	37,9%	Electricity
Reykjanes	98,7	0,00	276,7	35,7%	Electricity
Bjarnarflag	1,81	3,4	28,7	18,3%	Electricity+ DH+lagoon

Utilization efficiency from Dipippo, case studies (DiPippo, 2008):

Power plants	Utilization efficiency	MW_{net}
Larderello (Farinello - Valle Secolo geothermal area)	60%	149,07
The Geyser PE&G plants	52%	53,00
Miravalles	46%	164,00
Cerro Prieto	35%	36,67
Magmamax	15%	11,20

Primary energy efficiency:

Power plant	Net generated [MWe]	Net generated [PJ]	Primary energy use [PJ]	Primary energy efficiency
Nesjavellir	111	3,50	22,46	15,6%
Hellisheidi	129	4,07	29,97	13,6%
Krafla	55,6	1,75	13,95	12,6%
Svartsengi	64,7	2,04	16,69	12,2%
Reykjanes	98,7	3,11	26,12	11,9%
Bjarnarflag	1,81	0,06	2,85	2,0%

Appendix A-2: Reserve Capacity – Calculations

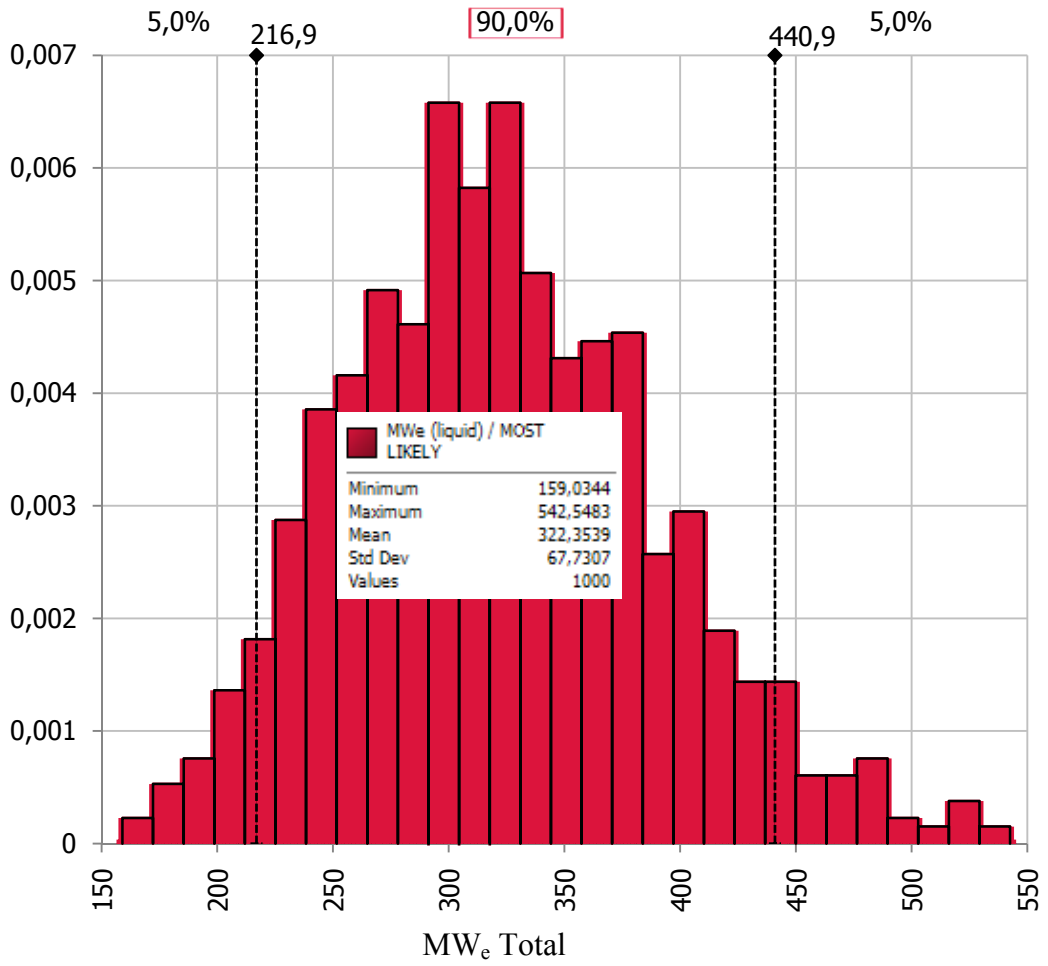
Volumetric method for Krafla:

VOLUMETRIC STORED HEAT RESERVE ESTIMATES

KRAFLA GEOTHERMAL FIELD

INPUT VARIABLES	UNITS	MOST LIKELY	MIN	MAX	PROBABILITY DISTRIBUTION	
LIQUID PHASE VOLUME						
Area, A	km^2	42	29	55	42,0	triang
Thickness, d	m	3000			3000	single value
Rock Density, ρ_r	kg/m^3	3000			3000	single value
Porosity, Φ		0,1	0,005	0,2	0,102	triang
Recovery Factor, R_f		0,15	0,1	0,2	0,150	triang
Rock Specific Heat, C_r	$kj/kjg\ °C$	0,88			0,9	single value
Temperature, T_i	$°C$	250	230	260	247	triang
Fluid Density, ρ_w	kg/m^3	760			760	f(temp)
Conversion Efficiency, C_e		0,12			0,12	f(temp)
Fluid Specific Heat, C_1	$kj/kjg\ °C$	5,2			5,2	f(temp)
Plant Life, t	$years$	50			50	single value
Load Factor, P_f		0,95	0,9	1	0,95	triang
Rejection Temperature, T_e	$°C$	170			170	single value
OUTPUT VARIABLE						
POWER CAPACITY						
	MWe (liquid)	321,9				
	MWe (total)	**321,9**				

Results from Monte Carlo simulations using @Risk:



Proven and probable reserves:

		Probable reserves**		Proven reserves			
	Area*	t=50 years	t=100 years	Installed	Unused***	Total	Planned$^{\Psi}$
Field+	*[km²]*	*[MW50]*	*[MW100]*	*[MW]*	*[MW]*	*[MW]*	*[MW]*
Reykjanes	9	45	22,5	100	0	100	0
Svartsengi - Eldvörp	30	150	75	75	5	80	0
Hengill	142	710	355	333	67	400	315
Krafla- Námafjall	62	310	155	60	65	125	240
Theistareykir	48	240	120	0	50	50	200

+Data from (Ketilsson, Björnsson, Halldórsdóttir, & Axelsson, 2009)
* Area of high resistivity core
**Using 5 MW/km^2
***Available team that is not in use
$^{\Psi}$Planned power plants that have gone through or are in the EIA process

Reserve capacity ratio:

	Proven reserve		
Field	*Installed*	*Unused*	*Reserve capacity ratio*
Reykjanes (45 MW)*	2,22	0,00	-1,22
Svartsengi - Eldvörp (150 MWe)	0,50	0,03	0,47
Hengill (710 MWe)	0,47	0,09	0,44
Krafla- Námafjall (310 MWe)	0,19	0,21	0,60
Theistareykir (240 MWe)	0,00	0,21	0,79

*The Reykjanes field has higher installed capacity than the calculated probable reserve and therefore the reserve capacity ratio is negative.

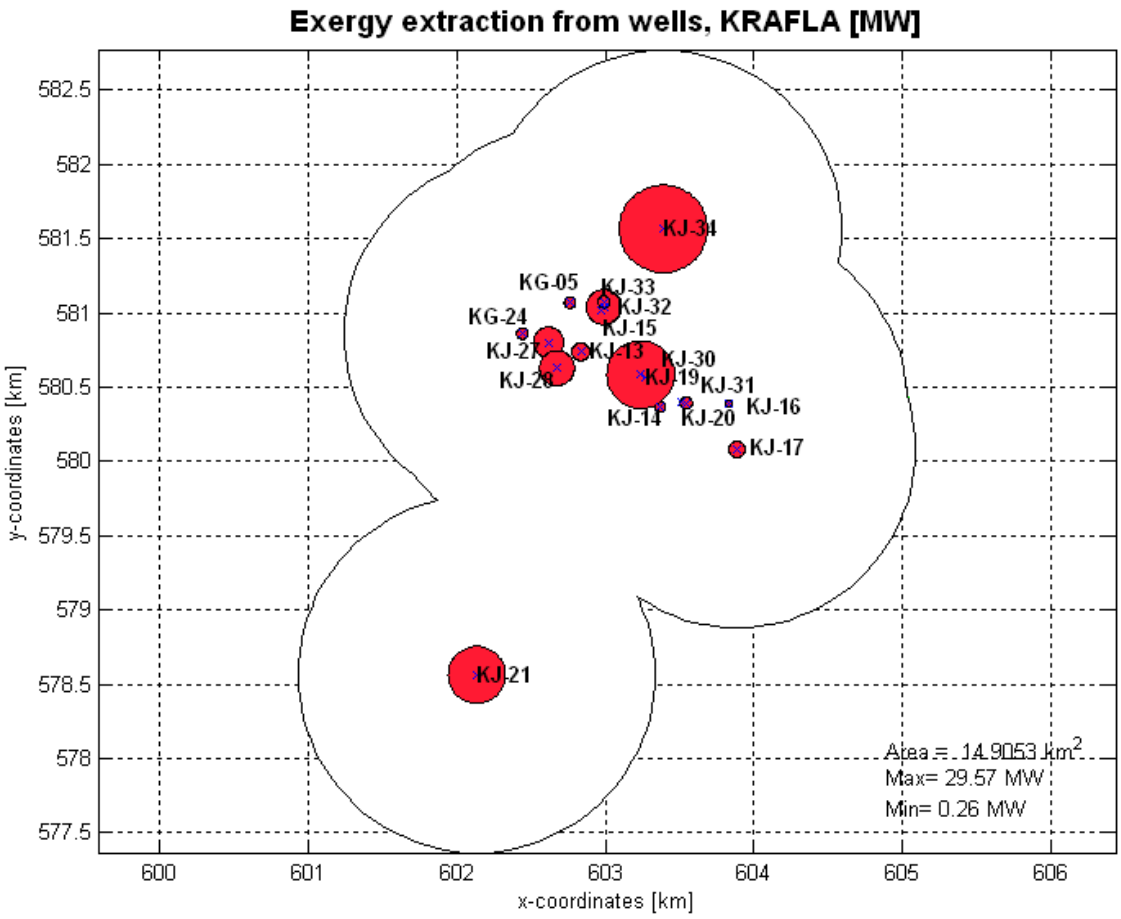
Appendix A-3: Summary of Indicators

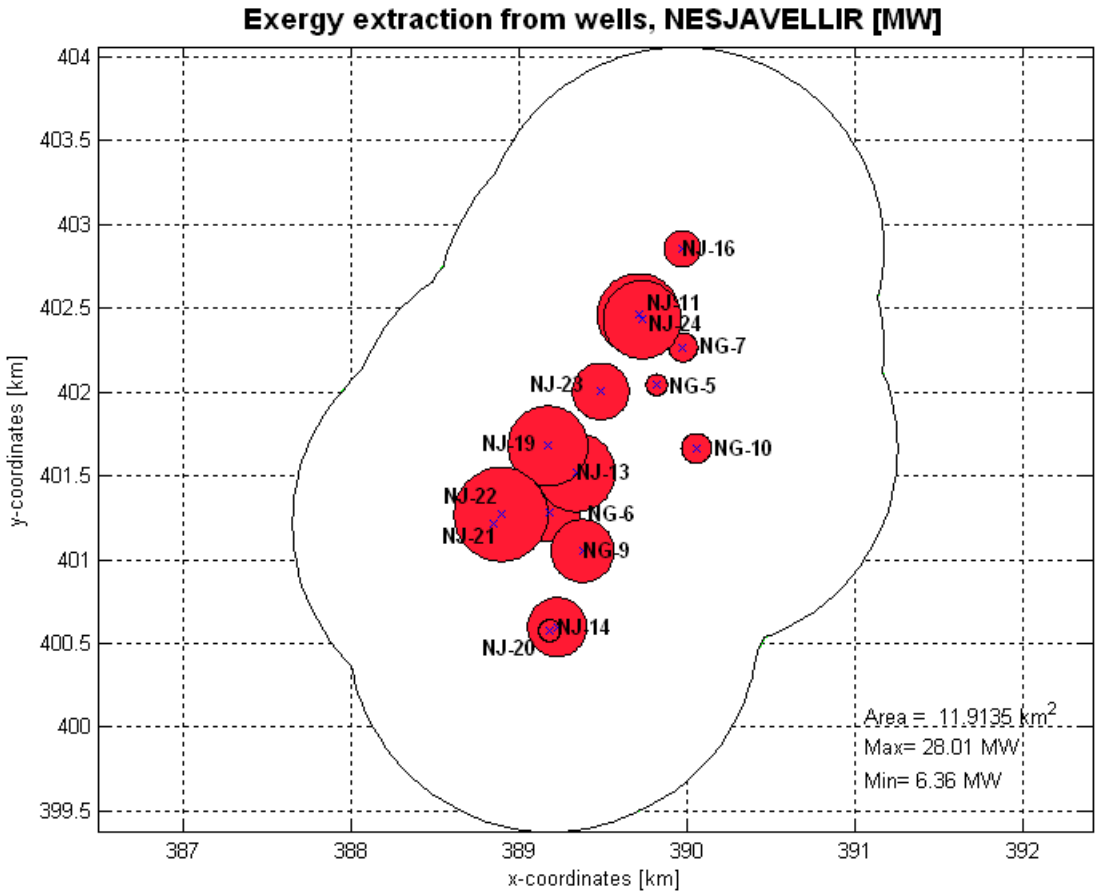
Summary of indicators:

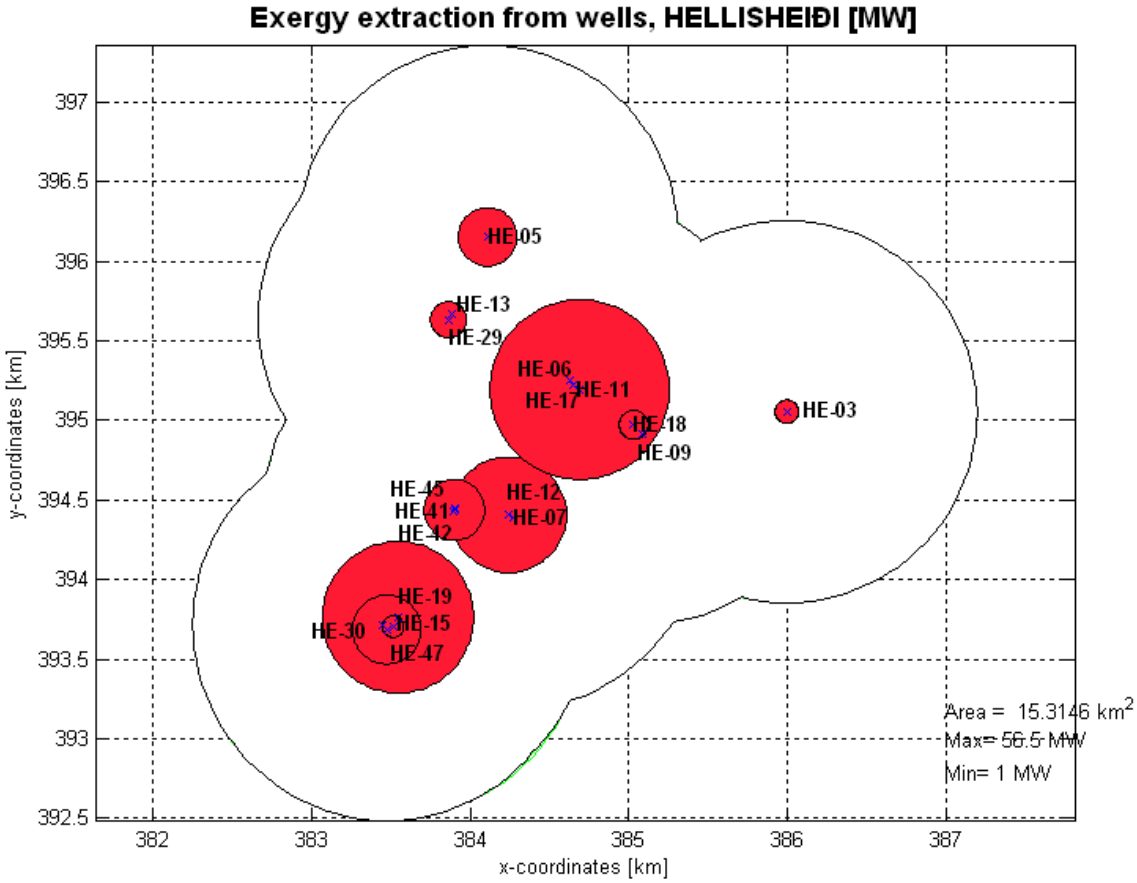
Indicator Name Description of Data	*1. Utilization efficiency, η_B* Production reports from owner	*2. Productive lifetime* Production reports and models from owner	*3. Reserve Capacity ratio* Production reports and data from owner	*4. Reclamation time* Production reports and models from owner	*5. Dissolved chemicals* Production reports from owner	*6. Ground subsidence* Measurement report from owner	*7. Micro seismic activity* Measurement report from owner
1. Responsiveness	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Relevance	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Available data that is updated regularly	Yes	Yes & No	Yes	Yes & No	Yes	Yes	Yes
4. Clear and unambiguous	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. International comparison and standards	Yes & No	Yes & No	Yes & No	Yes & No	Yes & No	Yes & No	Yes & No
6. Threshold or reference value	Yes	No	Yes	Yes	Yes	Yes	Yes
7. Theoretically well founded	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Resolution	Use	Use	Use	Use	Use	Use	Use
Benchmark	Comparison of power plants– Mean value and standard deviation	100 years is sustainable	Reserve capacity ratio should be higher than 0,5	Not longer than the productive lifetime	Chemical changes should not indicate much cooling	Subsidence should not have negative impacts on the surroundings	Micro seismic activity should not have negative impacts on the surroundings
Scoring (from 1 5)	1 $\eta_B < -2\sigma$ 2 $-2\sigma \leq \eta_B < -\sigma$ 3 $-\sigma \leq \eta_B$ <average 4 average $\leq \eta_B < +\sigma$ 5 $+\sigma \leq \eta_B$	1 Under 25 years 2 25-49 years 3 50-74 years 4 75-99 years 5 100 years and over	1 Below 0 2 0-0.24 3 0.25-0.49 4 0.50-0.74 5 0.75-1.0	1 Not possible to reclaim 2 Longer than productive lifetime 3 Close to productive lifetime 4 Shorter than productive lifetime 5 No reclamation time needed	1 Major negative impacts 2 Moderate negative impacts 3 Minor negative impacts 4 Insignificant impacts 5 Positive impacts	1 Major negative impacts 2 Moderate negative impacts 3 Minor negative impacts 4 Insignificant impacts 5 Some positive impacts	1 Negative impacts 2 Some negative impacts 3 Neutral impacts 4 Some positive impacts 5 Positive impacts
Data Collected	Mass flow, pressure and enthalpy from wells	Changes in physical conditions in the reservoir	Installed power and reserve data	Changes in physical conditions in the reservoir	Dissolved Cl and SiO_2 in discharge from wells	Ground subsidence measurements	Maps of micro seismic activity

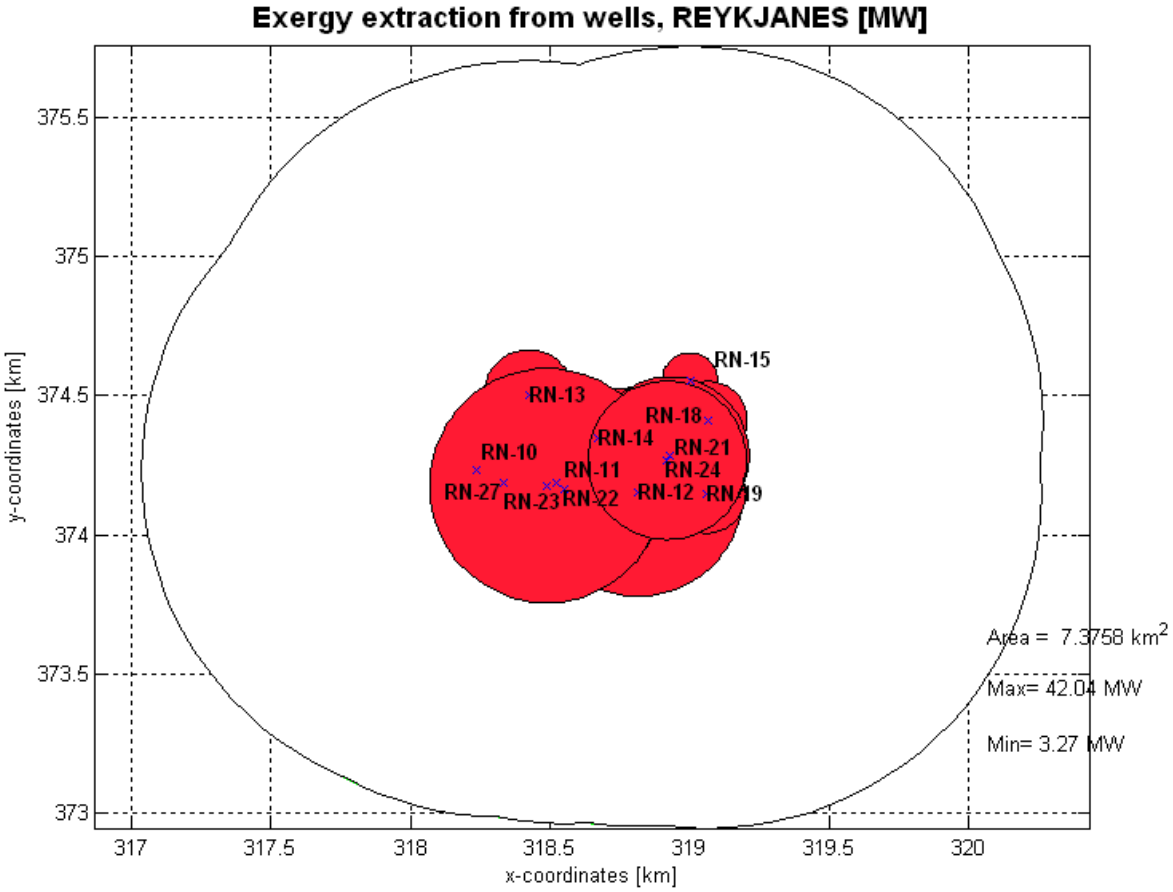
Appendix A-4: Area of Geothermal Fields

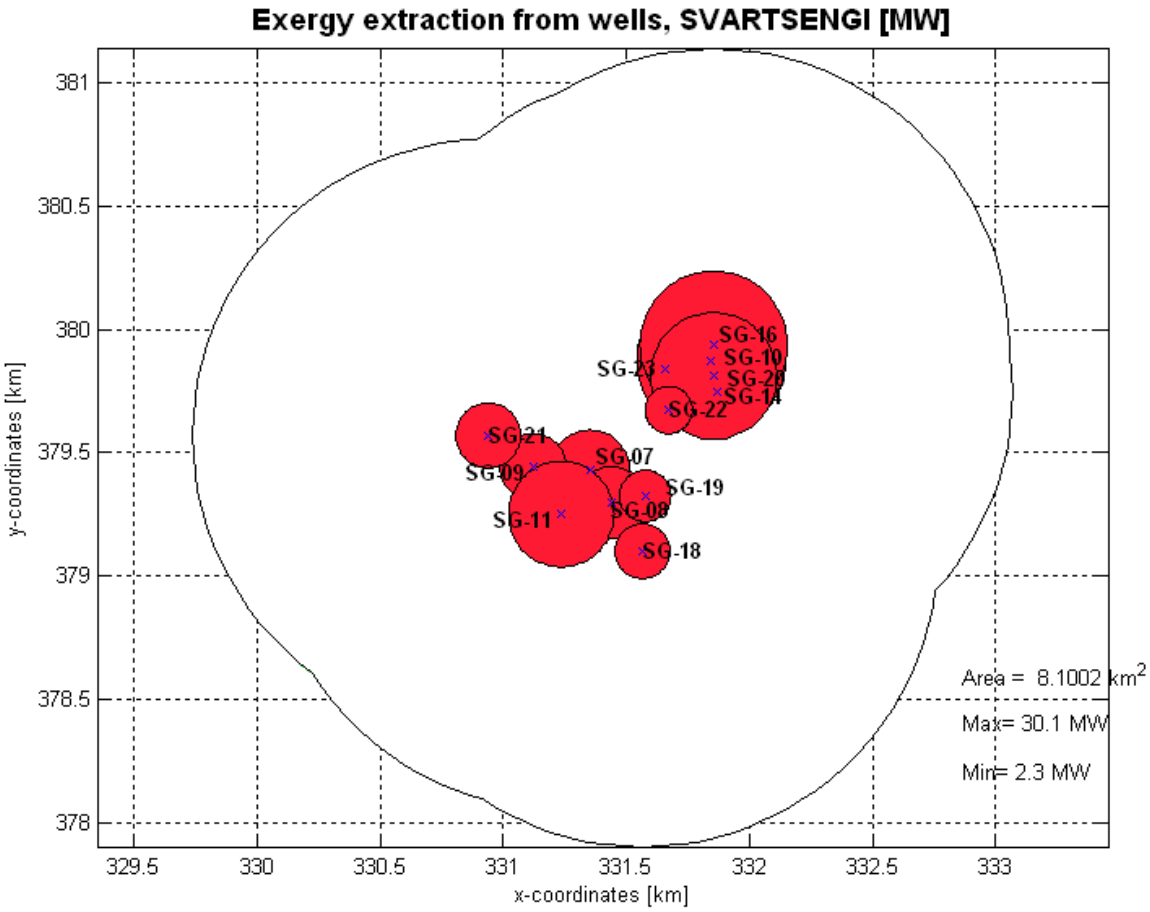
Area of geothermal fields in Iceland using 1200 m circles around production wells. Red dots represent exergy extracted from each well.




Exergy extraction from wells, NESJAVELLIR [MW]
y-coordinates [km]
x-coordinates [km]
NJ-16
NJ-11
NJ-24
NG-7
NJ-23
NG-5
NJ-19
NG-10
NJ-13
NJ-22
NG-6
NJ-21
NG-9
NJ-14
NJ-20
Area = 11.9135 km2
Max= 28.01 MW
Min= 6.36 MW


Exergy extraction from wells, HELLISHEIÐI [MW]
y-coordinates [km]
x-coordinates [km]
HE-05
HE-13
HE-29
HE-06
HE-11
HE-17
HE-18
HE-09
HE-03
HE-45
HE-41
HE-42
HE-12
HE-07
HE-19
HE-30
HE-15
HE-47
Area = 15.3146 km2
Max= 56.5 MW
Min= 1 MW


Exergy extraction from wells, REYKJANES [MW]
375.5
375
374.5
374
373.5
373
317
317.5
318
318.5
319
319.5
320
x-coordinates [km]
y-coordinates [km]
RN-15
RN-13
RN-18
RN-14
RN-21
RN-10
RN-11
RN-24
RN-27
RN-23
RN-22
RN-12
RN-19
Area = 7.3758 km2
Max= 42.04 MW
Min= 3.27 MW


Exergy extraction from wells, SVARTSENGI [MW]
381
380.5
380
379.5
379
378.5
378
329.5
330
330.5
331
331.5
332
332.5
333
x-coordinates [km]
y-coordinates [km]
SG-16
SG-10
SG-23
SG-20
SG-14
SG-22
SG-21
SG-07
SG-09
SG-19
SG-08
SG-11
SG-18
Area = 8.1002 km2
Max= 30.1 MW
Min= 2.3 MW