ÍSLENSKAR ORKURANNSÓKNIR
ICELAND GEOSURVEY

Medium Enthalpy Geothermal Systems in Iceland

Thermal and Electric Potential

Björn Már Sveinbjörnsson

Prepared for Orkustofnun
(National Energy Authority of Iceland, NEA)

ÍSOR-2016/008

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Abstract

Geothermal systems with formation temperatures between 100 and 200°C in the uppermost 2,000 meters are classified as medium enthalpy geothermal resources. The report describes 37 medium enthalpy geothermal systems in Iceland and 81 well fields within these systems. The dataset on which the report is based has been collected from the national well registry of boreholes and available reports. To the extent verifiable data are available, the assembled dataset is presented in an Excel document accompanying the report on CD.

There were 655 exploratory and production wells drilled in the medium enthalpy systems in the years 1928-2014.

The production wells were 289, ranging from 10-3,085 m in drilled depth, average 650 m. About 60% of them were productive after drilling, and 62% of those are still in use. Data on yield are available from 132 productive wells and 54 not productive wells. The average yield for these 186 wells is 12.1 l/s.

Of the total, 193 wells, that found temperature above 90°C, were subjected to further analysis from the viewpoint of medium enthalpy utilization. They range between 52-3,085 m in depth, average 861 m. In this group 77% were productive after drilling, 70% of those are still in use. The average yield of 132 productive and the 44 not productive wells is 13 l/s. About 89% of the main feeders are in the uppermost 1,000 meters, with a broad range in flow values, within 62 l/s except for 2 wells; of 100 l/s and 110 l/s. Feeders below 1,000 meters give a more limited flow, generally within 20 l/s. At those depths only 3 wells have a flow above 18 l/s.

Wells with a discharge temperature above 80°C are considered successful for space heating. Successful wells are 132 out of 193 or 68%. Wells with a discharge temperature above 95°C are considered successful for electric production. Successful wells are 109 out of 193 or 56.5%.

The analysis indicates that the 37 medium enthalpy systems have an aggregate thermal potential above 35°C of 935 MW_{th} or an electric potential of 44 MW_e, using an organic Rankine cycle, yielding aggregate 494 MW_{th} of remaining thermal potential of 80°C effluent water for cascade direct use. The ten largest systems have a range of 37 to 132 MW_{th} and 1.0 to 7.4 MW_e.

As an addendum the Ölfusdalur system is evaluated. This system in intermediate between a medium enthalpy and a high enthalpy system. It has a thermal potential of 334 MW_{th} and an electric potential of 25.4 MW_e.

Key words	ISBN-number
Medium enthalpy geothermal resources, cascade utilization, binary cycles, thermal potential, electric potential, yield of wells	
	Project manager's signature Steinunn Hauksdóttir
	Reviewed by Benedikt Steingrímsson

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1 Introduction

Geothermal areas in Iceland have been classified as high temperature areas when temperatures above about 200°C are found in the uppermost 1,000 m, but as low temperature areas where temperatures are less than about 150°C in the uppermost 1,000 m. (Böðvarsson, 1961; Friðleifsson, 1979; Arnórsson, 1995). Geothermal areas with reservoir temperatures between 100 and 200°C have been referred to as boiling low temperature areas (e.g. Arnórsson and Þórhallsson, 2001). In this report we prefer a classification similar to that used by Rubio-Maya et al (2015), (see also Sæmundsson et al., 2013a; Stober and Bucher, 2013; Chandrasekharam and Bundschuh, 2008; Bendritter and Cormy, 1990). They distinguish between high, medium and low enthalpy resources. In a high enthalpy resource the geothermal fluid is under high pressure and temperature. High enthalpy resources have been widely used to generate electricity in flash steam turbines, preferably at temperatures above 200°C. We take 200°C as the lower limit of high enthalpy resources. In low enthalpy resources the temperature of the geothermal fluid is below 100°C. They are valuable for direct use of the heat but not feasible for generation of electricity. When the geothermal fluid is at temperatures between 100°C and 200°C, we define it as a medium enthalpy resource, see Fig. 1.

≤374.15°C		≤2,107 kJ/kg
	High enthalpy resource	
>200°C		>852 kJ/kg
≤200°C		≤852 kJ/kg
	Medium enthalpy resource	
>100°C		>419 kJ/kg
≤100°C		≤419 kJ/kg
	Low enthalpy resource	
0°C		0 kJ/kg

Figure 1. *Classification of geothermal resources by enthalpy and temperature used in this report.*

Low enthalpy resources have been utilized in Iceland for nearly 100 years, mainly for space heating but also for cultivation of plants and vegetables in greenhouses, balneology, industrial processing, aquaculture and snow melting (Björnsson, 2009).

High enthalpy resources have been developed in seven fields in Iceland for generation of electricity and in three of those for cogeneration of hot water and steam for space heating and industrial uses. A report on the success of high temperature geothermal wells in Iceland was published in 2014 (Sveinbjörnsson, 2014).

Medium enthalpy resources are abundant in Iceland but their development has lagged behind. They are too large and technically difficult for the individual user and less feasible to generate electricity than high enthalpy resources which provide steam for the commonly used Rankine thermodynamic cycle. Medium enthalpy resources could, however, be used to generate electricity by using a Rankine cycle with working fluids that boil at lower temperatures than water as in the Organic Rankine Cycle (ORC) and Kalina Cycle (KC) (Schuster et al., 2009). A recent research indicates that for moderate temperatures of geothermal resources, ORCs integrated in hybrid renewable energy power systems are the most effective approach to reduce electricity generation cost, improve plant efficiency and extend the lifespan of reservoir (Zheng et al., 2015).

Orkustofnun, the National Energy Authority of Iceland (NEA) maintains a well registry covering all drilled wells in Iceland. In order to evaluate the potential of medium enthalpy resources in Iceland for cascade utilization, data have been collected on medium enthalpy wells from the national well registry of boreholes grouped after geothermal systems. In addition to the standard documentation in the well registry, data on success and capacity of wells were collected from available reports. This report presents data on 289 medium enthalpy production wells in about 37 geothermal systems in Iceland. Of these wells, 193 found formation temperatures above 90°C. These systems have a thermal potential ranging up to 132 MW_{th} and an electric potential up to 7.4 MW_e.

In an Addendum to this report we have included for the sake of completeness an account of the Ölfusdalur system which is intermediate between a high enthalpy and a medium enthalpy system. It was not included in the report on success of high temperature geothermal wells in Iceland (Sveinbjörnsson, 2014) and is not classified as one of the medium enthalpy systems in this report. Wells in this system have maximum temperatures of 185-232°C, a thermal potential above 35°C of 334 MW_{th} or an electric potential of 25 MW_e and a remaining thermal potential of 85.6 MW_{th}.

This report is a partial contribution from Iceland to the International Energy Agency-Geothermal Implementing Agreement (IEA-GIA), Annexes VII and XI and the Lower Cost Drilling Annex of the International Partnership for Geothermal Technology (IPGT).

1.1 Potential for exploitation

1.1.1 Thermal potential

A mass flow of Q (kg/s) from a geothermal source at a temperature t with an enthalpy h_t (kJ/kg) carries a thermal power of $P = Q * h_t$. Direct use of this thermal power depends on the possibilities for cascade utilization down to environmental temperatures. For the mean annual temperature in Iceland of 5°C the ultimate thermal potential would be $P_5 = Q * (h_t – h_5)$. For district heating services a final temperature of 35°C is common and for generation of electricity with steam or organic Rankine cycles a final temperature of 80°C is considered feasible. In Chapter 4 the thermal potential above 35°C of wells, fields or systems is calculated using the formula $P_{35} = Q * (h_t - h_{35})$. The enthalpy values are based on the steam table "Properties of water and steam in SI units" edited by Grigull (1979).

1.1.2 Generation of electricity

Generation of electricity from medium enthalpy geothermal resources is generally based on the Rankine thermodynamic cycle. The cycle begins with a working fluid in a low pressure liquid state. The working fluid passes through a pump which elevates the pressure and sends the fluid to a vaporizer (higher temperature heat source) where it is converted from a liquid into a high pressure vapor. The high pressure vapor is then expanded across a power-producing turbine before being converted back into a low pressure liquid in a condenser (low temperature heat sink). The steam Rankine cycle uses water as a working fluid. It is well developed and utilized worldwide. An Organic Rankine Cycle (ORC) uses a carbon based working fluid. Although steam cycles are the most widely used by a large margin, Organic Rankine Cycles are attractive for medium enthalpy resources because hydrocarbon or other carbon based working fluids can be vaporized at lower temperatures. However, working fluid cost, decomposition, and temperature limits are an Organic Rankine Cycle's primary disadvantages.

The Kalina Cycle (KC) uses a solution of two fluids with different boiling points for its working fluid. Since the solution boils over a range of temperatures as in distillation, more of the heat can be extracted from the source than with a pure working fluid. The same applies on the exhaust (condensing) end. By appropriate choice of the ratio between the components of the solution, the boiling point of the working solution can be adjusted to suit the heat input temperature. Water and ammonia is the most widely used combination, but other combinations are also feasible.

The ORC and KC cycles generally achieve an efficiency of 10-12% in converting the thermal energy into electric energy. Fig. 2 illustrates the mass flow required from a medium enthalpy resource to produce 1 MW_e assuming a thermal efficiency of 11% and cooling of the effluent water down to 80°C. This graph is used to find the electric potential of wells, fields or systems listed in Chapter 4.

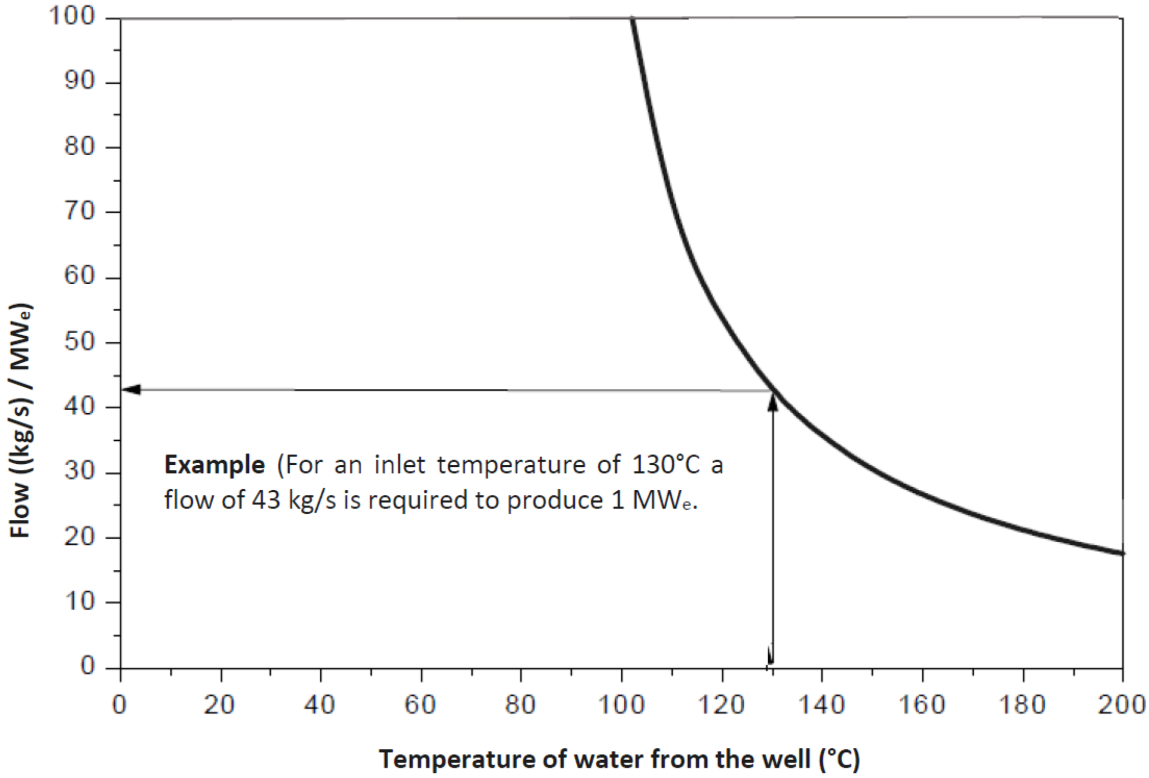

Figure 2. *Generation of electricity with medium enthalpy geothermal water. The curve indicates the flow in kg/s required at the respective initial temperature to produce 1 MW_e assuming a thermal efficiency of 11% in an Organic Rankine Cycle, cooling the water to 80°C. (Adapted from Arnórsson and Þórhallsson, 2001).*

1.1.3 Other geothermal utilization

The Líndal Diagram gives an overall view of geothermal utilization depending on the resource temperature, see Fig. 3.

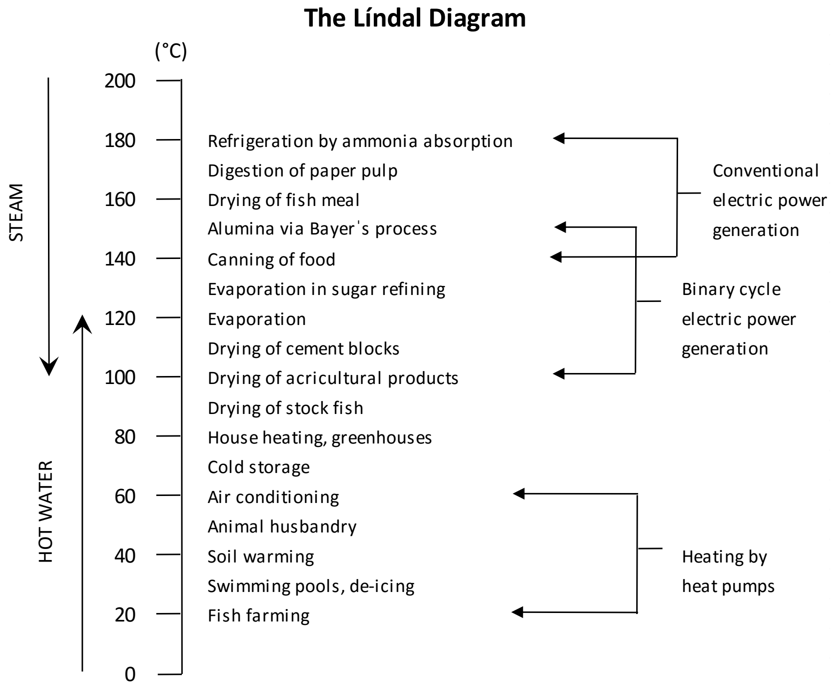

Figure 3. *Líndal Diagram over different utilization of geothermal resources. (Redrawn from Guðmundsson, et al., 1985.)*

Recently Rubio-Maya et al. (2015) presented a comprehensive review of cascade utilization of low and medium enthalpy geothermal resources, see Fig. 4. Utilization in cascade levels is identified as a mean of sequential operation of geothermal heat by integrating different technologies for electricity generation, distribution and use of thermal energy, drying and dehydration processes, recreational uses, and any other direct-use of geothermal heat.

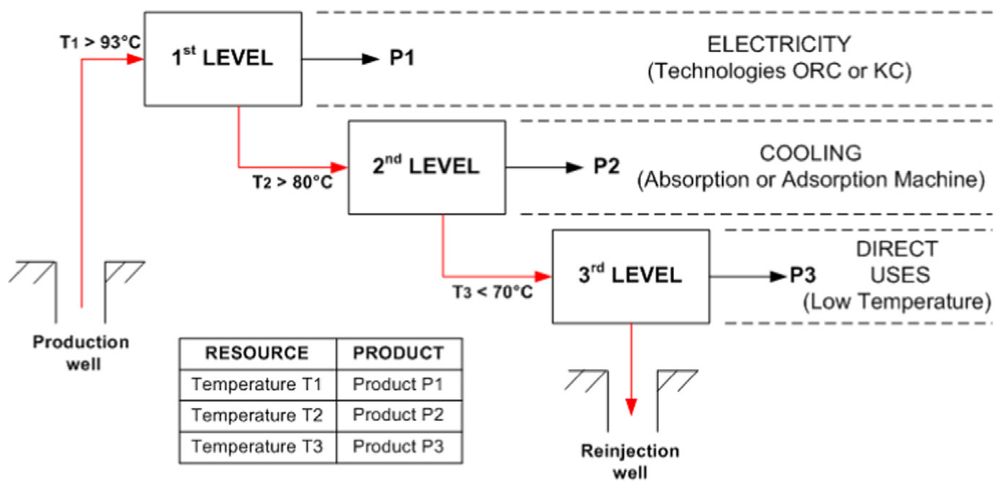

Figure 4. *Conceptual diagram of the cascade utilization of geothermal energy. (Rubio-Maya et al., 2015.)*

2 Definitions and Overview over the Dataset

The dataset on which this report is based covers 289 production wells, out of which 193 wells found formation temperature over 90°C according to recorded maximum temperatures in wells or indications from silica geothermometers. For the estimates of the potential of medium enthalpy systems, major boiling springs in 6 systems are also included. The dataset describes 37 medium enthalpy systems in Iceland and 81 well fields within these systems. To the extent verifiable data are available, the assembled dataset is presented in an Excel document accompanying the report on CD. Description of the columns is as follows:

2.1 Location of well

Column A: District
Defined name of the district in Iceland where wells are located. Districts can include several geothermal systems.

Column B: System
Defined name of the system where wells are located. A geothermal system may consist of several well fields.

Column C: Well field
Defined name of the well field where wells are located.

Column D: Well
Recorded the name of the well.

Column E: Code number
Code number of the well.

Column F: Commune
Name of the commune in which the well is located.

Column G: Older shire
Name of the older shire in which the well is located.

2.2 Well status

Column I: Purpose of drilling the well
Purpose with which the well was drilled.

Column J: Productive
Whether the well was productive or not after drilling.

Column K: In use
Whether the well is in use or not

Column L: Reason for not in use
Reason for that the well is not in use.

Column M: Successful – For heating (T≥80°C)
Whether the well was successful for heating (T≥80°C) or not.

Column N: Successful – For electric generation (T≥95°C)
Whether the well was successful for electric generation (T≥95°C) or not.

2.3 Description of well

Column O: Drilling completed
Date when the drilling or deepening of the well was completed.

Column P: Measured depth of well
Drilled length of the well in meters (MD), not the true vertical depth, if the well is directionally drilled.

Column Q: Elevation of wellhead
Height of the wellhead (well flange) in meters above sea level.

Column R: Inclination
Whether the well was drilled directionally or vertical (d/v).

Column S: Bit
Diameter of the drill bit in the production section of the well, in inches.

Column T: Production casing diameter
Outer diameter of the production casing in the well, in inches.

Column U: Production casing depth
Length of the production casing in the well, in meters.

2.4 Reservoir characteristics

Column V: Maximum temperature
Maximum measured temperature in the well in Celsius degrees.

Column W: Depth of maximum temperature
Depth (along the well length) of the maximum measured temperature in the well, in meters.

Column X: Date of maximum temperature
Date of the maximum measured temperature in the well.

Column Y: Depth of feeder 1
Drilled depth of the main feeder in the well, in meters.

Column Z: Temperature of feeder 1
Temperature of the main feeder in the well, in Celsius degrees.

Column AA: Depth of feeder 2
Drilled depth of the second largest feeder in the well, in meters.

Column AB: Temperature of feeder 2
Temperature of the second largest feeder in the well, in Celsius degrees.

Column AC: Depth of feeder 3
Drilled depth of the third largest feeder in the well, in meters.

Column AD: Temperature of feeder 3
Temperature of the third largest feeder in the well, in Celsius degrees.

2.5 Production characteristics

Column AF: Date of P_o or watertable depth
Date when the wellhead pressure of the shut-in well or depth of watertable in the well was measured.

Column AG: P_o shut in
Wellhead pressure of the well closed in bar-g.

Column AH: Depth of watertable
Measured depth of the watertable in the well, in meters.

Column AI: Date of production test
Date at which the values for the wellhead pressure P_o, discharge enthalpy (H_o), and total flow (Q_{tot}) were obtained.

Column AJ: WHP flowing (P_o Q_{tot})
Wellhead pressure of the total flow from the well in bar-g.

Column AK: Free-flowing (Q_w)
Amount of free-flow from the well in kg/s.

Column AL: Pumped (Q_w)
Amount of pumped flow from the well in kg/s.

Column AM: Wellhead/flange temperature
Temperature of flow at the wellhead, in Celsius degrees.

Column AN: Date of wellhead temperature
Date when the flow at the wellhead temperature was measured.

2.6 Power potential of systems

Column AO: System proven – Thermal (MW_{th})
Proven thermal power above 35°C of the system in megawatts.

Column AP: System proven – Electric (MW_e)
Proven electric power in megawatts of the system, assuming 80°C effluent water for direct use.

Column AQ: System possible – Thermal (MW_{th})
Possible thermal power above 35°C of the system in megawatts.

Column AR: System possible – Electric (MW_e)
Possible electric power in megawatts of the system, assuming 80°C effluent water for direct use.

Column AS: Remaining thermal – Proven (MW_{th})
Proven remaining thermal power of effluent water from 80 to 35°C after electric production in a binary cycle.

Column AT: Remaining thermal – Possible (MW_{th})
Possible remaining thermal power of effluent water from 80 to 35°C after electric generation in a binary cycle.

3 Overview of the Districts, Systems and Well fields

3.1 Location of the geothermal systems in Iceland

Fig. 5 shows where the 37 geothermal systems studied in the report are located in Iceland and the age of the bedrock.

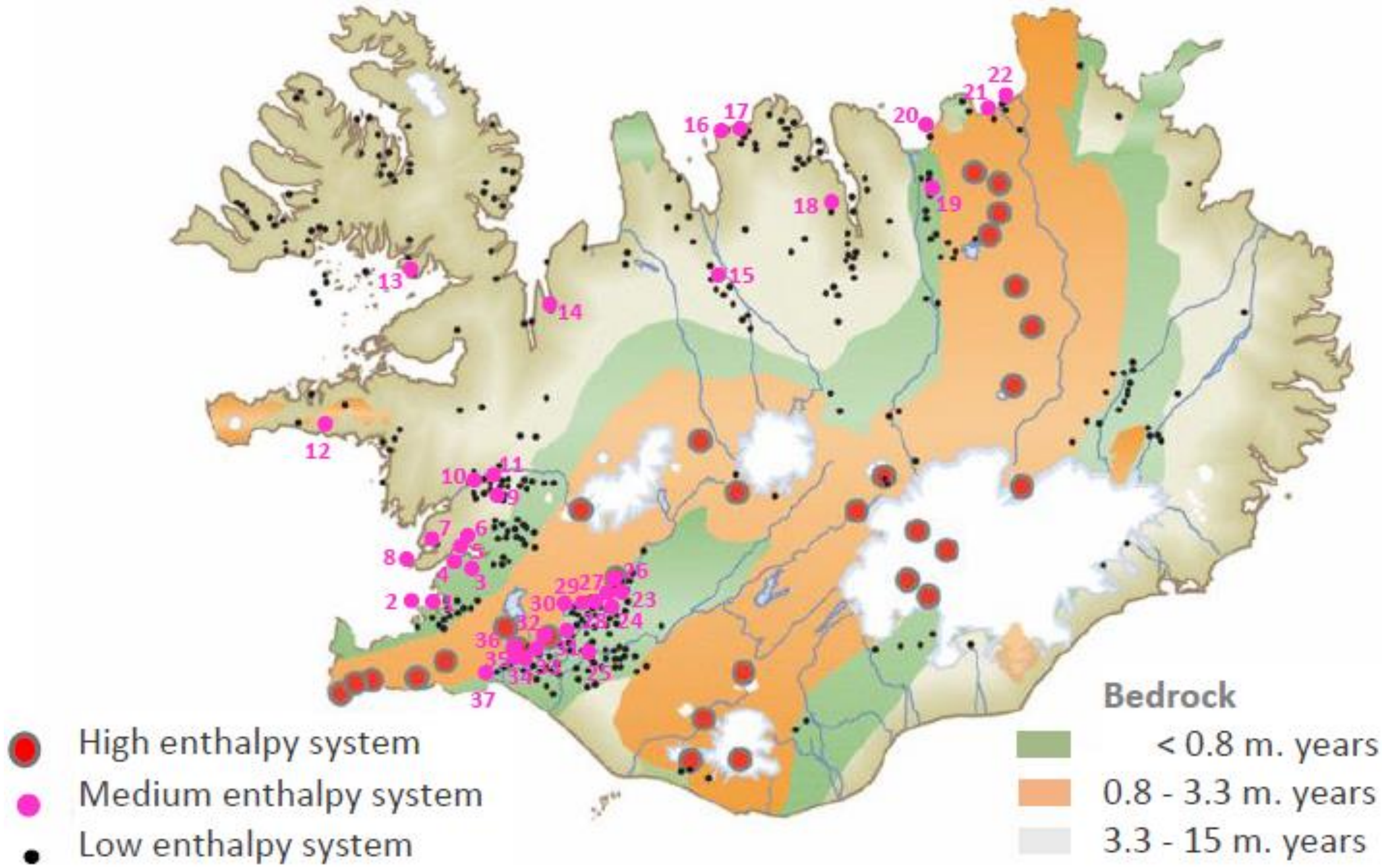

Figure 5. *The location of the 37 geothermal systems studied and age of Icelandic bedrock. (Adapted from Iceland GeoSurvey, 2015.)*

3.2 Districts, systems and well fields

Districts of the country may have several medium enthalpy geothermal systems which can include several fields were the wells are drilled. Table 1 lists the names of the 37 medium enthalpy geothermal systems marked in Fig. 5 numbered clockwise, starting from the capital, Reykjavík. The table reports all 655 drilled exploratory and production wells listed in the national well registry in 81 well fields. Of these wells we count 289 as production wells. Eighteen of them were originally registered as exploratory wells but turned out as production wells. Of the 289 production wells 173 are known to have been productive after drilling, 54 were not productive and no information about productivity is available for 62 wells.

Table 1. *Names of districts, medium enthalpy systems and fields. Number of drilled exploration and production wells and wells that were productive after drilling. Numbers in parenthesis indicate how many of the production wells were planned as exploratory wells but turned out as production wells.*

District	System	System / *Well field*	Wells			
(name)	(no.)	(name)	Drilled exploration and production wells	Production wells	Unknown result	Productive wells
Reykjavík	**1**	**Laugarnes**	**47**	**36 (1)**		**35 (1)**
	-	*Laugarnes*	33	23		*23*
	-	*Lækjarhvammur*	5	5		*5*
	-	*Rauðarárholt*	4	4 (1)		*4(1)*
	-	*Hátún*	5	4		*3*
Seltjarnarnes	**2**	**Seltjarnarnes**	**14**	**7**		**7**
	-	*Bakki*	*3*	*1*		*1*
	-	*Nes*	*3*	*1*		*1*
	-	*Nýibær*	*1*	*1*		*1*
	-	*Bygggarður*	*4*	*3*		*3*
	-	*Ráðagerði*	*3*	*1*		*1*
Hvalfjörður	**3**	**Fremri-Háls**	**6**	**2**		**1**
	4	**Möðruvellir**	**21**	**2**		**2**
	5	**Hvammsvík**	**10**	**1**		**1**
	6	**Miðsandur**	**9**	**2 (1)**		**1**
Akranes and Leirársveit	**7**	**Leirá-Geldingaá**	**12**	**5**		**2**
	-	*Leirá*	*4*	*4*		*2*
	-	*Geldingaá*	*8*	*1*		*0*
	8	**Stillholt**	**2**	**1 (1)**		**0**
Borgarfjörður	**9**	**Brautartunga-England**	**18**	**3**		**3**
	-	*Stóra-Drageyri*	*6*	*1*		*1*
	-	*Hvammur*	*7*	*1*		*1*
	-	*Snartarstaðir*	*5*	*1*		*1*
	10	**Bær-Varmaland**	**16**	**15**		**6**
	-	*Hellur*	*4*	*3*		*0*
	-	*Bær*	*4*	*4*		*1*
	-	*Laugarholt*	*1*	*1*		*1*
	-	*Varmaland/Laugaland*	*7*	*7*		*4*
	11	**Reykholt**	**4**	**3**	**1**	**1**
Snæfellsnes	**12**	**Eiðhús-Dalur**	**26**	**7 (3)**		**3 (1)**
	-	*Eiðhús*	*23*	*6 (3)*		*2 (1)*
	-	*Dalur*	*3*	*1*		*1*
Barðaströnd	**13**	**Reykhólar**	**8**	**8**	**1**	**7**
Miðfjörður,	**14**	**Ytri-Reykir, Laugarbakki**	**3**	**3**		**3**
Skagafjörður	**15**	**Reykjarhóll Varmahlíð**	**12**	**3**		**2**
	16	**Reykjarhóll on Bakkar,**	**5**	**5**	**4**	**1**
	17	**Langhús in Fljót**	**2**	**2**		**2**
Eyjafjörður	**18**	**Laugaland, Þelamörk**	**17**	**6**		**5**
Norðurþing	**19**	**Hveravellir, Reykjahverfi**	**18**	**6 (1)**		**3**
	20	**Húsavík**	**8**	**2 (1)**	**1**	**1 (1)**
	21	**Ytribakki in Öxarfjörður**	**3**	**3 (1)**		**2**
	22	**Ærlækjarsel in Öxarfjörður**	**4**	**3 (1)**		**2**

Table 1. *(Cont.)*

District	System	System / *Well field*	Wells			
(name)	(no.)	(name)	Drilled exploration and production wells	Production wells	Unknown result	Productive wells
Hrunamanna-hreppur	**23**	**Reykjaból**	**9**	**9 (1)**		**4**
	-	*Reykjaból*	*1*	*1*		*1*
	-	*Þórarinsstaðir*	*1*	*1*		*1*
	-	*Reykjadalur*	*1*	*1*		*1*
	-	*Kópsvatn*	*2*	*2*		*1*
	-	*Kotlaugar*	*2*	*2*		*0*
	-	*Jata*	*1*	*1*		*0*
	-	*Haukholt*	*1*	*1 (1)*		*0*
	24	**Flúðir**	**12**	**11**	**5**	**6**
	-	*Flúðir*	*1*	*0*		*0*
	-	*Hellisholt*	*9*	*9*	*4*	*5*
	-	*Grafarbakki*	*2*	*2*	*1*	*1*
Holtahreppur	**25**	**Laugaland in Holt**	**6**	**4 (1)**	**2**	**1**
Biskupstungur	**26**	**Haukadalur**	**21**	**10 (1)**	**2**	**7 (1)**
	-	*Haukadalur*	*4*	*3*		*2*
	-	*Gýgjarhóll*	*1*	*0*		*0*
	-	*Kjarnholt*	*7*	*2*	*1*	*1*
	-	*Neðri-Dalur*	*6*	*2 (1)*		*2 (1)*
	-	*Helludalur*	*3*	*3*	*1*	*2*
	27	**Bergstaðir, Eystritunga**	**3**	**1**		**1**
	28	**Reykholt, Stórafljót**	**11**	**9**	**5**	**2**
	-	*Stórafljót*	4	2		2
	-	*Reykjavellir*	7	7	5	0
	-	*Laugarás*	0	0		0
	29	**Efri-Reykir**	**46**	**9 (2)**		**5 (1)**
	-	*Efri-Reykir*	*23*	*3*		*3*
	-	*Syðri-Reykir*	*2*	*0*		*0*
	-	*Böðmóðsstaðir*	*21*	*6 (2)*		*2 (1)*
Laugardalur	**30**	**Laugarvatn**	**1**	**0**		**0**
Grímsnes	**31**	**Eyvík**	**9**	**2**		**2**
	32	**Klausturhólar**	**46**	**14**		**11**
	-	*Hallkelshólar*	*27*	*1*		*0*
	-	*Klausturhólar*	*12*	*10*		*8*
	-	*Hæðarendi*	*7*	*3*		*3*
	33	**Öndverðarnes**	**28**	**6**	**3**	**3**
Flói	**34**	**Þorleifskot/Laugardælir**	**60**	**13 (1)**		**10 (1)**
	-	*Ósabotnar*	*8*	*3*		*3*
	-	*Þorleifskot/Laugardælir*	*52*	*10 (1)*		*7 (1)*
Ölfus	**35**	**Árbær**	**13**	**5**		**3**
	36	**Hveragerði**	**117**	**65 (2)**	**38**	**21**
	-	*Hveragerði*	*38*	*27 (1)*	*22*	*3*
	-	*Hverasvæðið*	11	11	7	4
	-	*Reykir*	8	8	4	4
	-	*Reykir - Fagrihvammur*	3	3	2	0
	-	*Reykir - NLFÍ*	2	2		2
	-	*Reykir - Ölfusborgir*	2	2 (1)		1
	-	*Gljúfurárholt*	*9*	*3*	*1*	*2*
	-	*Vellir*	*2*	*1*		*1*
	-	*Öxnalækur*	*7*	*1*		*1*
	-	*Kröggólfsstaðir*	*2*	*2*		*1*
	-	*Núpar*	*16*	*5*	*2*	*2*
	-	*Bæjarþorpsheiði*	*17*	*0*		*0*
	37	**Bakki**	**8**	**6**		**6**
	-	*Þóroddsstaðir*	*2*	*1*		*1*
	-	*Eystribakki*	*1*	*1*		*1*
	-	*Bakki*	*1*	*1*		*1*
	-	*Hjallakrókur*	*1*	*1*		*1*
	-	*Vindheimar*	*2*	*1*		*1*
	-	*Litlaland*	*1*	*1*		*1*
SUM			**655**	**289**	**62**	**173**

4 Description of Districts, Medium Enthalpy Systems and Well Fields

This chapter gives a brief account of the results of drilling in 37 known medium enthalpy systems in Iceland. The chapter covers most significant medium enthalpy systems in Iceland. Among few possible systems that are not included one may mention the systems Reykjanes in Djúp, Reykir in Hrútafjörður and Reykir in Fnjóskadalur.

The districts are listed from the capital Reykjavik, clockwise around the country. The location of wells is shown on maps. Some of them lack, however, coordinates and can therefore not be marked on the maps.

4.1 The Reykjavík District

4.1.1 The Laugarnes System

The Laugarnes System is within the capital town of Reykjavik. It consists of the four geothermal fields Hátún, Laugarnes, Lækjarhvammur and Rauðarárholt, see Fig. 6. Prior to drilling the natural flow from hot springs was 11 l/s of 75-88°C water (Pálmason et al, 1985).

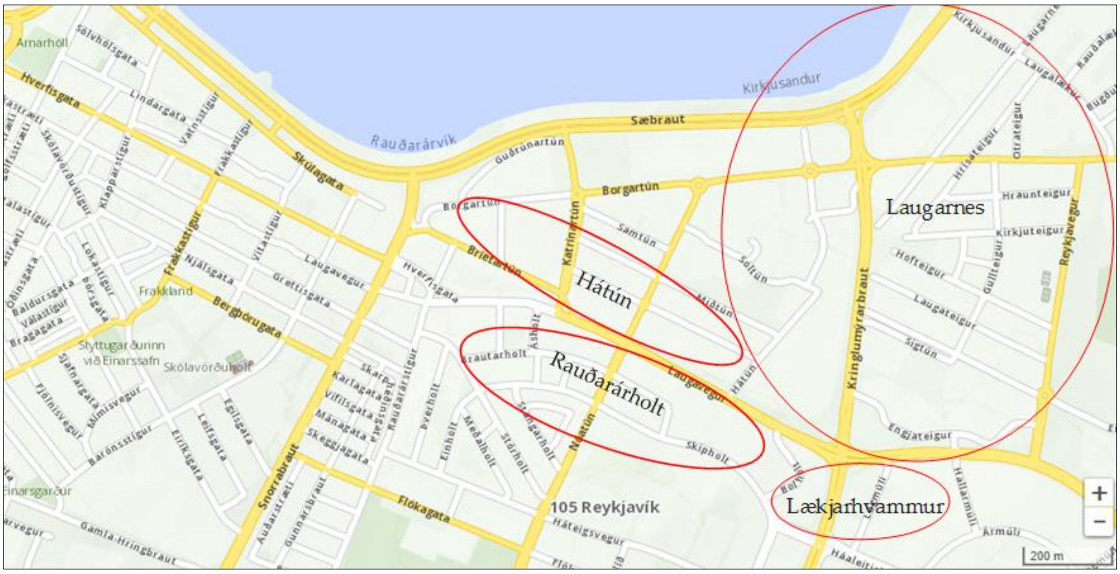

Figure 6. *Location of the well fields Laugarnes, Lækjarhvammur, Rauðarárholt and Hátún in the Laugarnes System. (Adapted from ja.is)*

First attempts to drill geothermal wells in Iceland found place in Laugarnes in August 1755 (Stefánsson et al., 1993). Hot water was used for washing and bathing but it was not until 1928 that drilling for hot water to heat houses began.

In the period 1928-1965 forty-one well, ranging 20-770 m in depth, were drilled in the town Reykjavik. A new rig capable of drilling down to 2,000 m was acquired in 1958. It was then decided to redrill the area with deeper and wider wells, using downhole pumps to increase the yield. Another large rig with drilling capacity down to 3,600 m was bought in 1975. This led to drilling of 43 additional wells in Reykjavik, ranging from 633-3,085 m in depth (Björnsson, 2007).

Twenty-six of these new wells were drilled in the Laugarnes system. The wells found a deep reservoir with 130-165°C from 700 m down to 3,085 m depth. Ten of those, ranging from 600 to 2,850 m in depth, are presently used as production wells to serve the district heating service. The description of wells in the Laugarnes system is limited to these ten wells. Fig. 7 shows well depth, depth of downhole pump, average yield and the water temperature of each well (Ívarsson, 2014).

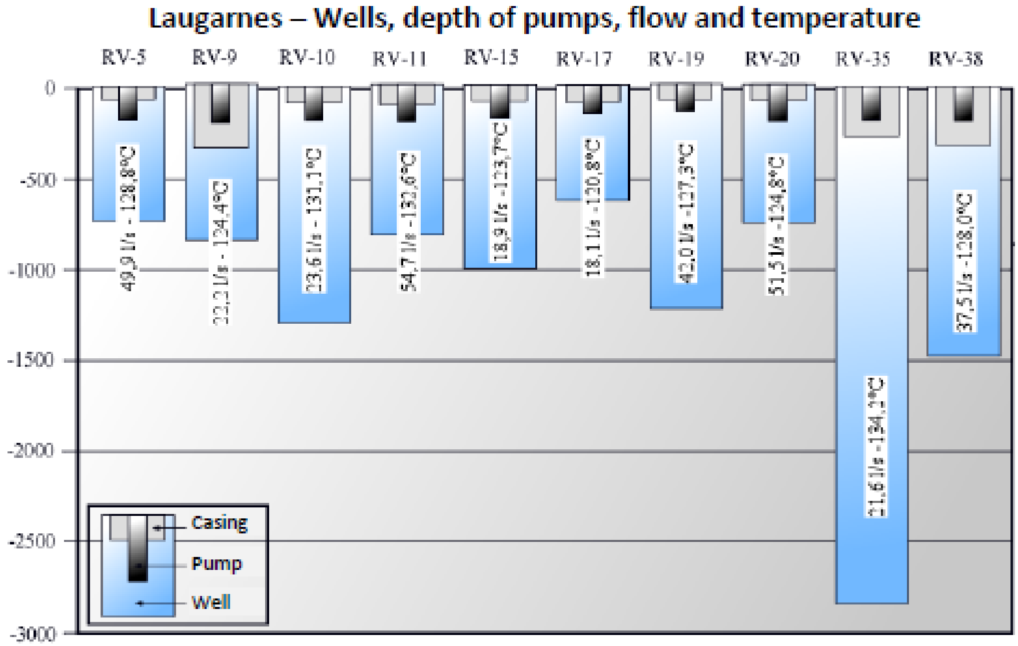

Figure 7. *Well depth, depth of downhole pump, average yield and temperature of production wells in the Laugarnes System in the year 2013 (Ívarsson, 2014).*

Fig. 8 shows the location of wells in the Laugarnes System.

Figure 8. *Overview of the wells in the Laugarnes System. (NEA's well registry.)*

4.1.1.1 The Laugarnes well field

Four wells are in use, R-5, R-10, R-17 and R-35, see Fig. 8. The depths range from 633-2,857 m. Maximum measured temperatures range from 131-164°C. The wells produced with pump 113 l/s of 121-134°C hot water on average in the year 2013. (Friðleifsson, et al., 1995; Ívarsson, 2014).

4.1.1.2 The Lækjarhvammur well field

Four wells are in use, R-11, R-15, R-19 and R-20, see Fig. 8. The depths range from 765-1,239 m. Maximum measured temperatures range from 135-139°C. The wells produced with pump 167 l/s of 124-133°C hot water on average in the year 2013 (Ívarsson, 2014).

4.1.1.3 The Rauðarárholt well field

One well, R-9, is in use, see Fig. 8. It is 862 m deep, has a maximum measured temperature of 124°C and produced with pump 22 l/s of 124°C hot water on average in the year 2013.

4.1.1.4 The Hátún well field

One well is in use, R-38, see Fig. 8. It is 1,488 m deep. Maximum temperature of 141°C was found at 1,130 m depth. The well yields on average 37.5 l/s at 128°C (Ívarsson, 2014; Thorsteinsson, 1982).

The total output of the wells in the Laugarnes System is 340 kg/s of 127°C water, corresponding to a total thermal power above 35°C of 132 MW_{th} (Ívarsson, 2014). According to Fig. 2 a flow of 46 kg/s of 127°C hot water would be required to generate 1 MW_e with binary cycles. The electric potential of the Laugarnes system (340 l/s at 127°C) is thus 7.4 MW_e yielding 80°C effluent water for space heating with a remaining thermal potential above 35°C of 63.9 MW_{th}.

4.2 The Seltjarnarnes District

4.2.1 The Seltjarnarnes System

The Seltjarnarnes System is on the western border of the capital Reykjavik. There was no natural outflow of thermal water but high geothermal gradients indicated hidden fields. The well fields are Bakki, Nes, Nýibær, Bygggarður and Ráðagerði, see Fig. 9.

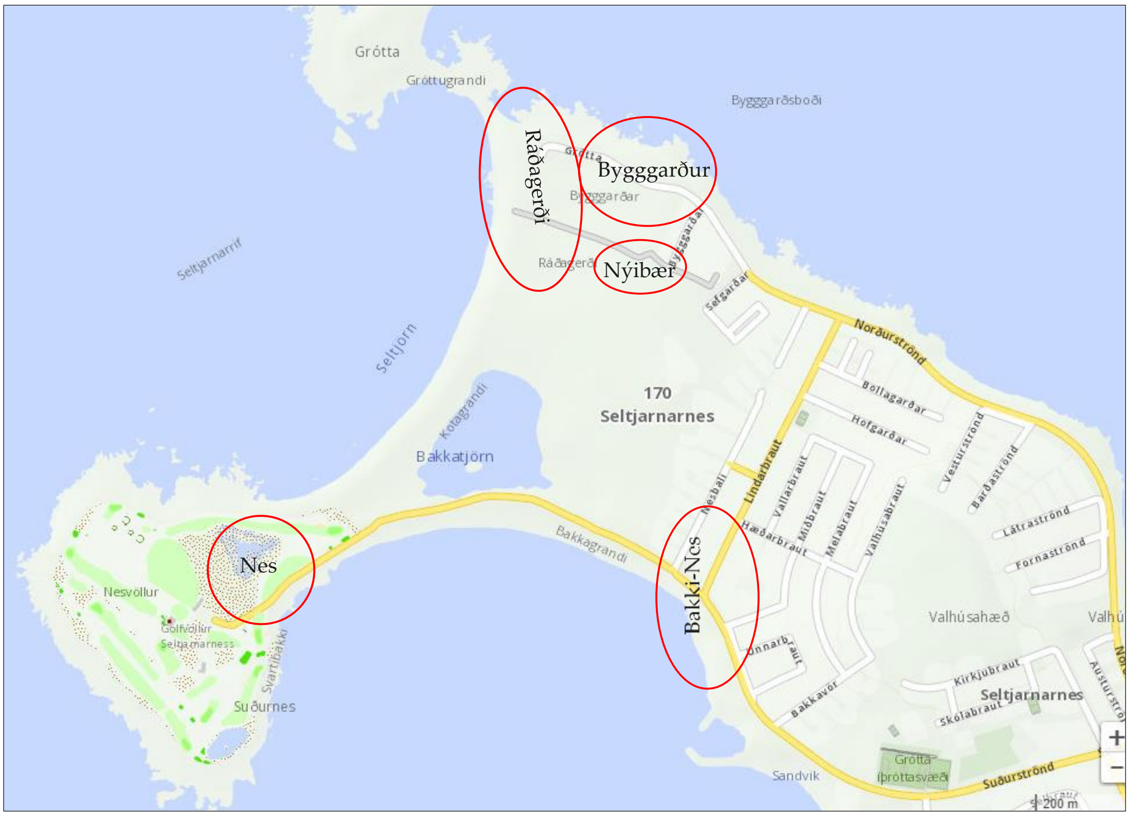

Figure 9. *Location of the well fields Bakki, Nes, Nýibær, Bygggarður and Ráðagerði in the Seltjarnarnes System. (Adapted from ja.is)*

Originally the water had a salinity of 1‰ 550 ppm Cl, but the salinity has now increased to 3.5‰. The salinity comes from the shallower aquifers. The deepest aquifers are 120-140°C hot and there are indications of less saline and >150°C hot water at greater depth. Eight exploration wells and six production wells have been drilled in the Seltjarnarnes system, see Fig. 10 (Kristmannsdóttir et al., 2001, Kristmannsdóttir and Björnsson, 2014).

Figure 10. *Overview of the wells in the Seltjarnarnes System. (NEA's well registry.)*

4.2.1.1 The Bakki Field

Two exploratory wells and one production well have been drilled in the Bakki Field, see Fig. 9 and 10. The production well SN-1, is 1,283 m deep, has a maximum measured temperature of 117°C but is not in use (Kristmannsdóttir et al., 2001).

4.2.1.2 The Nes Field

Two exploratory wells and one production well have been drilled in the Nes Field, see Fig. 9 and 10. None of them reached measured temperature over 100°C and none of them is in use (Kristmannsdóttir et al., 2001).

4.2.1.3 The Nýibær Field

One production well, SN-6 has been drilled in the Nýibær Field, see Fig. 9 and 10. It is 2,701 m deep, has maximum measured temperature of 144°C at 2,650 m depth and is in use. The yield is up to 25 l/s of 118-121°C water (Kristmannsdóttir et al., 2001, Kristmannsdóttir and Björnsson, 2014).

4.2.1.4 The Bygggarður Field

One exploratory well and three production wells have been drilled in the Bygggarður Field, see Fig. 9 and 10. Two of them SN-4 and SN-5 are 2,025 and 2,207 m deep, have highest measured temperatures of 127°C at 2,000 m depth and 119°C at 2,180 m depth, respectively. Both are in use. The yield of SN-04 is up to 35 l/s of 85-114°C water and that of SN-05 up to 25 l/s of 98-109°C water. (Kristmannsdóttir et al., 2001; Kristmannsdóttir and Björnsson, 2014).

4.2.1.5 The Ráðagerði Field

Two exploratory wells and one production well, SN-12, have been drilled in the Ráðagerði Field, see Fig. 9 and 10. SN-12 is 2,714 m deep and has maximum measured temperature of 145°C at 2,700 m depth and is in use. That well yields up to 35 l/s at 106-113°C. (Kristmannsdóttir et al., 2001; Kristmannsdóttir and Björnsson, 2014).

The four production wells that are used in the Seltjarnarnes System are interconnected and the average production temperature depends on which wells are being pumped. If one assumes an average production of 46.4 l/s of 108°C water the wells deliver a thermal output above 35°C of 14.2 MW_{th} or an electric potential of 0.6 MW_e with 80°C effluent water of remaining thermal potential 8.7 MW_{th} above 35°C. With the aid of downhole pumps the production capacity of the field could be increased considerably. The system would also benefit from increased reinjection. A possible potential of 100 l/s of 103°C water would be 28.5 MW_{th} or 1.06 MW_e and a remaining thermal potential above 35°C of 18.8 MW_{th}.

4.3 The Hvalfjörður District

There are four geothermal systems in the Hvalfjörður District, Fremri-Háls, Möðruvellir, Hvammsvík and Miðsandur, see Fig. 11.

Figure 11. *Location of the geothermal systems Fremri-Háls, Möðruvellir, Hvammsvík and Miðsandur in the Hvalfjörður District. (Adapted from ja.is)*

4.3.1 The Fremri-Háls System

Four exploration wells and two production wells have been drilled in the Fremri-Háls System, see Fig. 12.

Figure 12. *Overview of the wells in the Fremri-Háls System. (NEA's well registry.)*

Well FH-5 is 873 m deep. It found 120°C at 800 m and yields about 20-30 l/s of 89°C hot pumped water with 65 m drawdown (Stefánsson et al., 1993). Well FH-6 is 404 m deep and 97°C were found there at 400 m depth but the well has a minor yield and is used to heat the farm houses.

The thermal potential above 35°C of 25 l/s of 89°C is 5.7 MW_{th}.

The system is affected by pumping activity of Reykjavík Energy in the geothermal wells in the Reykir well field in Mosfellssveit (Hafstað, 2015b; Stefánsson et al., 1993; Steingrímsson, 1992).

4.3.2 The Möðruvellir System

The Möðruvellir System is at the farm Möðruvellir in Kjós. There have been drilled nineteen shallow exploratory wells and two deep production wells into the Möðruvellir System, see Fig. 13.

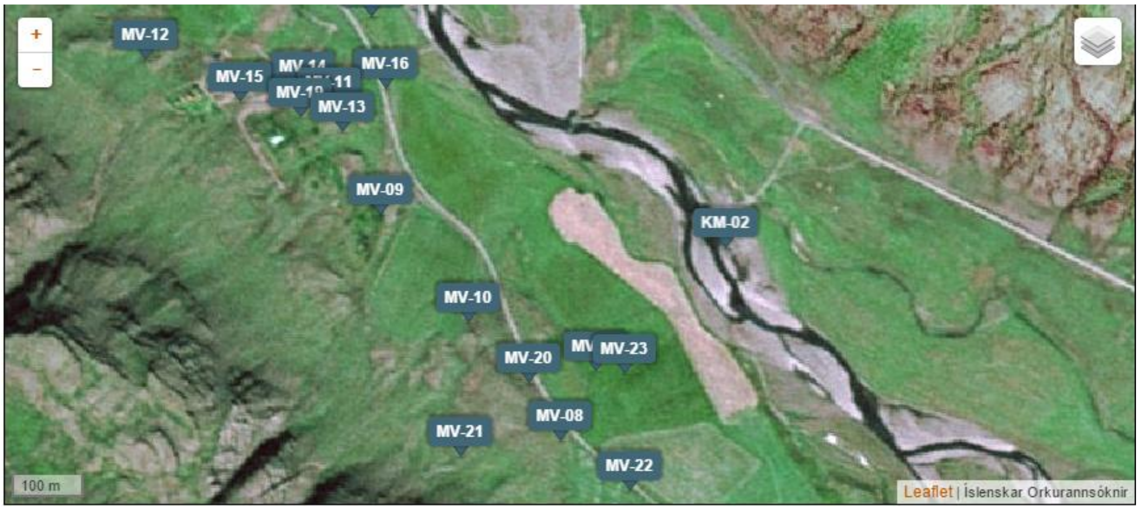

Figure 13. *Overview of the wells in the Möðruvellir System. (NEA's well registry.)*

Well MV-19 is 822 m deep and found 80°C water at 650 m depth. Pumping tests indicated a yield of 20 l/s with 100 m drawdown. The thermal potential above 35°C of well MV-19 is 3.8 MW_{th}. MV-24 is 1,704 m deep and discovered a deeper reservoir with a temperature of 144°C at 1,630 m. The formation temperature at 1,000 m depth is 140°C. Well MV-24 yields 19 l/s of 135°C free-flowing and 40 l/s with 120 m drawdown (Hafstað, 2015b; Hjartarson and Sæmundsson, 2003b; Hafstað and Sæmundsson, 2013).

If one assumes a flow of 40 l/s of 135°C the thermal potential above 35°C of well MV-24 corresponds to 16.8 MW_{th} or an electric potential of 0.98 MW_e and 80°C effluent water for space heating with a remaining potential of 7.5 MW_{th}. The proven thermal potential at Möðruvellir is thus 20.6 MW_{th}.

4.3.3 The Hvammsvík System

Nine exploration wells and one production well have been drilled in the Hvammsvík System, see Fig. 14.

Figure 14. *Overview of the wells in the Hvammsvík System. (NEA's well registry.)*

Well HV-10 is 1,466 m deep, with highest measured temperature 117°C near bottom (at 1,458 m) and yields free-flowing about 3.7 l/s of 82.8°C hot water. The well was pumped for 12 days and it gave about 17 l/s 89°C hot water. If the well is pumped 25 l/s, there will be 85 m drawdown. The reservoir temperature is about 95-100°C (Björnsson, 1992; Sigurðsson, 1995).

Assuming a flow of 25 l/s at 89°C we obtain a thermal potential above 35°C of 5.7 MW_{th}.

4.3.4 The Miðsandur System

There have been drilled eight exploratory wells and one production well in the Miðsandur System, see Fig. 15.

Figure 15. *Overview of the wells in the Miðsandur System. (NEA's well registry.)*

Well MS-4, drilled to 1,513 m, yields about 7 kg/s of 140°C water at about 2 bar-g wellhead pressure. For long term operation a flow of 5-6 kg/s of water and a wellhead pressure of 4 bar is expected (Þórhallsson et al., 2015).

If one assumes a flow of 7 l/s of 140°C the thermal output above 35°C of well MS-4 corresponds to 3.1 MW_{th} or an electric potential of 0.19 MW_{e} and a remaining potential above 35°C of 1.3 MW_{th}.

4.4 The Akranes and Leirársveit District

There are two geothermal systems in the Akranes and Leirársveit District, the Leirá-Geldingaá and Stillholt, see Fig. 16.

Figure 16. *Location of the geothermal systems Leirá-Geldingaá and Stillholt in the Akranes and Leirársveit District. (Adapted from ja.is)*

4.4.1 The Leirá-Geldingaá System

The Leirá-Geldingaá System includes well fields at Leirá and Geldingaá, see Fig. 17.

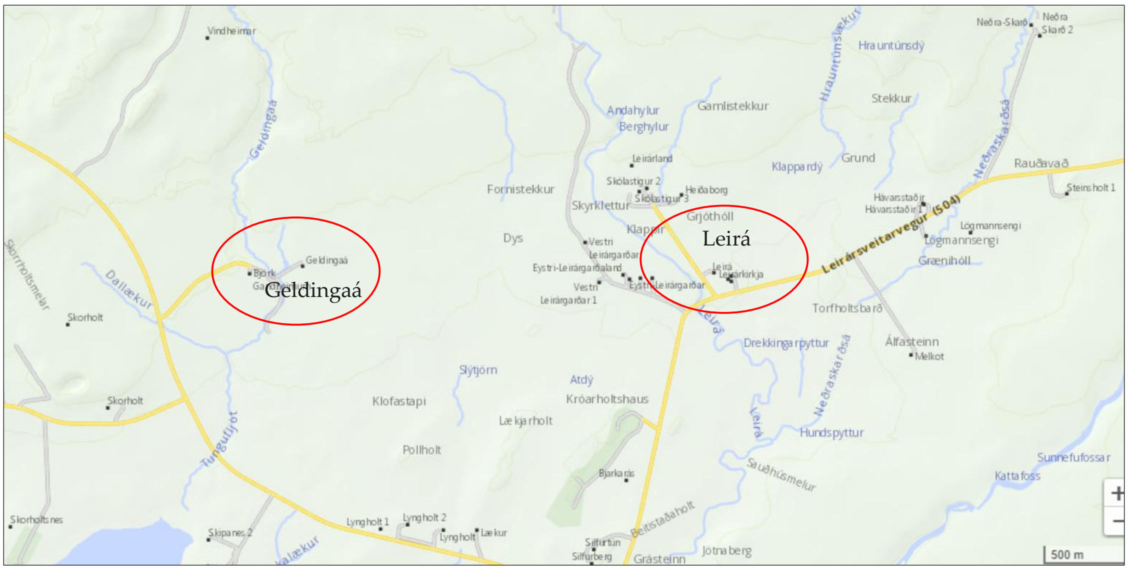

Figure 17. *Location of the well fields at Leirá and Geldingaá in the Leirá-Geldingaá System. (Adapted from ja.is)*

4.4.1.1 The Leirá Field

Four deep production wells have been drilled in the Leirá Field, see Fig. 18.

Figure 18. *Overview of the wells at the Leirá field. (NEA's well registry.)*

One of them, LG-4 is 2,019 m deep and pumped it yields about 9 l/s of 128 °C hot water with a drawdown of 65 m. The water is rich in CO_2 and low in pH. It cannot be used directly for space heating due to corrosiveness and calcite scaling (Hjartarson and Sæmundsson, 2003a; Þórhallsson et al., 1976).

The thermal power above 35°C is 3.5 MW_{th} or the electric potential 0.2 MW_e yielding 1.7 MW_{th} of remaining thermal potential.

4.4.1.2 The Geldingaá Field

The well field at Geldingaá, see Fig. 16, is some 2 km west of the Leirá Field. Seven exploratory wells and one production well have been drilled, see Fig. 19.

Figure 19. *Overview of the wells at the Geldingaá Field. (NEA's well registry.)*

The well field has similar chemistry of water as the water at the Leirá well field. Exploratory wells have indicated a geothermal gradient in excess of 300°C/km. Well GÁ-8, is 657 m deep, but not productive.

4.4.2 The Stillholt System

Two exploratory wells were drilled at the Stillholt System in Akranes, see Fig. 20.

Figure 20. *Overview of the wells at the Stillholt Field. (NEA's well registry.)*

The well ST-2 was not productive but showed a linear temperature gradient of 129°C/km, reaching 186°C at 1,350 m depth. Water in the well contained 2,500–3,000 ppm Cl (Hjartarson and Sæmundsson, 2003a; Sæmundsson et al., 1968).

4.5 The Borgarfjörður District

The Borgarfjördur District is the largest low-temperature region in Iceland. The natural discharge of the hot springs is estimated to be equivalent to more than 450 l/s of boiling water. The geothermal activity has been divided into four separate geothermal systems, three of which, Brautartunga-England, Bær-Varmaland and Reykholt, have formation temperatures in excess of 100°C (Georgsson et al., 2010), see Fig. 21.

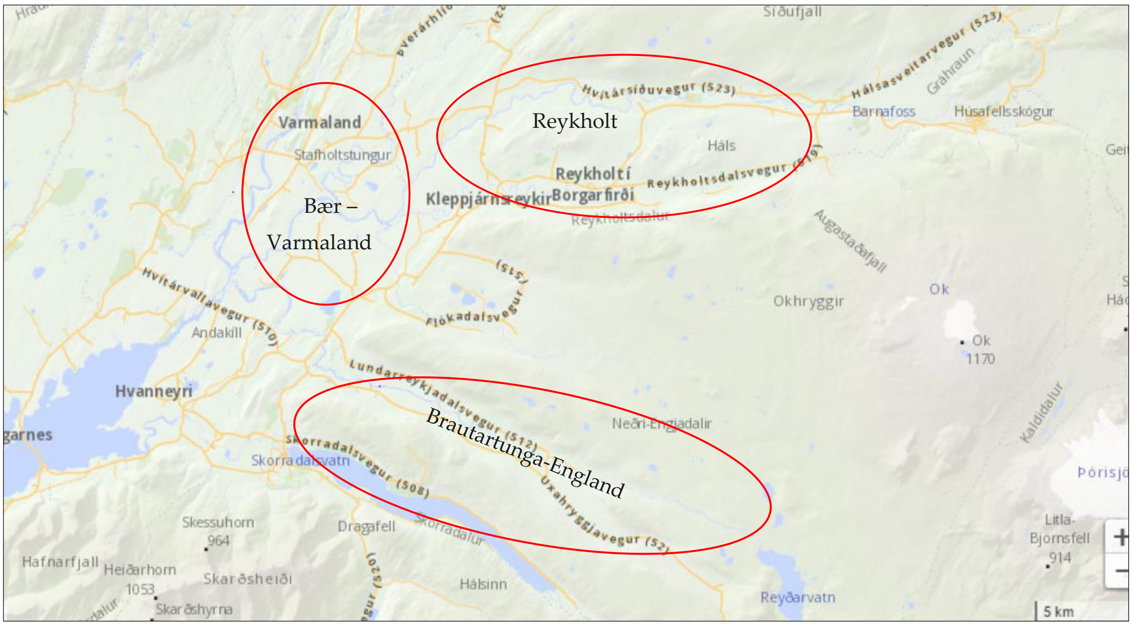

Figure 21. *Location of the geothermal systems Brautartunga-England, Bær-Varmaland and Reykholt in the Borgarfjörður District. (Adapted from ja.is)*

Fig. 22 shows the main hot springs of the Borgarfjörður area and the four geothermal systems, Húsafell, Brautartunga-England, Bær-Varmaland and Reykholt. Also shown are the locations of the main production wells in Borgarfjörður

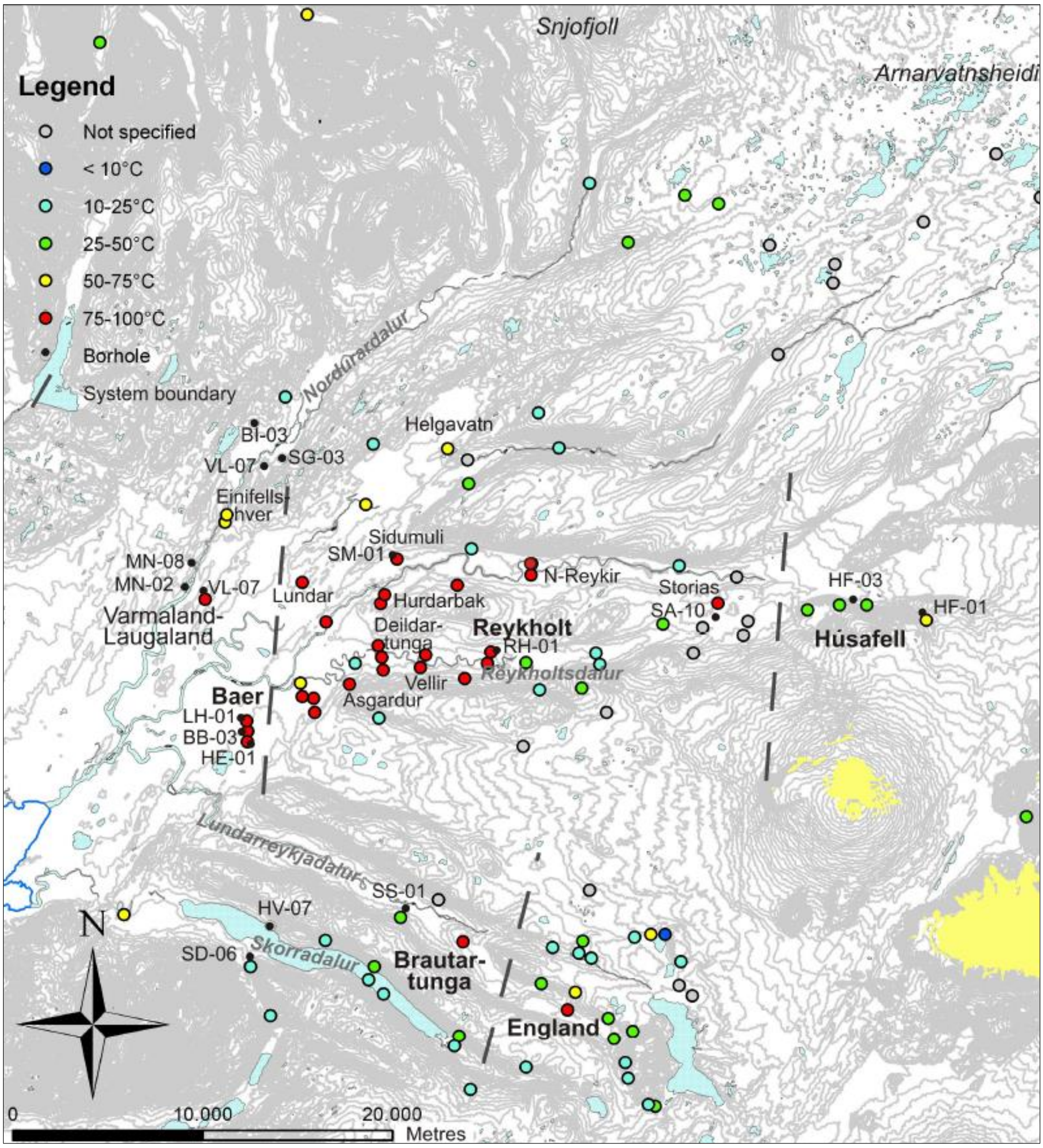

Figure 22. *The main hot springs of the Borgarfjörður area and the four geothermal systems, Brautartunga-England, Bær-Varmaland, Reykholt and Húsafell. Also shown are the locations of the main production wells in Borgarfjörður (Georgsson et al., 2010).*

4.5.1 The Brautartunga-England System

The Brautartunga-England System is centered in the mid and inner part of the Lundareykjadalur valley, some 20-25 km south of the Reykholt System, see Fig. 21 and 22. The system includes the well fields, England, Stóra-Drageyri, Hvammur, and Snartarstaðir, see Fig. 23.

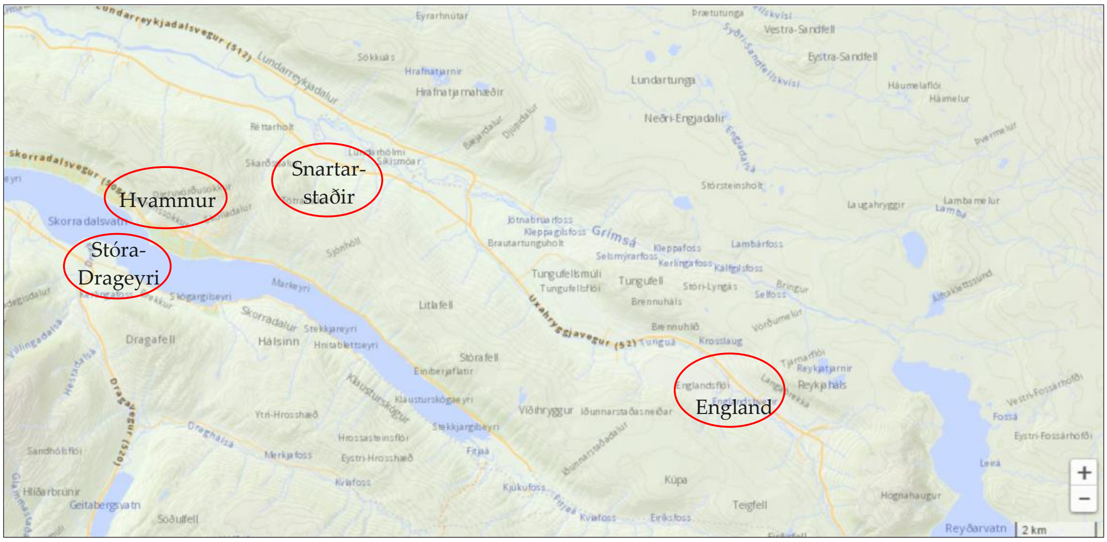

Figure 23. *Location of the well fields England, Stóra-Drageyri, Hvammur and Snartarstaðir in the Brautartunga-England System. (Adapted from ja.is)*

4.5.1.1 The England hot spring field

No boreholes have been drilled in the England Field but several hot springs bear evidence of possible thermal potential. The hottest springs are Englandshverir, yielding 2.9 l/s of 94°C in the largest spring and 5.8 l/s at 60-93°C in total. The activity is found on a 1 km long fracture from the farm Reykir up to the farm England. SiO_2 points to subsurface temperatures above 100°C (Sæmundsson, 1992).

The thermal potential above 35°C of the largest spring is 0.7 MW_{th}.

4.5.1.2 The Stóra-Drageyri well field

Five exploratory wells and one production well, have been drilled at Stóra-Drageyri, see Fig. 22 and 24.

Figure 24. *Overview of the wells at the Stóra-Drageyri Field. (NEA's well registry.)*

Well SD-6 is 836 m and deep produces 10-15 l/s of 98°C water in pumping ((Björnsson and Sæmundsson, 1994; Georgsson et al., 2010).

Assuming a flow of 12.5 l/s of 98°C water one obtains a thermal potential above 35°C of 3.3 MW_{th}.

4.5.1.3 The Hvammur Field

Six exploratory wells and one production well have been drilled at Hvammur, see Fig. 22 and Fig. 25.

Figure 25. *Overview of the wells at the Hvammur Field. (NEA's well registry.)*

Well HV-7 at Hvammur is the deepest well in the Borgarfjörður area, 1,237 m deep. It has a bottom temperature of 120°C and 6 l/s can be pumped with 90 m drawdown and 10 l/s with 180 drawdown to the casing depth (Hafstað and Björnsson, 2000b).

Assuming 10 l/s of 90°C hot water the thermal power above 35°C is 2.3 MW_{th}.

4.5.1.4 The Snartarstaðir Field

Four exploratory wells and one production well, have been drilled at Snartarstaðir, see Fig. 22 and Fig. 26.

Figure 26. *Overview of the wells at the Snartarstaðir Field. (NEA's well registry.)*

Well SS-5 is 309 m deep and yields 7-8 l/s free-flowing 100°C water. (National Energy Authority, 1992). The thermal power above 35°C is 2.0 MW_{th}.

Adding up the potentials of the Brautartunga-England system we obtain 8.4 MW_{th}.

4.5.2 The Bær-Varmaland System

The Bær-Varmaland System includes the well fields at Hellur, Bær and Laugarholt as well as the field at Varmaland/Laugaland, see Fig. 27.

Figure 27. *Location of the well fields Hellur, Bær, Laugarholt and Varmaland/Laugaland in the Bær-Varmaland System. (Adapted from ja.is)*

4.5.2.1 The Hellur Field

One exploratory well and three production wells have been drilled at Hellur, see Fig. 28.

Figure 28. *Overview of the wells in the well fields Hellur, Bær and Laugarholt in the Bær-Varmaland System. (NEA's well registry.)*

Well HE-1 is 1,108 m deep and has a maximum temperature 112°C at 690 m, but the logging tool could not go deeper. In free-flow the well only yields 0.1 l/s. (Georgsson, et al., 1981)

4.5.2.2 The Bær Field

Four production wells have been drilled at Bær, see Fig. 28. One of them, BB-3 is 1,151 m deep and it yields with pump about 17 l/s 110-115°C hot water from rather shallow aquifers (Axelsson, 2010; Georgsson et al., 1981; Georgsson et al., 2010; Olsen, 2014a).

Assuming a flow of 17 l/s at 112°C we obtain a thermal output above 35°C of the well of 5.5 MW_{th} or an electric potential of 0.25 MW_e and a remaining thermal potential of 3.2 MW_{th}.

4.5.2.3 The Laugarholt Field

One production well has been drilled at Laugarholt, see Fig. 28. LH-1 is 1,013 m deep and was a real success giving 28 l/s of 93°C water in free flow from two main aquifers at 323 and 580 m depth. With downhole pump a yield of 45 l/s of 93°C water is obtained (Axelsson, 2010). The thermal potential of that well above 35°C is 11.3 MW_{th}.

It is estimated that the geothermal fields at Bær and Laugarholt could yield 170 l/s of boiling water from 5 wells with a drawdown of 160 m (Axelsson, 2010; Georgsson, et al., 1981; Georgsson et al., 2010).

That gives a possible thermal output of these fields of 46.3 MW_{th} or an electric potential 1.57 MW_e and a remaining thermal potential of 32.0 MW_{th}.

4.5.2.4 The Varmaland/Laugaland Field

The Varmaland/Laugaland Field is located at the western margin of the Borgarfjörður thermal region, see Fig. 27. Seven production wells have been drilled in the Varmaland/-Laugaland Field, see Fig. 29.

Figure 29. *Overview of the wells at the Varmaland/Laugaland Field. (NEA's well registry.)*

The natural manifestations consisted of small hot springs at 80-97°C yielding 5-10 l/s. Well VL-7, 671 m deep, was a major success. In free flow the well gave 41.5 l/s of 105°C water at the top, but temperature logs in the well showed the temperature in the geothermal system to be 113°C at 650 m depth. Production tests showed that the well could be expected to sustain at least a production of 15 l/s in free flow, and more with pumping if necessary (Georgsson et al., 1984). With the well producing under slight wellhead pressure, it has so far not had much effect on flow from the hot springs and the old wells.

Assuming a yield of 15 l/s of 105°C the thermal output above 35°C of the well corresponds to 4.4 MW_{th} or an electric potential of 0.17 MW_e and a remaining thermal potential of 2.8 MW_{th}.

The total proven potential of the Bær-Varmaland system is 21.2 MW_{th} or 0.42 MW_e and a remaining thermal potential of 6.0 MW_{th}. Adding the potential of Varmaland to the possible potential of the fields Bær and Laugarholt one obtains a possible potential of 50.7 MW_{th} or 1.74 MW_e and a remaining thermal potential of 34.8 MW_{th}.

4.5.3 The Reykholt System

The Reykholt System is by far the largest system in Borgarfjörður with some of the most powerful low temperature geothermal fields in Iceland, most notably the Deildartunga-Kleppjárnsreykir Field with the Deildartunga hot spring discharging 180 l/s of boiling water and the Kleppjárnsreykir hot spring with 70 l/s, see Fig. 21 and 22. The total natural discharge is about 450 l/s and the thermal output is assessed to be equivalent to more than 400 l/s of boiling water (Georgsson et al., 2010) or thermal power above 35°C of 109 MW_{th} and an electric power of 3.6 MW_e.

The system includes the geothermal fields Reykholt, Deildartunga-Kleppjárnsreykir, Hurðarbak-Síðumúli, Vellir, Hægindi-Kópareykir and Norður-Reykir. Few wells have been drilled in these fields as there is abundant free flow from springs.

4.5.3.1 The Reykholt Field

The Reykholt Field is in Reykholtsdalur, see Fig. 21 and Fig. 22. Three production wells have been drilled, see Fig. 30.

Figure 30. *Overview of the wells at the Reykholt Field. (NEA's well registry.)*

Well, RH-1, was drilled at Reykholt in 1974. It is 251 m deep and produces about 20 l/s in free flow with a temperature of 116°C, but has a maximum temperature of 127°C at 225 m depth. To avoid rock fragments in the flow the discharge is limited to 8 l/s. It is still the hottest producing well in the region (Georgsson et al., 2010; Sæmundsson, 2010a; Þorbjörnsson and Guðmundsson, 2010).

If one assumes a flow of 20 l/s of 116°C the thermal output above 35°C of the well corresponds to 6.8 MW_{th} or an electric potential of 0.33 MW_e and a remaining thermal potential of 3.8 MW_{th}.

Adding this potential to that of the natural flowing springs, 400 l/s of 100°C or 109 MW_{th} and 3.7 MW_e, one obtains a total potential for the Reykholt system of 115.8 MW_{th} or 4.03 MW_e and a remaining thermal potential of 79.1 MW_{th}.

4.6 The Snæfellsnes District

4.6.1 The Eiðhús-Dalur System

The Eiðhús-Dalur System consists of the fields Eiðhús and Dalur, see Fig. 31. Maximum temperature found in the wells of the Eiðhús-Dalur System lies in the range 112-125°C.

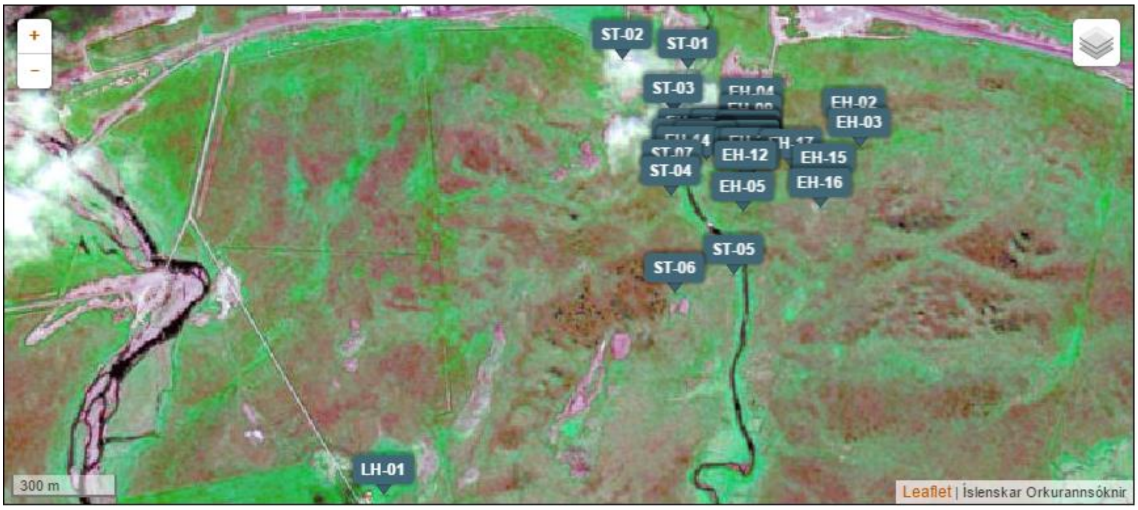

Figure 31. *Overview of the wells at the Eiðhús-Dalur System. (NEA's well registry.)*

4.6.1.1 The Eiðhús Field

The Eiðhús well field lies between the rivers Fáskrúður and Grímsá in Snæfellsnes. There have been drilled twenty exploratory wells and three production wells, see Fig. 31. Highest temperature measured in the field is 125°C in well EH-8 at 1,142 m depth but 122°C in well EH-12 at 848 m depth. Two of the wells, EH-10 and EH-12, which are 350 and 1,026 m deep, yield together about 5 l/s of free-flowing 104°C hot water. There is an estimate that the wells could be pumped to produce 20 l/s with a 100 m drawdown or 9.5 l/s with a 30 m drawdown (Sæmundsson, 2013).

Assuming a flow of 20 l/s of 104°C hot water we obtain a thermal output above 35°C of 5.9 MW_{th} or an electric potential of 0.22 MW_{e} and a remaining thermal potential of 3.8 MW_{th}.

4.6.1.2 The Dalur Field (Lynghagi)

The Dalur (Lynghagi) field is just south-west of Eiðhús Field. There have been drilled two exploratory wells and one production well, see Fig. 31. The production well, LH-1, is 724 m deep, with highest measured temperature 121°C at the bottom and yields about 6.5 l/s of free-flowing 103°C hot water (Skessuhorn, 2013). The thermal potential of this well is 1.9 MW_{th} or an electric potential 0.07 MW_{e} with remaining thermal potential of 1.2 MW_{th}.

If the fields are not interconnected the total potential of the Eiðhús-Dalur System would be about 7.8 MW_{th} or 0.29 MW_{e} and 5.0 MW_{th} of thermal potential.

4.7 The Barðaströnd District

4.7.1 The Reykhólar System

The Reykhólar System is at Barðaströnd. Eight production wells have been drilled, see Fig. 32.

Figure 32. *Overview of the wells in the Reykhólar System. (NEA's well registry.)*

Total natural discharge prior to drilling was about 30 l/s of 60-100°C water (Torfason, 2003). Six of those wells, ranging 186-1,070 m in depth, with highest measured temperature in well RH-4 of 117°C at 690 m depth, yield about 55 l/s of 90-111°C hot water, with weighted average of 108°C. (Björnsson and Sigvaldason, 1989; Hafstað, 2012; Hafstað and Björnsson, 2000a; Harðardóttir, 2012a, b).

That thermal output of the wells, 55 l/s of 108°C water, corresponds to a thermal potential above 35°C of 16.8 MW_{th} or an electric potential of 0.71 MW_e and a remaining thermal potential of 10.4 MW_{th}.

4.8 The Miðfjörður District in the western Húnaþing

4.8.1 The Ytri-Reykir, Laugarbakki System

The Ytri-Reykir System is in Miðfjörður. Three production wells have been drilled at Ytri-Reykir, 230, 350 and 888 m deep, see Fig. 33.

Figure 33. *Overview of the wells in the Ytri-Reykir, Laugarbakki System. (NEA's well registry.)*

One of them, LB-2, has highest measured temperature of 107°C found near bottom, just day after drilling. Well LB-3 is in use and yielded 14.5 l/s of 95.8°C pumped hot water on average in the year 2014 (Ólafsson, 2015). Estimated pumped potential for a long period is 40-50 l/s with 90 m drawdown and it is estimated that the field could deliver a long term flow of some 50-100 l/s of 95°C water if more wells were drilled (Björnsdóttir and Axelsson, 2007).

Assuming a flow of 50 l/s of 95°C hot water one obtains a thermal potential above 35°C of 12.6 MW_{th} or an electric potential of 0.38 MW_e and a remaining thermal potential of 9.4 MW_{th}.

4.9 The Skagafjörður District

In Skagafjörður District there are the three geothermal systems, Reykjarhóll in Varmahlíð, Reykjarhóll on Bakkar in Fljót and Langhús in Fljót, see Fig. 34.

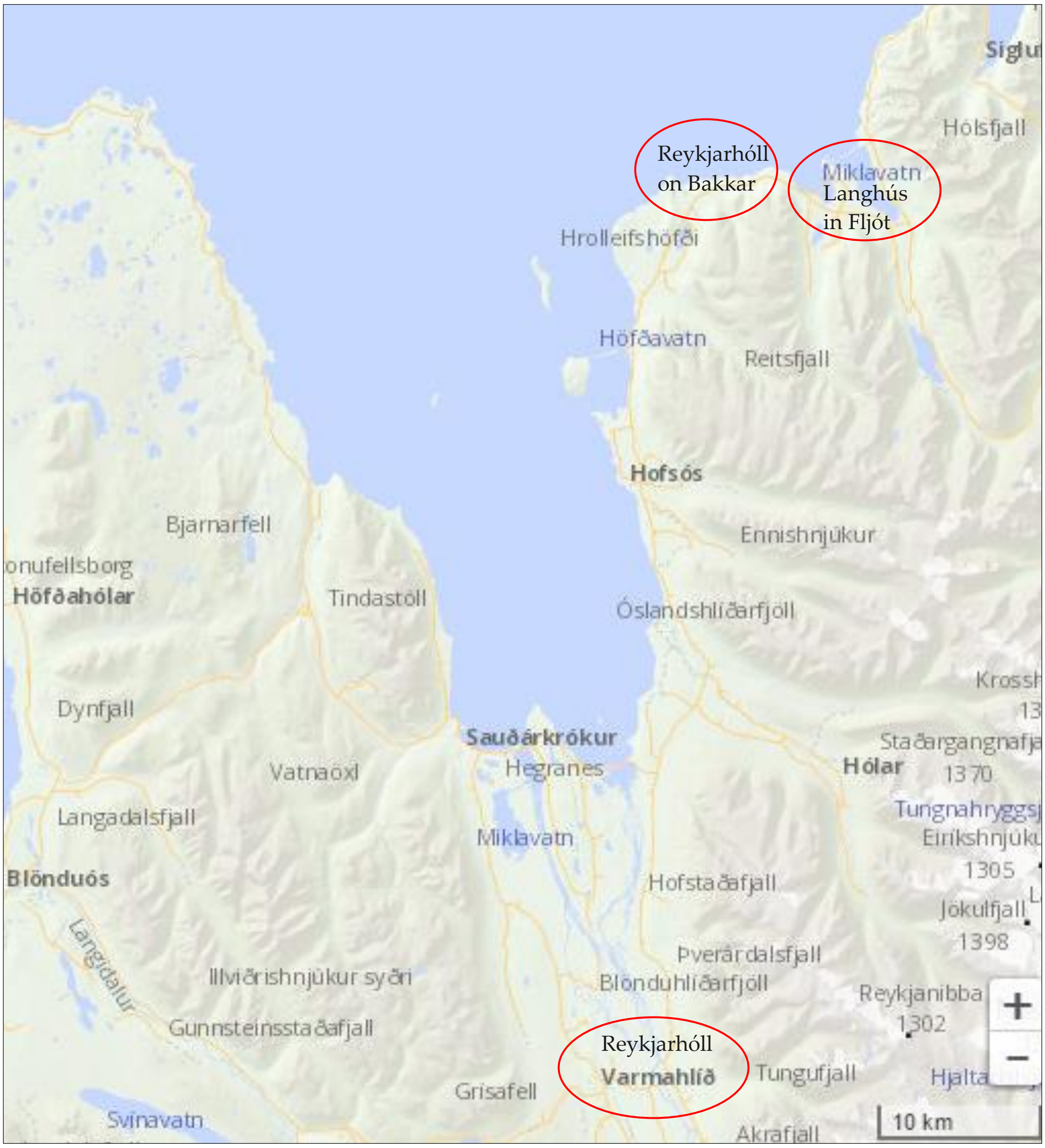

Figure 34. *Location of the geothermal systems Reykjarhóll in Varmahlíð, Reykjarhóll on Bakkar in Fljót and Langhús in Fljót in the Skagafjörður District. (Adapted from ja.is)*

4.9.1 The Reykjarhóll System (Varmahlíð)

The Reykjarhóll System is in Varmahlíð in Skagafjörður. Nine exploratory wells and three production wells have been drilled at Reykjarhóll (Varmahlíð), see Fig. 35.

Figure 35. *Overview of the wells in the Reykjarhóll System (Varmahlíð). (NEA's well registry.)*

Well VH-3 is 414 m deep. It delivers 20 l/s of 90°C water in free flow. VH-12 is 427 m deep, with highest measured temperature of 95°C at 200 m depth. It yielded on a year average, 2013, about 20 l/s of pumped 95 °C hot water. There is an estimate that the well has a potential of over 40 l/s (Skagafjarðarveitur, 2015; Tryggvason et al., 2014).

The combined potential of these wells, 40 l/s at 95°C, corresponds to 10.1 MW_{th} above 35°C or an electric potential of 0.31 MW_e and a remaining thermal potential of 7.5 MW_{th}.

4.9.2 The Reykjarhóll System on Bakkar in western Fljót

The Reykjarhóll System is at Bakkar in western Fljót in Skagafjörður. Five production wells have been drilled, see Fig. 36.

Figure 36. *Overview of the wells in the geothermal systems Reykjahóll on Bakkar and Langhús in Fljót. (NEA's well registry.)*

In well RH-5, which is 479 m deep, 95°C were found at 460 m depth. There was an estimate of the free-flow 5.0 l/s of 84.5°C water (Ólafsson, 1987) but 10-15 l/s with maximum drawdown in pumping (Sæmundsson, 2005b).

Assuming 12.5 l/s of 84.5°C water one obtains a thermal potential above 35°C of 2.6 MW_{th}.

4.9.3 The Langhús System in Fljót

Two production wells have been drilled in the Langhús System, see Fig. 36. LH-1, which is in use and LH-2 which will be used, are 79 and 204 m deep, with highest measured temperature of 106°C at 120 m depth in well LH-2, yield 1.3 and 5.4 l/s of 101 and 102°C hot water (Hafstað, 2014b; Hafstað, 2015a; Tryggvason et al., 2014). Well LH-2 has a shut-in pressure of 2.7 bar-g and primary outcome of overall performance is approximately 8 l/s.

So if they yield together about 9 l/s of 102°C hot water the thermal potential above 35°C is 2.5 MW_{th} or the electric potential 0.09 MW_e and the remaining thermal potential 1.7 MW_{th}.

4.10 The Eyjafjörður District

4.10.1 The Laugaland, Þelamörk System

The Laugaland geothermal system is in Eyjafjörður. Twelve production wells have been drilled, see Fig. 37

Figure 37. *Overview of the wells at the Laugaland, Þelamörk Field. (NEA's well registry.)*

One of them, well LL-10 is 1,707 m deep and yields on a year average about 14 l/s of 103 °C hot water but can give 25 l/s (Norðurorka, 2015).

Well LL-2 is 1,089 m deep, gave 5 l/s of free-flowing 91°C hot water and has measured temperature of 93°C at 600 m. Well LL-3 is 668 m deep, gave 10-15 l/s of free-flowing 91°C hot water and has measured temperature of 93°C at 640 m. Well LL-11 is 645 m deep, gave 5 l/s by pump of 91°C hot water and has measured temperature of 90°C at 640 m. (Flóvenz et al, 1985). Only LL-10 is used presently for production.

The 14 l/s of 103°C water give a thermal potential above 35°C of 4.0 MW_{th} or an electric potential of 0.15 MW_e and a remaining thermal potential of 2.6 MW_{th}.

4.11 The Norðurþing District

There are four geothermal systems in the Norðurþing District, Hveravellir in Reykjahverfi, Húsavík, Ytribakki and Ærlækjarsel in Öxarfjörður, see Fig. 38.

Figure 38. *Location of the geothermal systems Hveravellir in Reykjahverfi, Húsavík, Ærlækjarsel and Ytribakki in Öxarfjörður in the Norðurþing District. (Adapted from ja.is)*

4.11.1 The Hveravellir System in Reykjahverfi

The Hveravellir System is at the farm Stóru-Reykir in Reykjahverfi, see Fig. 39 and 40.

Figure 39. *Overview of the wells in the Hveravellir System. (NEA's well registry.)*

The field has boiling hot springs and the spouting geysers Ystihver and Strokkur, Uxahver, Syðstihver and Strútur. Total natural discharge prior to drilling was 55-60 l/s of boiling water (Georgsson et al., 2005). Thirteen exploratory wells and five production wells have been drilled in the Hveravellir System, see Fig. 39 and 40. Three of those wells, HV-1, HV-10 and HV-16, (450, 652 and 1,027 m deep) yield 95 l/s of 124°C water at 1.5 bar-g wellhead pressure. Highest measured temperature is 128°C at 449 m depth in well HV-1 and at 540 m depth in well HV-17. A reservoir estimate indicates sustainable yield of 190 l/s free-flowing from wells without drastic reduction in the hot springs. (Hjartarson et al., 2002; Ólafsson, 2011).

Fig. 40 shows the main fractures/faults observed by magnetic measurements and locations of wells in the Hveravellir System.

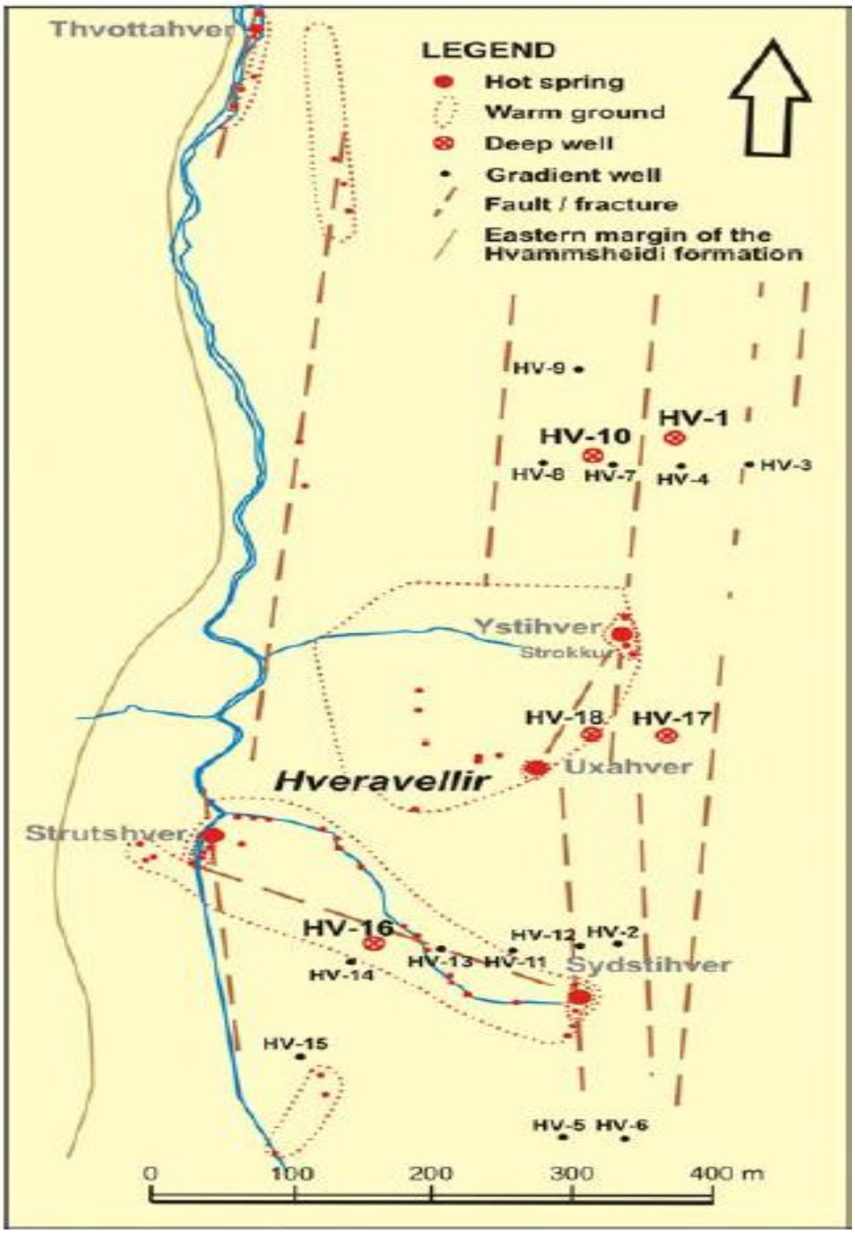

Figure 40. *Main fractures/faults observed by magnetic measurements and locations of wells in the Hveravellir System. (Georgsson et al., 2005.)*

The thermal potential above 35°C of the wells delivering 190 l/s at 124°C corresponds to 71.1 MW_{th} or an electric potential of 3.88 MW_e and a remaining thermal potential of 35.8 MW_{th}. The springs, 55 l/s of 100°C, have a thermal potential above 35°C of 15.0 MW_{th} or an electric potential of 0.51 MW_e and a remaining thermal potential of 10.4 MW_{th}.

Adding the potential of the springs to that of the wells one obtains a combined thermal potential of 86.1 MW_{th} or an electric potential of 4.39 MW_e and a remaining thermal potential of 46.2 MW_{th}.

4.11.2 The Húsavík System

Seven exploratory wells have been drilled in the Húsavík System. Well HU-1, is 1,505 m deep, found 110°C at 1,145 m depth, see Fig. 41.

Figure 41. *Overview of the wells in the Húsavík System and vicinity. (NEA's well registry.)*

The water is salty. It is estimated that the well may yield 8 l/s of about 100°C water with 70 m drawdown (Hafstað, 2014a).

The thermal output above 35°C of the well corresponds to 2.2 MW_{th} or an electric potential of 0.07 MW_e and a remaining thermal potential of 1.5 MW_{th}.

4.11.3 The Ytribakki, Bakkahlaup System in Öxarfjörður

The Ytribakki (Bakki) System is in Bakkahlaup in Öxarfjörður. One exploratory well and two production wells have been drilled in the Ytribakki System, see Fig. 42.

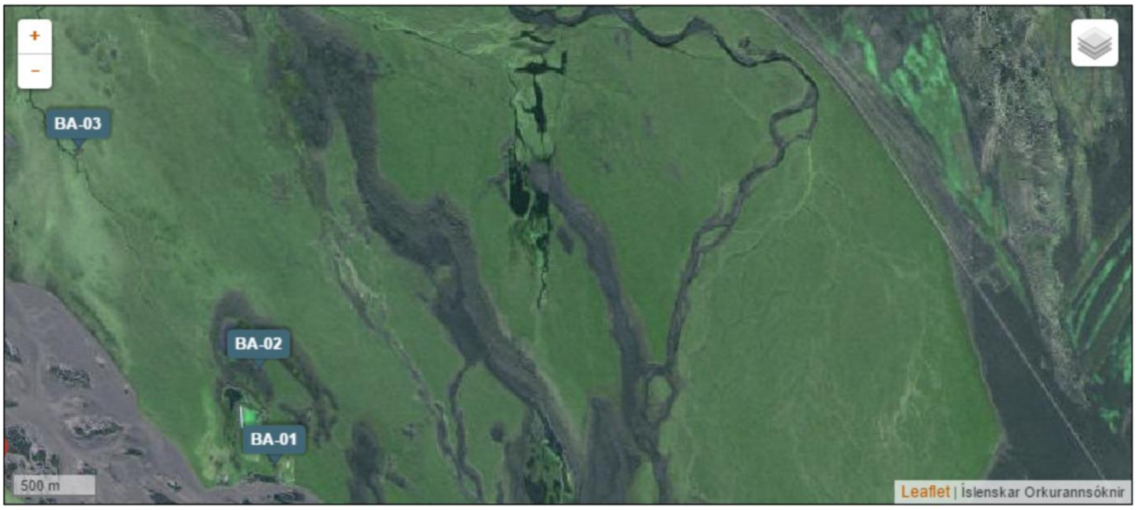

Figure 42. *Overview of the wells in the Ytribakki System. (NEA's well registry.)*

One of them, well BA-2, 1,962 m deep, found 198°C at 362 m depth and yields about 7.5 l/s of free-flowing 120°C hot water. There is an estimate that the well could be pumped of 50 l/s with 80 m drawdown. The water contains 2.500 ppm of Cl. Well BA-03 which is 704 m deep, was measured 2 days after drilling and it gave free-flowing 17 l/s of 71°C hot water. Further wells must aim at the upflow zone around well BA-02 (Axelsson and Gautason, 2010).

The thermal potential above 35°C of 50 l/s at 120°C would be 17.9 MW_{th} or the electric potential 0.93 MW_e with remaining thermal potential of 9.4 MW_{th}. It is considered likely that a flow of 50 l/s of 200°C water could be obtained from the system. The possible thermal potential above 35°C would then be 35.3 MW_{th} or the electric potential 2.78 MW_e and the remaining thermal potential 9.4 MW_{th}.

4.11.4 The Ærlækjarsel, (Skógarlón) System in Öxarfjörður

Two exploratory wells and two production wells have been drilled in the Ærlækjarsel System, see Fig. 43.

Figure 43. *Overview of the wells in the Ærlækjarsel System. (NEA's well registry.)*

Well ÆR-3 is 322 m deep and has highest measured temperature of 121°C at 203 m depth. It yields 47 l/s of 106°C free-flowing hot water (Ólafsson, 1995). Well ÆR-4 is 455 m deep with highest measured temperature of 150°C at 340 m depth. It yields over 10 l/s of 132°C hot water with a wellhead pressure of 2.6 bar-g (Ólafsson et al, 1992).

The thermal potential above 35°C of these wells is 14.0 and 4.1 MW_{th} or the electric potential 0.56 and 0.24 MW_e and the remaining thermal potential 8.9 and 1.9 MW_{th} respectively. If a flow of 50 l/s of 132°C could be obtained the possible thermal potential would be 20.4 MW_{th} or the electric potential 1.20 MW_e and the remaining thermal potential 9.4 MW_{th}.

4.12 The Hrunamannahreppur District

The Hrunamannahreppur District contains the two geothermal systems Reykjaból and Flúðir, see Fig. 44.

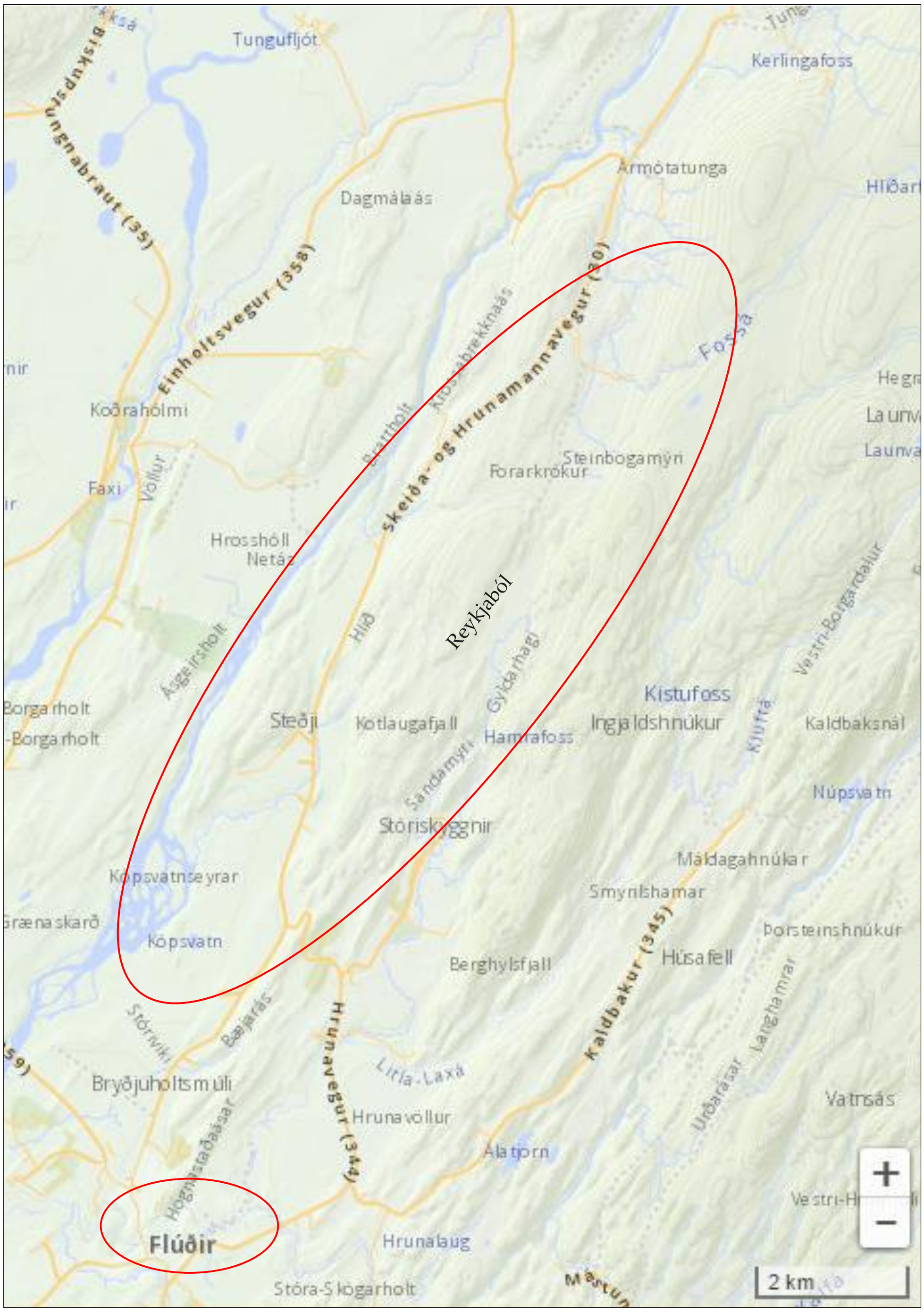

Figure 44. *Location of the geothermal systems Reykjaból and Flúðir in the Hrunamannahreppur District. (Adapted from ja.is)*

4.12.1 The Reykjaból System

Reykjaból is an extensive and powerful system with a temperature of 160-180°C in the hottest centrum somewhere between Reykjaból and Jata, possibly extending westward to Kotlaugar, see Fig. 45. Lateral outflow to southwest is thought to feed the Flúðir System. The centrum has not yet been drilled into but several wells appear to be on the periphery of the system. The wells are at Reykjaból and Þórarinsstaðir to the east, Reykjadalur and Kópsvatn to the south, Kotlaugar to the west and Jata and Haukholt to the north, see Fig. 46 (Björnsson and Sæmundsson, 2006).

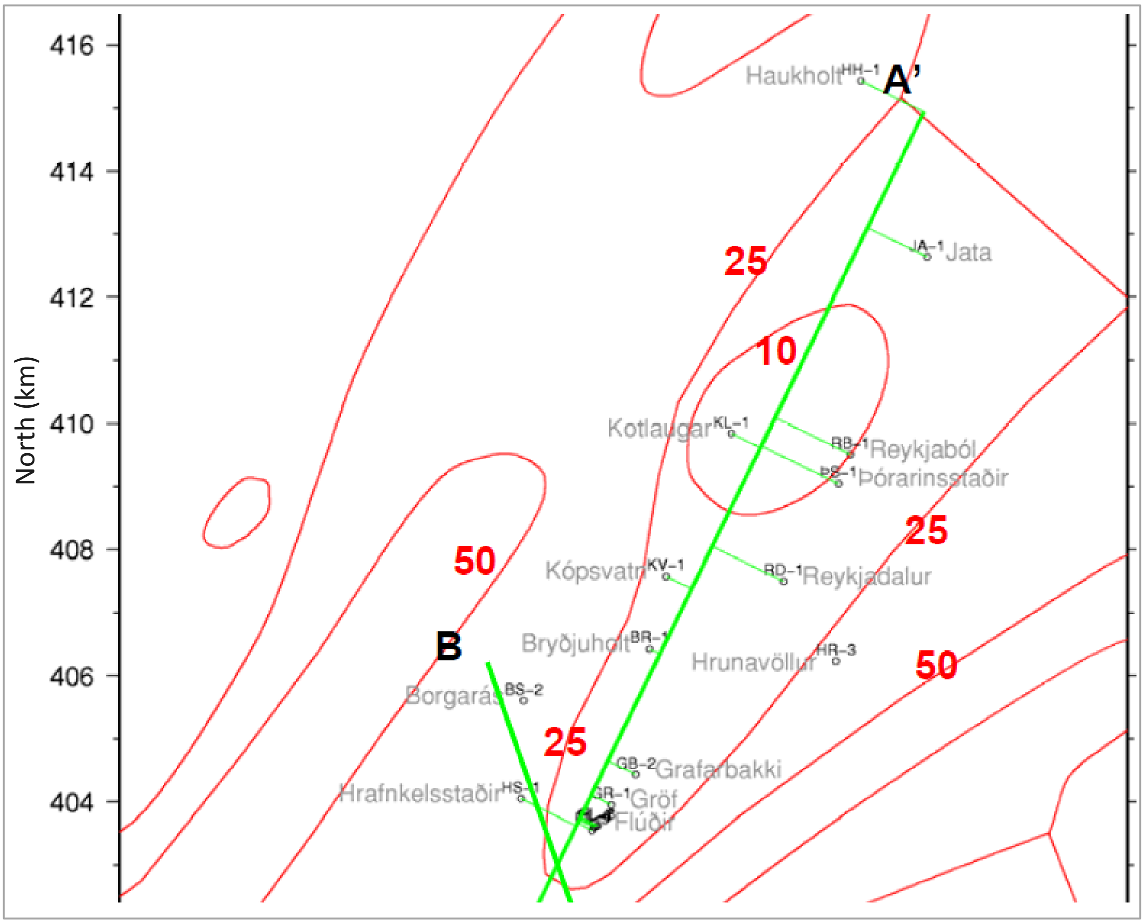

Figure 45. *Overview of the Reykjaból System and it's resistivity (Björnsson and Sæmundsson, 2006).*

4.12.1.1 The Reykjaból well field

The Reykjaból well field has a natural discharge of 2 l/s of 100°C (Torfason, 2003). One production well, RB-1, has been drilled to 820 m depth, see Fig. 46.

Figure 46. *Overview of the wells at Reykjaból, Þórarinsstaðir, Reykjadalur, Kópsvatn and Kotlaugar in the Reykjaból System. (NEA's well registry.)*

Well RB-1 has a bottom temperature of 147°C and highest measured temperature is 152°C at 400 m. There is a slight reversal in the temperature profile, indicating that the well may be southwest of the main up-flow where silica sinter indicates former natural outflow from the system. The well yields 13 kg/s at 3 bar-g wellhead pressure with enthalpy of 628 kJ/kg. The enthalpy corresponds to an inflow of 149°C water (Björnsson and Sæmundsson, 2006; Sæmundsson, 2005a; Þórhallsson et al., 1976).

Assuming a flow of 13 l/s of 149°C water the thermal potential above 35°C is 6.3 MW_{th} or the electric potential 0.4 MW_e and the remaining thermal potential 2.4 MW_{th}.

4.12.1.2 The Þórarinsstaðir well field

One production well has been drilled in the Þórarinsstaðir Field, ÞS-1, see Fig. 45 and 46. The well is 657 m deep and reaches 127°C at the bottom. The well was pumped with air for five hours, before it was measured in 1994, and it gave 5 l/s with 20 m drawdown.

Assuming a wellhead temperature of 100°C the well has a thermal potential above 35°C of 1.4 MW_{th} or an electric potential of 0.05 MW_e and a remaining thermal potential of 0.9 MW_{th}.

4.12.1.3 The Reykjadalur well field

One production well has been drilled in the Reykjadalur Field, RD-1, see Fig. 45 and 46. The well is 784 m deep and attains a temperature of 114°C at 520 m depth and a bottom temperature of 105°C. There is no free-flow from the well, but it is estimated that it will give 2-4 l/s pumped of 100°C hot water (Sæmundsson and Friðleifsson, 1980).

Assuming a flow of 3 l/s and a wellhead temperature of 100°C the well has a thermal potential above 35°C of 0.8 MW_{th} or an electric potential of 0.03 MW_e and a remaining thermal potential of 0.6 MW_{th}.

4.12.1.4 The Kópsvatn well field

Two production wells have been drilled in the Kópsvatn Field, see Fig. 46. The latter of them, KV-2, is 1,500 m deep and yields about 62 l/s of 143°C water at 1.6 bar-g wellhead pressure (Flúðir District Heating, 2015; Sæmundsson and Friðleifsson, 1980).

The thermal potential above 35°C is 28.2 MW_{th} or an electric potential of 1.78 MW_e and a remaining thermal potential of 11.7 MW_{th}.

4.12.1.5 The Kotlaugar well field

Natural discharge of the Kotlaugar field is about 3 l/s of 90-100°C. (Torfason, 2003). Two shallow production wells have been drilled in the Kotlaugar Field, see Fig. 46. The well KL-1 is 180 m deep but attains 113°C at 12 m depth. KL-2 is 66 m deep. It attains 110°C at 12 m depth but below that the temperature reverses down to 80°C.

4.12.1.6 The Jata well field

One production well, JA-1, has been drilled at Jata, see Fig. 47. It is 320 m deep reaches only 55°C at the bottom.

Figure 47. *Overview of the wells at Jata and Haukholt in the Reykjaból System. (NEA's well registry.)*

4.12.1.7 The Haukholt well field

The well field is at the farm Haukholt, between the farms Drumboddsstaðir (DR-1 and DR-2) and Foss (FS-1) in Hrunamannahreppur, see Fig. 47. One exploratory well, HH-1, has been drilled. It is 1,346 m deep, has a linear thermal gradient and attains a temperature of 162°C near the bottom (Vilmundardóttir et al., 1999; Sæmundsson and Friðleifsson, 1980). The well is either at the periphery of the Reykjaból System or the Geysir high temperature system. The well is not a producer.

The total potential of the Reykjaból system above 35°C is 36.7 MW_{th} or an electric potential of 2.27 MW_e and a remaining thermal potential of 15.6 MW_{th}.

4.12.2 The Flúðir System

The Flúðir System includes the well fields at the farms Hellisholt and Grafarbakki. One exploratory well and eleven production wells have been drilled, see Fig. 48.

Figure 48. *Overview of the wells at Hellisholt and Grafarbakki in the Flúðir System. (NEA's well registry.)*

4.12.2.1 The Hellisholt well field

Total natural discharge prior to drilling was about 28 l/s of boiling water (Pálmason et al, 1985; Torfason, 2003). Eight exploratory wells and one production well have been drilled, see Fig. 48. Four of them, (FL-4, FL-6, FL-7, and FL-8) ranging from 205-365 m in depth, yield 100-115 l/s of 104°C water at 0.6 bar-g wellhead pressure (Flúðir District Heating, 2015).

The thermal potential of these wells above 35°C with a flow of 107 l/s of 104°C is 31.4 MW_{th} or the electric potential 1.49 MW_e and the remaining thermal potential 20.2 MW_{th}.

4.12.2.2 The Grafarbakki well field

At Grafarbakki well field the natural discharge before drilling was 20 l/s of boiling water (Chaturvedi, 1969; Torfason, 2003). Two production wells have been drilled (see Fig. 48) and the latter of them, GB-2, is 187 m deep, yields about 110 l/s of 108°C water at 1.6 bar-g wellhead pressure (Björnsson, 1999).

The well has a thermal potential above 35°C of 33.7 MW_{th} or an electric potential of 1.42 MW_e and a remaining thermal potential of 20.7 MW_{th}.

Together the fields in the Flúðir System yield a thermal potential above 35°C of 65.1 MW_{th} or an electric potential of 2.91 MW_e and a remaining thermal potential of 40.9 MW_{th}.

4.13 The Holtahreppur District

4.13.1 The Laugaland System in Holt

The Laugaland System is at the farm Nefsholt. Three exploratory wells and three production wells have been drilled in the Laugaland System, see Fig. 49.

Figure 49. *Overview of the wells in the Laugaland System. (NEA's well registry.)*

The system proved to be have in the natural state a relatively high reservoir pressure of 6.5 bar-g. Two wells, LL-3 and LL-4 reached temperature over 100°C. LL-3 is 1,308 m deep and highest measured temperature is 102°C at 1,055 m but it produces only 0.5 l/s of 33°C and is not in use. LL-4 is 1,014 m deep with highest measured temperature of 106°C at the bottom and with a pump at 180 m depth, it produces nearly 20 l/s of 97°C. The production capacity with 80-110 m drawdown is about 35 l/s of 97°C water (Olsen, 2014d; Sæmundsson and Hafstað, 2015; Thorsteinson and Georgsson, 1982).

Assuming 35 l/s of 97°C water one obtains a thermal potential above 35°C of 9.1 MW_{th} or an electric potential of 0.29 MW_e and a remaining thermal potential of 6.6 MW_{th}.

4.14 The Biskupstungur District

There are four geothermal systems in the Biskupstungur District, Haukadalur, Bergstaðir, Reykholt at Stórafljót and Efri-Reykir, see Fig. 50.

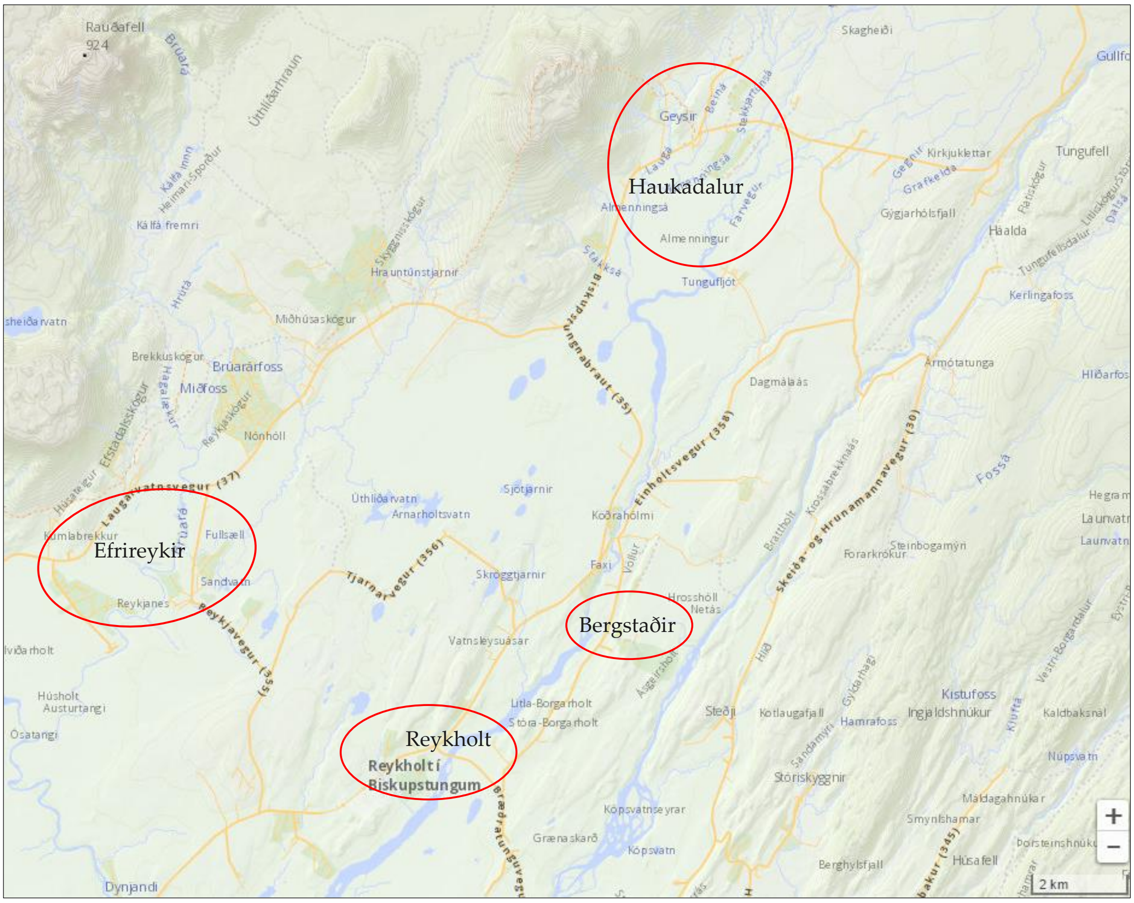

Figure 50. *Location of the geothermal systems Haukadalur, Bergstaðir, Reykholt and Efri-Reykir in the Biskupstungur District. (Adapted from ja.is*)

4.14.1 The Haukadalur System

The Geysir area in Haukadalur is classified as a high temperature system which is cooling down (Sæmundsson, 2009a). The most famous erupting spring Geysir has given name to erupting springs the world over. Another smaller geyser, called Strokkur, is a famous tourist attraction. The eruption funnel of Strokkur was blocked with rocks. These rocks were cleared with a drill rig. That operation is registered as the well “Strokkur” in the well registry. Total natural discharge of the Geysir system is 20 l/s of 98-100°C (Torfason, 2003). The fluid indicates a reservoir temperature of 250°C (Óskarsson, 2011). The Geysir system is represented by an up-flow along an earthquake fracture but the location of the main reservoir is not known. To avoid damages to the erupting geysers no deep wells are permitted.

Several wells have been drilled at nearby farms on the periphery of the Geysir system. Wells are at Gýgjarhóll, Kjarnholt, Neðridalur, and Helludalur see Fig. 51. These fields are here defined as the Haukadalur medium enthalpy system.

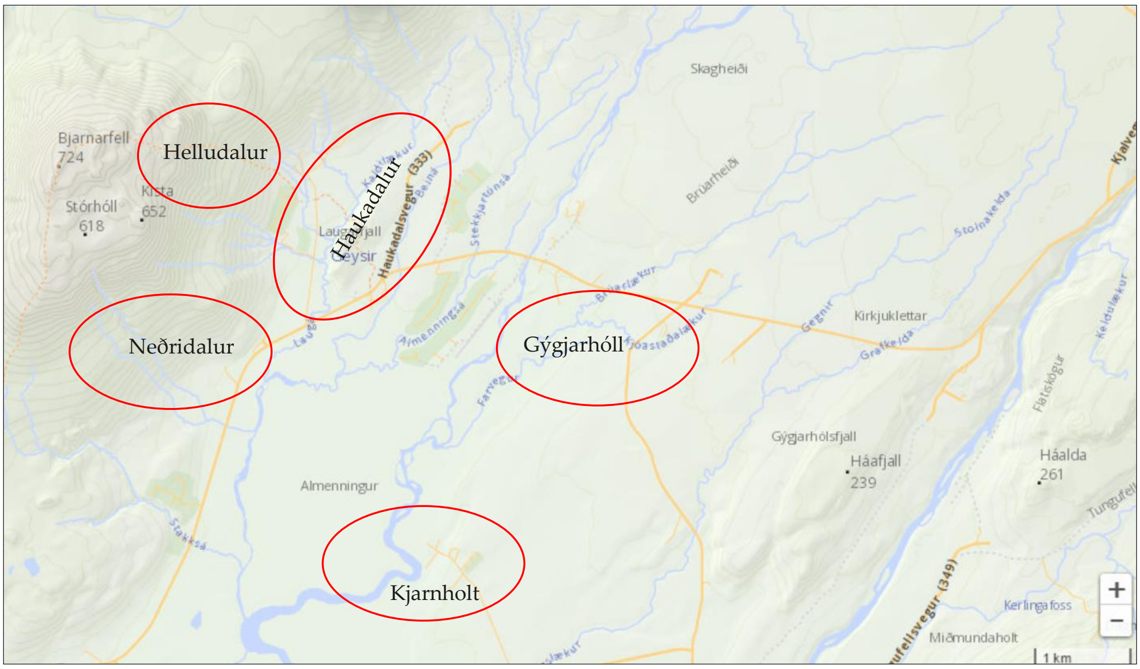

Figure 51. *Location of the well fields Gýgjarhóll, Kjarnholt, Neðridalur and Helludalur on the periphery of the Geysir high temperature system. (Adapted from ja.is)*

The high downhole temperatures found in these fields reflect the boundaries of the Geysir high temperature system. Fig. 52 shows the locations of some hot springs and geysers in the Geysir area and location of wells at Kjarnholt (KH), Neðridalur (ND) and Helludalur (HD).

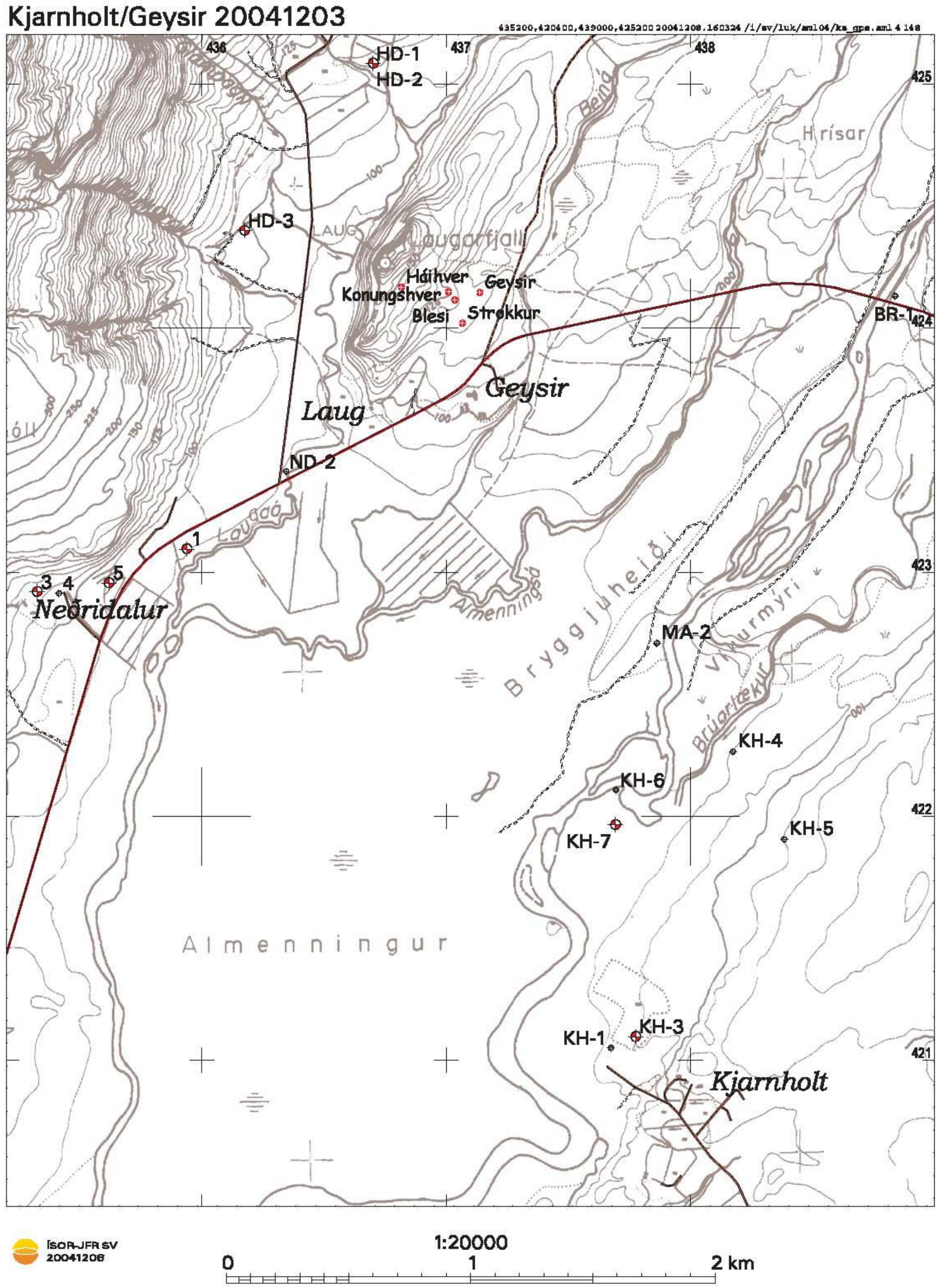

Figure 52. *Locations of hot springs and geysers in the Geysir area and location of wells near Kjarnholt, Neðridalur and Helludalur (Axelsson et al., 2006a).*

4.14.1.1 The Gýgjarhóll well field

The location of the Gýgjarhóll field is shown in Fig. 51. The field lies in the farmland of Gýgjarhóll and Gýgjarhólskot. (Wells GK-2 and GK-3 in this field are registered under the name Haukadalur in the well registry.

Figure 53. *Overview of the wells at Gýgjarhóll, Kjarnholt and Neðridalur on the periphery of the Geysir high temperature system. (NEA's well registry.)*

Well, GK-3 is 1,002 m deep with highest measured temperature of 170°C at 1,000 m depth and about 7 l/s of 74°C can be pumped out of it with 61 m drawdown (Sæmundsson, 2009a).

4.14.1.2 The Kjarnholt well field

The Kjarnholt well field is between Neðridalur and Gýgjarhóll, see Fig. 51. Five exploratory wells and two production wells have been drilled, see Fig. 52. One of them, KH-7 is 1,343 m deep with highest measured temperatures of 187°C at 864 m depth and yields 3 l/s of 90°C with a pump at 150 m depth (Axelsson et al., 2006b).

4.14.1.3 The Neðridalur well field

The Neðridalur well field is just west of the farm Haukadalur, see Fig. 51 and Fig. 52. Five exploratory wells and one production well have been drilled in the field, see Fig. 53. Two of them, ND-1 and ND-3, are 850 m and 600 m deep and have highest measured temperatures of 172°C and 119°C near their bottoms. The wells can produce about 10 l/s of 65-70°C water (Axelsson et al., 2006a; Axelsson et al., 2006b; Þórhallsson et al., 2004).

The high temperatures in the fields Gýgjarhóll, Kjarnholt and Neðri-Dalur reflect boundaries of the Geysir high temperature reservoir.

4.14.1.4 The Helludalur well field

The Helludalur well field is just north of Neðridalur, see Fig. 51. Three production wells have been drilled, see Fig. 54.

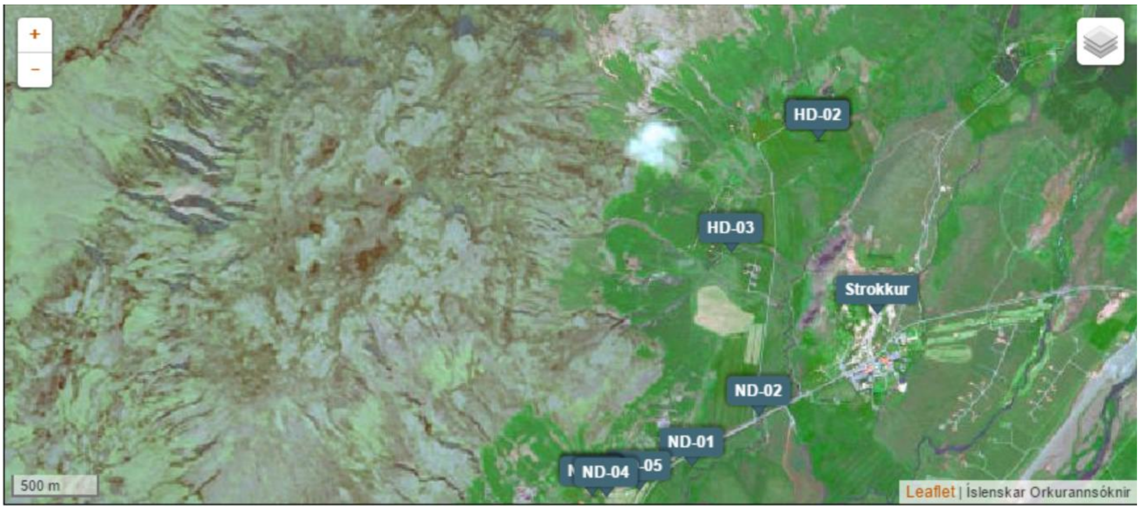

Figure 54. *Overview of the wells in Helludalur Field. (NEA's well registry.)*

Two of them, HD-2 and HD-3 are 360 m and 481 m deep with highest measured temperatures of 116°C at 364 m depth and 104°C at 380 m. Well HD-2 gave 1.8 l/s of 54°C hot water and well HD-03 gave 2.0 l/s (Þórhallsson et al., 2004).

4.14.2 The Bergstaðir System in Eystritunga

The Bergstaðir System is at the farm Bergstaðir, between the rivers Tungufljót and Hvítá in Eystritunga, see Fig. 50. Two exploratory wells and one production well have been drilled, see Fig. 55.

Figure 55. *Overview of the wells in the Bergstaðir System. (NEA's well registry.)*

The production well, BS-3 is 972 m deep with highest measured temperatures of 105°C at 932 m depth and it gives 6 l/s of 96°C (Sæmundsson, pers. comm., November 24, 2015).

The thermal potential above 35°C is 1.5 MW_{th}.

4.14.3 The Reykholt System at Stórafljót

The Reykholt System includes the geothermal fields Stórafljót, Reykjavellir and Laugarás, see Fig 56.

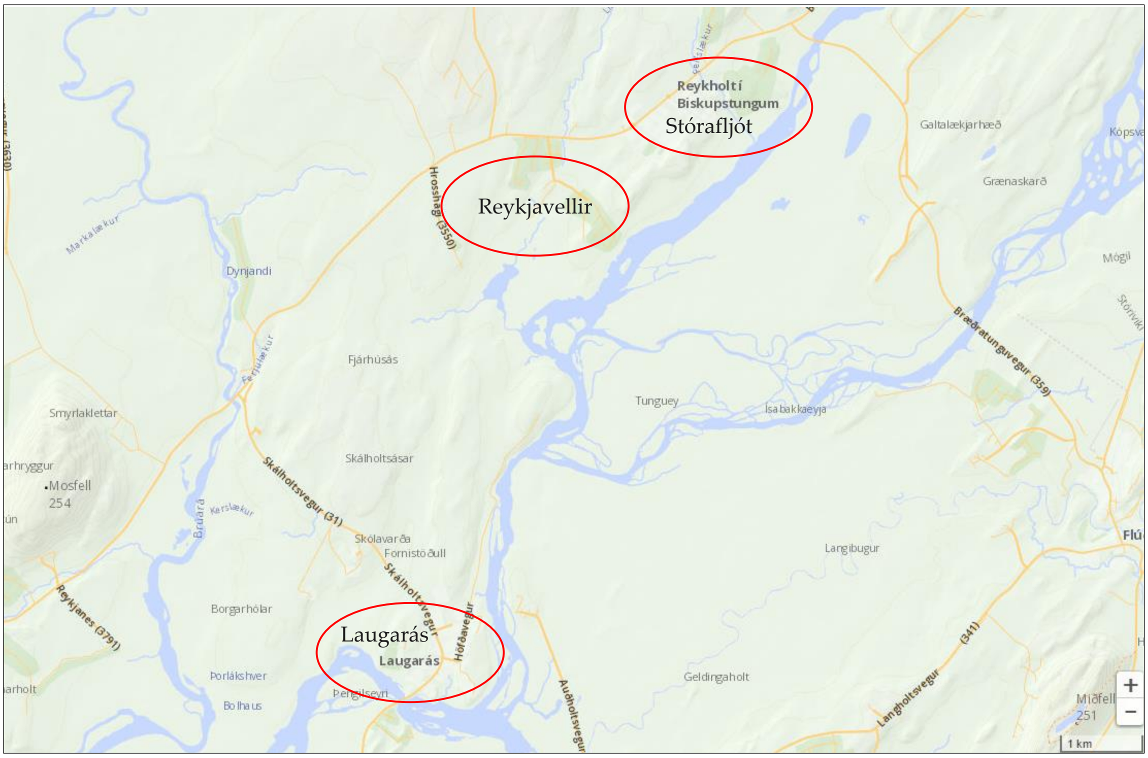

Figure 56. *Location of the well fields Stórafljót, Reykjavellir and Laugarás in the Reykholt System. (Adapted from ja.is)*

4.14.3.1 The Stórafljót Field

Two exploratory wells and two production wells have been drilled at the Stórafljót field, see Fig. 57.

Figure 57. *Overview of the wells at the Stórafljót well field. (NEA's well registry.)*

The production wells, RH-1 and RH-4, 756 and 1,146 m deep, yield 13 and 15 l/s of 128°C water. The hot spring Reykholtshver delivers 14 l/s of 98°C water (Ólafsson, 2010; Þorbjörnsson and Guðmundsson, 2010).

The wells have a flow of 28 l/s at 128°C with a thermal potential above 35°C of 11.0 MW_{th} or the electric potential 0.62 MW_e and a remaining thermal potential of 5.3 MW_{th}. The hot spring delivers additional 3.7 MW_{th}.

4.14.3.2 The Reykjavellir well field

The Reykjavellir field is about 3 km southwest of Reykholt, see Fig. 56. Seven 31-117 m deep production wells were drilled in the years 1946-1949 and have no coordinates in the NEA well registry. The deepest well, RV-1, has measured temperature of 103°C at 55 m depth while drilling.

4.14.3.3 The Laugarás hot spring field

The field is some 7 km southwest of Reykholt, see Fig. 56. No wells have been drilled in Laugarás but there are large hot springs. Hildarhver delivers 55 l/s of 96°C water, Þvottahver 14.5 l/s of 90°C (Ólafsson, 1988). Total flow of hot springs is 90 l/s of 90–99°C water. (Pálmason et al., 1985). The field is here taken as an outflow of the Reykholt System.

Assuming a total flow of 90 l/s at 95°C one obtains a thermal potential above 35°C of 22.6 MW_{th} or an electric potential of 0.69 MW_e and a remaining thermal potential of 17.0 MW_{th}.

The total thermal potential of the Reykholt-Stórafljót System is estimated 37.3 MW_{th} or an electric potential of 1.31 MW_e and a remaining thermal potential of 22.3 MW_{th}.

4.14.4 The Efri-Reykir System

The Efri-Reykir System consists of the three geothermal areas Efri-Reykir, Syðri-Reykir and Böðmóðsstaðir, see Fig. 58.

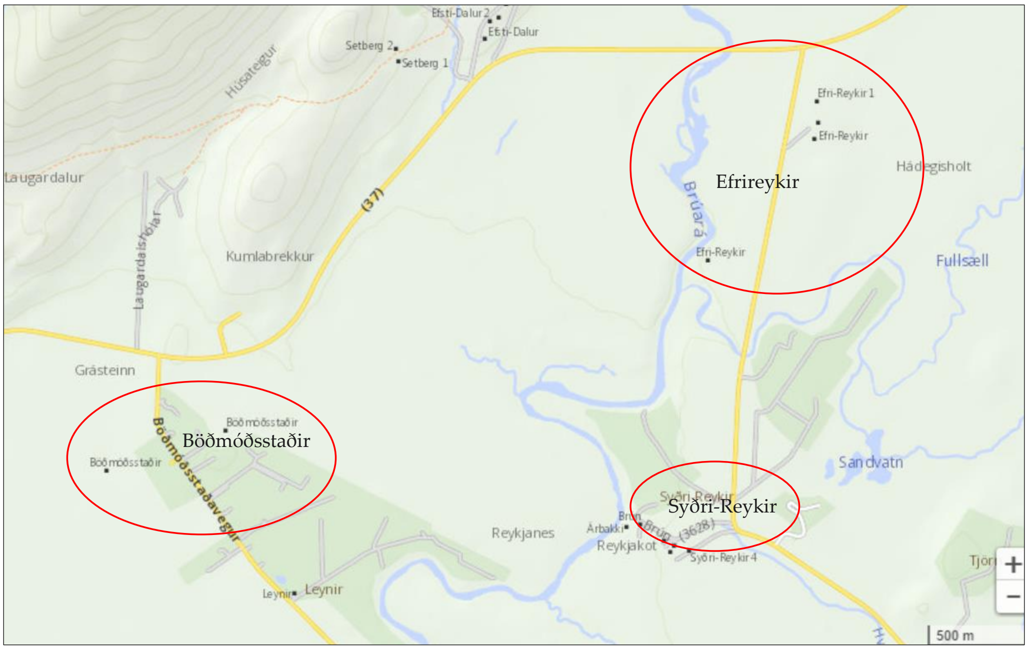

Figure 58. *Location of the well fields Efri-Reykir, Syðri-Reykir and Böðmóðsstaðir in the Efri-Reykir System. (Adapted from ja.is)*

4.14.4.1 The Efri-Reykir well field

The Efri-Reykir well field is on the eastern bank of the river Brúará, see Fig. 58. Twenty exploratory wells and two deep production wells showed high geothermal gradient but failed in finding upflow zone of the geothermal system, see Fig. 59.

Figure 59. *Overview of the wells at the Efri-Reykir Field. (NEA's well registry.)*

Finally, well ER-23, which is 722 m deep, struck a good aquifer near bottom. At 1.4 bar-g wellhead pressure the well yields 50 kg/s of 145 °C and 64 kg/s at 1 bar-g. (Björnsson and Steingrímsson, 1996; Olsen, 2014c).

The thermal output above 35°C for a flow of 64 kg/s at 145°C is 29.7 MW_{th} or an electric potential 1.89 MW_e and a remaining thermal potential of 12.1 MW_{th}.

4.14.4.2 The Syðri-Reykir well field

The Syðri-Reykir geothermal field is 2 km south of the Efri-Reykir Field, see Fig. 58. Only two temperature gradient wells have been drilled to 12 and 22 m and but nothing more was done because of reverse temperature, see Fig. 60.

Figure 60. *Overview of the wells that have coordinates at the fields Syðri-Reykir and Böðmóðsstaðir. (NEA's well registry.)*

The total flow of the hot springs is 40 l/s of 90-100°C hot water (Pálmason et al, 1985).

The thermal potential above 35°C of the 95°C hot springs is 10.1 MW_{th} or an electric potential of 0.31 MW_e and a remaining thermal potential of 7.5 MW_{th}.

4.14.4.3 The Böðmóðsstaðir well field

The Böðmóðsstaðir well field is in Laugardalur on the western bank of the river Brúará. The field is 4 km southwest of the Efri-Reykir well field, see Fig. 58. Natural discharge of the area is 1.5 l/s of 30-100°C hot water (Torfason, 2003). Geochemical analyses indicate a reservoir temperature above 120°C. Seventeen exploratory wells and four production wells have been drilled in the Böðmóðsstaðir Field to the depths of 480-1,096 m deep but only one of them has coordinates in the NEA registry, see Fig. 60. Maximum measured temperatures were between 116-130°C. One of them delivered 6 l/s of boiling water (Sæmundsson, 1991). The newest well gives some 3 liters (Sæmundsson, pers. comm., November 24, 2015).

Assuming a flow of 9 l/s of 116°C water the thermal potential above 35°C would be 3.1 MW_{th} or the electric potential 0.15 MW_e and a remaining thermal potential of 1.7 MW_{th}.

The total potential of the Efri-Reykir system adds up to 42.9 MW_{th} or an electric potential of 2.35 MW_e and a remaining thermal potential of 21.3 MW_{th}.

4.15 The Laugardalur District

4.15.1 The Laugarvatn System

One shallow exploratory well has been drilled to 32 m in the Laugarvatn System but it has no coordinates in the NEA registry. Fig. 61 shows the lake Laugarvatn and its surroundings.

Figure 61. *Overview of the Laugarvatn Lake in the Laugardalur District. The major hot springs area at the farms Laugarvatn the Útey. (Adapted from ja.is)*

The largest hot spring at Laugarvatn delivers 30 l/s of 100°C water. Silica geothermometers indicate a reservoir temperature of about 200°C. Hot springs at Útey deliver 17 l/s of 76–98°C water (Georgsson et al., 1988). They may belong to the Laugarvatn system.

Assuming a total of 40 l/s at 100°C one obtains a thermal potential above 35°C of 10.9 MW_{th} or an electric potential of 0.37 MW_{e} and a remaining thermal potential of 7.5 MW_{th}.

The system may be able to produce 40 l/s at 200°C. That would correspond to a possible thermal potential above 35°C of 28.2 MW_{th} or an electric potential of 2.22 MW_{e} and a remaining thermal potential of 7.5 MW_{th}.

4.16 The Grímsnes District

There are three geothermal systems in the Grímsnes District, Eyvík, Klausturhólar and Öndverðarnes, see Fig. 62.

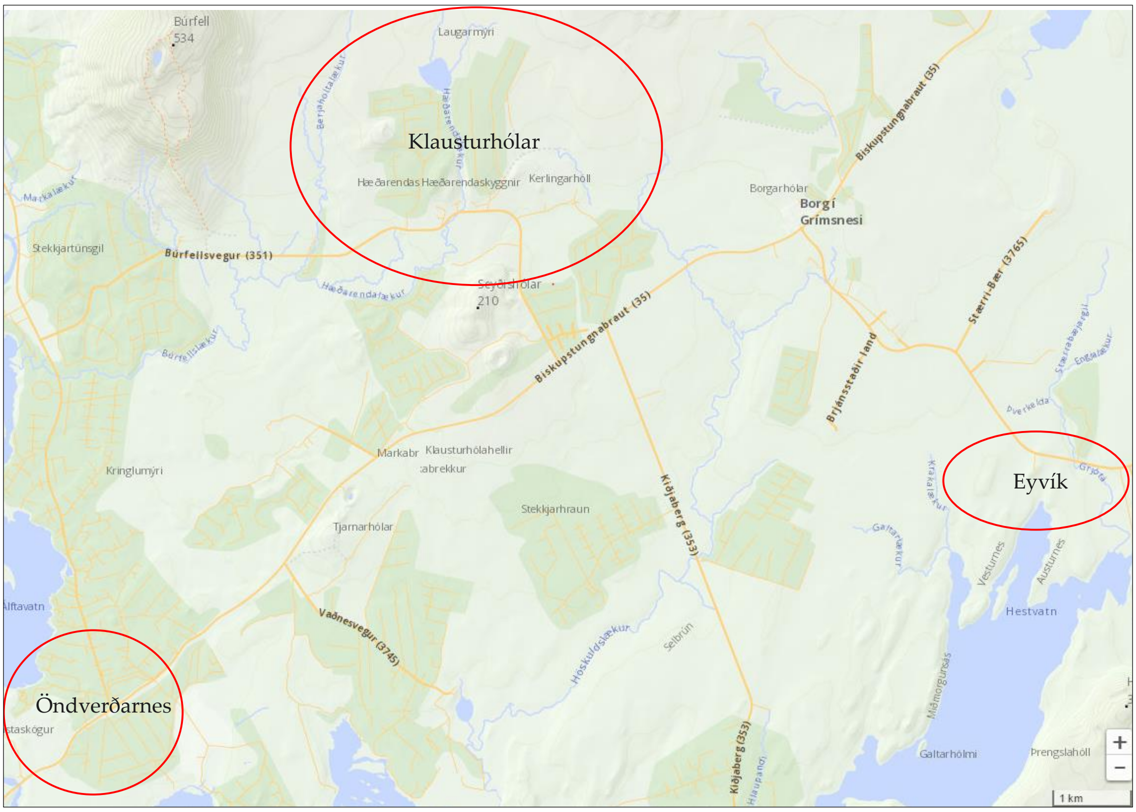

Figure 62. *Location of the geothermal systems Eyvík, Klausturhólar and Öndverðarnes in the Grímsnes District. (Adapted from ja.is)*

4.16.1 The Eyvík System

The Eyvík System is just north of the lake Hestvatn, see Fig 62. Seven exploratory wells and two production wells have been drilled in the Eyvík System, see Fig. 63.

Figure 63. *Overview of the wells in the Eyvík System. (NEA's well registry.)*

Well EV-1 is 650 m deep, 138°C near bottom. It yields 17.5 l/s of 68°C water. Well EV-8 is 642 m deep has maximum measured temperature of 123°C at 456 m. It yields 2.7 l/s of 130°C with 2.8 bar-g well head pressure and 6 l/s fully open. Maximum temperature in the system may be near 160°C. The Eyvík System is not as rich in Calcium (Ca) as the Klausturhólar System. Calcite scaling is therefore unlikely to happen but there is some risk of silica deposits from the geothermal water (Sæmundsson, 1995).

The thermal potential above 35°C assuming 6 l/s of 130°C water would be 2.4 MW_{th} or an electric potential 0.14 MW_e and a remaining thermal potential of 1.1 MW_{th}.

4.16.2 The Klausturhólar System

The Klausturhólar System is a former high temperature system that has now a reservoir temperature of 180-200°C. It extends from Seyðishólar in the South north to Hrólfshólar, west beyond Hæðarendi and east beyond Hallkelshólar. The water is very rich in Ca, the rocks are dense and the permeability lies in numerous young fractures. The wells tend to be blocked by calcite scaling (Sæmundsson and Þórhallsson, 2002). There are three well fields in the Klausturhólar System, Hallkelshólar, Klausturhólar and Hæðarendi, see Fig. 64.

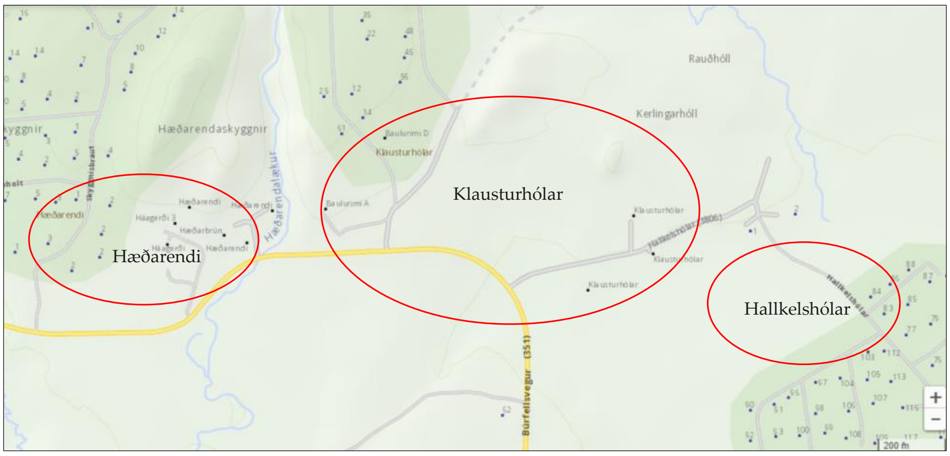

Figure 64. *Location of the well fields Hallkelshólar, Klausturhólar and Hæðarendi in the Klausturhólar System. (Adapted from ja.is)*

4.16.2.1 The Hallkelshólar well field

Twenty-six exploratory wells have been drilled at Hallkelshólar. One production well, HH-2, is 825 m deep, see Fig 65.

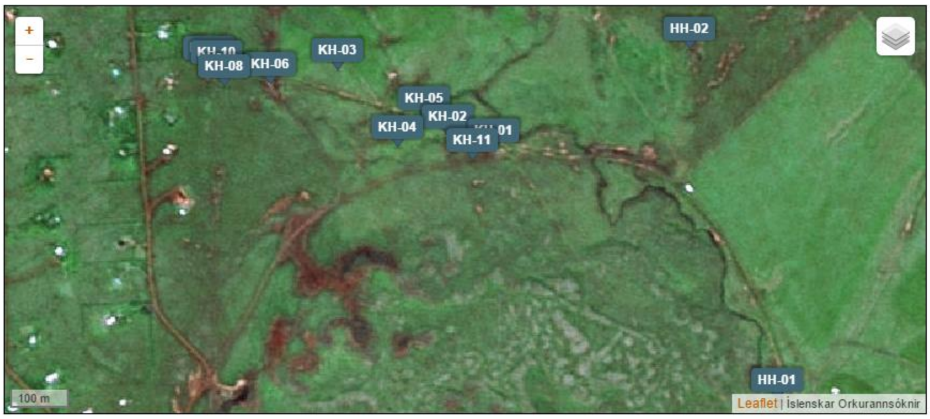

Figure 65. *Overview of the wells at the fields Hallkelshólar and Klausturhólar. (NEA's well registry.)*

A feeder at the bottom appears to be more than 150°C hot. (Sæmundsson and Þórhallsson, 1988). The well is not a producer.

4.16.2.2 The Klausturhólar well field

Two exploratory wells and ten production wells have been drilled at Klausturhólar, see Fig. 65. The first nine wells range from 184-1,096 m in depth. They found temperatures between 164 and 187°C at 600-1,100 m depth. Flow from the wells is 0-8 kg/s (Gunnarsdóttir et al., 2010; Sæmundsson, 1995; Sæmundsson, and Þórhallsson, 2002; Sæmundsson et al., 2007). Well KH-11 was drilled to 2,505 m depth and found a maximum temperature of 222°C at 2,400 m. It yields 13 kg/s at 190°C (Gunnarsdóttir et al., 2010).

Assuming a flow of 13 l/s of 190°C the thermal potential above 35°C would be 8.6 MW_{th} or an electric potential 0.68 MW_e and a remaining thermal potential of 2.4 MW_{th}.

4.16.2.3 The Hæðarendi well field

Six exploratory wells and three production wells have been drilled at Hæðarendi, see Fig. 66.

Figure 66. *Overview of the wells at Hæðarendi Field. (NEA's well registry.)*

The production wells, HE-2, HE-7 and HE-9 which are 546, 901 and 778 m deep, respectively, found 160-170°C hot water at 500-900 m. Well HE-2 yields 20 kg/s fully open (Hafstað and Hjartarson, 2003). Well HE-9 delivers 40 kg/s of 161°C at a wellhead pressure of 12.6 bar-g (Bjarnason, 2009).

Assuming 60 l/s of 161°C one obtains a thermal potential above 35°C of 32.0 MW_{th} or an electric potential of 2.25 MW_e and a remaining thermal potential of 11.3 MW_{th}.

The total potential of the Klausturhólar System adds up to 40.6 MW_{th} or an electric potential of 2.93 MW_e and a remaining thermal potential of 13.7 MW_{th}.

4.16.3 The Öndverðarnes System

The Öndverðarnes System lies between the rivers Hvítá and Sogið, see Fig. 62. Twenty-two exploratory wells and six production wells have been drilled, see Fig 67.

Figure 67. *Overview of the wells in the Öndverðarnes System. (NEA's well registry.)*

Well ÖN-30 is 960 m deep and attains 122°C near bottom. It yields about 30 kg/s in a free-flow of 111°C hot water and much more could probably be pumped (Axelsson et al., 2007).

Assuming a flow of 50 l/s of 111°C water one obtains a thermal potential above 35°C of 15.9 MW_{th} or an electric potential of 0.71 MW_e and a remaining thermal potential of 9.4 MW_{th}.

4.17 The Flói District

4.17.1 The Þorleifskot/Laugardælir System

The Þorleifskot/Laugardælir System consists of the two geothermal fields, Ósabotnar and Þorleifskot/Laugardælir, see Fig. 68.

Figure 68. *Location of the well fields Ósabotnar and Þorleifskot/Laugardælir in the Þorleifskot-/Laugardælir System. (Adapted from ja.is)*

4.17.1.1 The Ósabotnar well field

The Ósabotnar field is at the farm Stóra-Ármót about 4 km NNE of the town Selfoss, on the eastern bank of the river Ölfusá, see Fig. 68. There have been drilled five exploratory wells and three production wells, see Fig. 69.

Figure 69. *Overview of the wells at Ósabotnar. Also shown are wells at Laugarbakki on the western bank of the river (NEA's well registry.).*

Well ÓS-1 is 804 m deep. It yields 10-40 l/s of 80°C water (Axelsson and Ólafsson, 2006). Well ÓS-2 is 1,723 m deep and attains a temperature of 104°C at 1,720 depth. It yields 50-60 l/s of 92°C water with 80-110 m drawdown. (Snæbjörnsdóttir, 2009). Well ÓS-03 is 1,500 m deep. It yields 100 l/s of 83°C with 65 m drawdown (Hafstað and Gunnarsdóttir, 2014). An assessment of the performance of the area after four years of production history indicated that the geothermal system in Ósabotnar could give up to 100 l/s average production (Axelsson and Ólafsson, 2006).

A flow of 100 l/s of 92°C hot water would yield a thermal potential above 35°C of 23.9 MW_{th} or an electric potential of 0.69 MW_e and a remaining thermal potential of 18.8 MW_{th}.

4.17.1.2 The Þorleifskot/Laugardælir well field

The Þorleifskot/Laugardælir Field lies on the eastern bank of Ölfusá about 1 km north-east of the town Selfoss, see Fig. 68. There have been drilled twenty-seven exploratory wells and eight production wells, see Fig. 70.

Figure 70. *Overview of the wells at Þorleifskot/Laugardælir and wells in the neighborhood. (NEA's well registry.)*

Wells ÞK-9 to ÞK-17 range between 1,110 and 2,381 m in depth. They reach a temperature of 140-150°C at 1,600-1,900 m depth. The wells yield some 100-150 l/s of 70-120°C water but downward leakage of colder water limits the drawdown possible (Axelsson, 1989; Axelsson et al., 1999; Hafstað and Gunnarsdóttir, 2012; Haraldsdóttir, 2013; Harðardóttir and Ólafsson, 2013; Harðardóttir, 2014; Ólafsson and Axelsson, 2007; Tómasson et al., 1986). Cooling by downward leakage increased after the major earthquakes 2000 and 2008. Well ÞK-17 was cased down to 550 m to prevent cold inflow but did not hit on good feeders below 1,100 m depth. The well may yield 8 l/s with 150 m drawdown.

Assuming a flow of 100 l/s of 120°C water yields a thermal potential above 35°C of 35.7 MW_{th} or an electric potential of 1.85 MW_e and a remaining thermal potential of 18.8 MW_{th}.

The total potential of the Þorleifskot-Laugardælir system adds up to 59.6 MW_{th} or an electric potential of 2.54 MW_e and a remaining thermal potential of 37.6 MW_{th}.

4.18 The Ölfus District

The Ölfus District contains the three geothermal systems Árbær, Hveragerði and Bakki, see Fig. 71.

Figure 71. *Location of the geothermal systems Árbær, Hveragerði and Bakki in the Ölfus District. (Adapted from ja.is.)*

4.18.1 The Árbær System

Eight exploration wells and five production wells have been drilled in the Árbær System, see Fig. 72.

Figure 72. *Overview of the wells in the Árbær System. (NEA's well registry.)*

The deepest five of them range from 465 to 956 m in depth. Well AB-2 found 137°C at 930 m depth. (Sæmundsson and Flóvenz, 2007). The deeper reservoir of that field may be part of the Þorleifskot System. The wells give 5 l/s of free-flowing 60°C hot water and could give 15 l/s if pumped (Axelsson et al., 1994).

4.18.2 The Hveragerði System

The Hveragerði System is considered to be an outflow from the Grændalur high temperature system north of Hveragerði (Iceland GeoSurvey, 2015). The Hveragerði system defined here consists of the geothermal area Hverasvæðið in the town Hveragerði and wells in the vicinity at Reykir, Fagrihvammur, NLFÍ, Ölfusborgir, Gljúfurárholt, Vellir, Öxnalækur, Kröggólfsstaðir and Núpar, See Fig. 73.

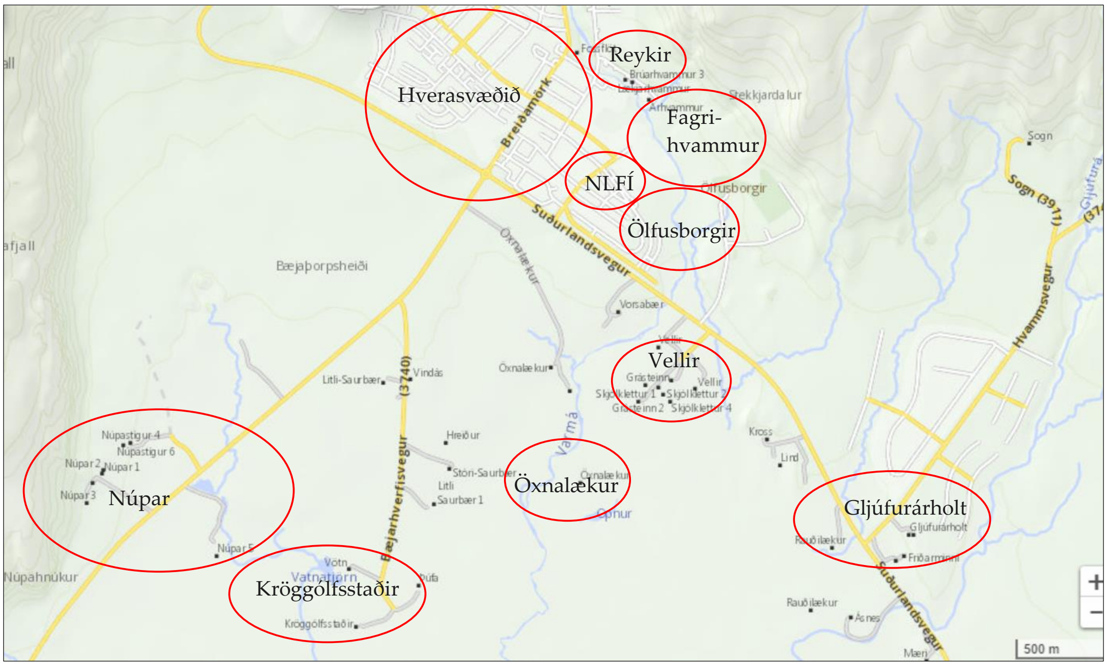

Figure 73. *Location of the well fields Hverasvæðið, Reykir, Fagrihvammur, NLFÍ, Ölfusborgir, Gljúfurárholt, Vellir, Öxnalækur, Kröggólfsstaðir and Núpar in the Hveragerði System. (Adapted from ja.is.)*

4.18.2.1 The Hverasvæðið well field

Eleven production wells have been drilled in Hverasvæðið. Four of them are in use, range 245-373 m in depth, and have found temperatures of 160-180°C, see Fig. 74.

Figure 74. *Overview of the main wells at Hverasvæðið and other neighboring well fields (NEA's well registry.)*

The wells yield some 80 kg/s at 5 bar-g and 150°C (Björnsson et al., 2000; Jónasson, 2008; Þórhallsson, 2008; Þórhallsson et al., 1999). The reservoir potential of Hverasvæðið is definitely much greater but no references are available.

A flow of 80 l/s of 150°C yields a thermal potential above 35°C of 38.8 MW_{th} or an electric potential of 2.58 MW_e and a remaining thermal potential of 15.1 MW_{th}.

4.18.2.2 The Reykir well field

We define the Reykir well field to consist of wells drilled at Reykir (RE), Fagrihvammur (FH), NLFÍ and Ölfusborgir (ASÍ), see Fig. 73 and Fig. 74. In the well registry six production wells are filed at Reykir. Wells RE-4, RE-5 and RE-6 are 140, 80 and 510 m deep and have highest measured temperatures of 174, 163 and 180°C. Wells RE-4 and RE-5 were productive (Sigurðsson, 1995) but they were damaged by an earthquake in 2008.

Four production wells have been drilled at Fagrihvammur, see Fig. 74. They found 150-163°C above 500 m depth but were not productive.

Two wells have been drilled at NLFÍ for steam, see Fig. 74. The wells, NLFÍ-1 and NLFÍ-2 are 883 and 190 m deep and have maximum measured temperatures of 170°C at 474 and 170 m depth, respectively. The wells yield about 44 l/s and 4 l/s of 150°C hot water at 4.9 bar-g wellhead pressure (Tryggvason and Þórhallsson, 2007; Þorbjörnsson and Kristinsson, 2010).

Assuming a flow of 48 l/s of 150°C water leads to a thermal potential above 35°C of 23.3 MW_{th} or an electric potential of 1.55 MW_e and a remaining thermal potential of 9.0 MW_{th}.

Two production wells have been drilled in the Ölfusborgir Field, see Fig. 74. Well ASÍ-2 is 487 m deep. It found 181°C at 484 m depth and delivers 5 l/s of 160°C water. The well has a thermal potential above 35°C of 2.6 MW_{th} or an electric potential of 0.19 MW_e and a remaining thermal potential of 0.9 MW_{th}.

The total potential of the Reykir well field adds up to 25.9 MW_{th} or an electric potential of 1.74 MW_e and a remaining thermal potential of 9.9 MW_{th}.

4.18.2.3 The Gljúfurárholt well field

Six exploratory wells and three production wells have been drilled at Gljúfurárholt, see Fig. 75.

Figure 75. *Overview of the wells at Gljúfurárholt. (NEA's well registry.)*

Wells GH-3 and GH-4 are 328 and 1,014 m deep. GH-3 was not in use in 2013 but before GH-4 was drilled it gave 15 l/s of 107°C hot water. GH-4 found 121°C at 850 m depth. It yields about 40 l/s of 115°C water pumped from 69 m depth (Hafstað and Danielsen, 2006; Olsen, 2014b). A flow of 9 l/s of 117°C water was stable with 2 m drawdown (Sæmundsson and Þórhallsson, 2007).

Assuming a flow of 40 l/s of 115°C water one obtains a thermal potential above 35°C of 13.4 MW_{th} or an electric potential of 0.65 MW_e and a remaining thermal potential of 7.5 MW_{th}.

4.18.2.4 The Vellir well field

Two exploratory wells and one production well have been drilled at Vellir, see Fig. 76.

Figure 76. *Overview of the wells at Vellir, Öxnalækur and Núpar in the Hveragerði System. (NEA's well registry.)*

Well VE-2 is 588 m deep. It found 144°C at 400 m depth, gave blowing 3 kg/s but was damaged after an earthquake in 2008. In 2009 it gave only 1 l/s of 65°C hot water with a pump (Sæmundsson, 2009b). The well was redrilled in 2011 but the outcome is not yet known.

4.18.2.5 The Öxnalækur well field

Six exploratory wells and one production well have been drilled at Öxnalækur, see Fig. 76. Well ÖL-1 is 967 m deep. It found 157°C at 900 m. The well yields 1.5 kg/s of 160°C with 2.35 bar-g wellhead pressure (Sæmundsson, 2009b).

That gives a thermal output above 35°C of 0.8 MW_{th} or an electric potential of 0.06 MW_e and a remaining thermal potential of 0.3 MW_{th}.

4.18.2.6 The Kröggólfsstaðir well field

Two production wells have been drilled at Kröggólfsstaðir, see Fig. 76. Well KS-1 is 939 m deep and found 166°C at 288 m depth. The well yields 10 kg/s of 140°C hot water (Axelsson et al., 1994).

That gives a thermal output of 4.4 MW_{th} or an electric potential of 0.27 MW_e and a remaining thermal potential of 1.9 MW_{th}.

4.18.2.7 The Núpar well field

Eleven exploratory wells and five production wells have been drilled at Núpar, see Fig. 76. Well NU-8 is 1,180 m deep and found 140°C at 665 m. NU-10 is 414 m deep and delivers 10-20 kg/s of boiling water (National Energy Authority, 1987).

Assuming 15 kg/s at 140°C gives a thermal output of 6.6 MW_{th} or an electric potential of 0.41 MW_e and a remaining thermal potential of 2.8 MW_{th}.

The total potential of the Hveragerði system is at least 89.9 MW_{th} or an electric potential of 5.71 MW_e and a remaining thermal potential of 37.6 MW_{th}.

4.18.3 The Bakki System

The Bakki System consists of the geothermal fields at Þóroddsstaðir, Eystribakki, Bakki, Hjallakrókur, Vindheimar (Hlíðardalsskóli) and Litlaland, see Fig. 77. (Sigurðsson et al., 2007).

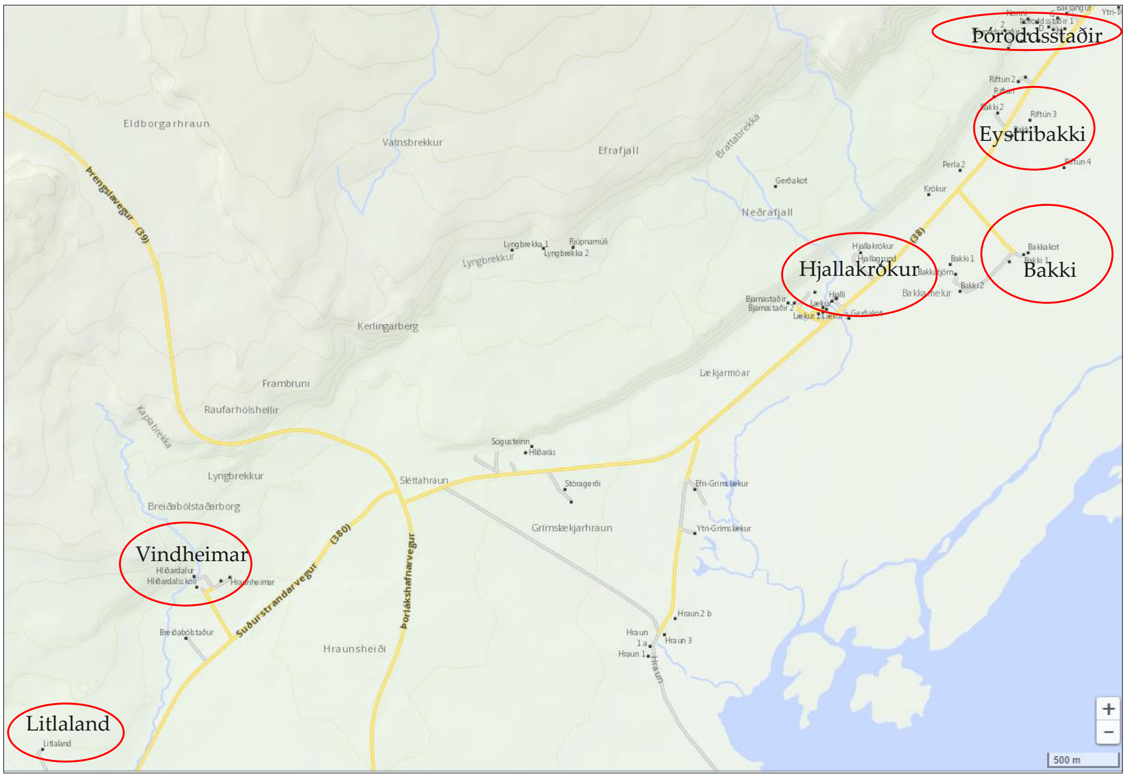

Figure 77. *Location of the well fields at Þóroddsstaðir, Eystribakki, Bakki, Hjallakrókur, Vindheimar (Hlíðardalsskóli) and Litlaland in the Bakki System. (Adapted from ja.is.)*

4.18.3.1 The Þóroddsstaðir well field

One exploratory well and one production well have been drilled at the Þóroddsstaðir Field, see Fig. 78.

Figure 78. *Overview of the wells at Þóroddsstaðir-, Eystribakki-, Bakki- and Hjallakrókur in the Bakki System. (NEA's well registry.)*

Well ÞS-1 was drilled to 1,734 m depth. It found 123°C at 838 m. The well gave 13 l/s of 117°C with 130 m drawdown, but in long term test it gave 10 l/s with 30-40 drawdown (Sæmundsson and Georgsson, 1983). The well is not productive since 2010 (Olsen, 2014e).

4.18.3.2 The Eystribakki well field

One production well, EB-1, has been drilled at Eystribakki. It is 1,045 m deep, see Fig. 78. It found 122°C at 592 m and delivers 2.9 kg/s of 119°C water (Olsen, 2014e).

That gives a thermal output of 1.0 MW_{th} or an electric potential of 0.05 MW_e and a remaining thermal potential of 0.5 MW_{th}.

4.18.3.3 The Bakki well field

One production well, BA-1, has been drilled at Bakki and it is 856 m deep, see Fig. 78. It found 138°C at 242 m. It delivered a free-flow of 11.6 kg/s of 113°C in 2012 (Olsen, 2013).

That gives a thermal output of 3.8 MW_{th} or an electric potential of 0.18 MW_e and a remaining thermal potential of 2.2 MW_{th}.

4.18.3.4 The Hjallakrókur well field

One production well, HJ-1, has been drilled at Hjallakrókur, it is 605 m deep, see Fig. 78. It found 117°C at 450 m. The well delivered 18.8 kg/s of 104°C water with 7,35 m drawdown in 2012 (Olsen, 2013).

That gives a thermal output of 5.4 MW_{th} or an electric potential of 0.21 MW_e and a remaining thermal potential of 3.5 MW_{th}.

4.18.3.5 The Vindheimar well field (Hlíðardalsskóli)

One exploratory well (HS-1) and one production well (HS-2) have been drilled at Vindheimar, see Fig. 79.

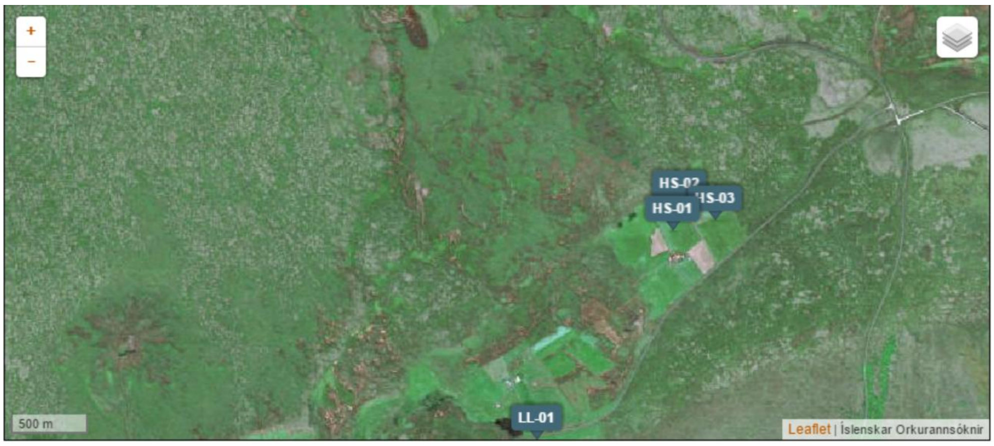

Figure 79. *Overview of the wells at the fields at Vindheimar and Litlaland in the Bakki System. (NEA's well registry.)*

Well HS-2 at Vindheimar is 1,230 m deep. It found 171°C at 1,122 m. It delivers about 5 kg/s erupting of 115-120°C (Tómasson, 1986b).

Assuming 5 l/s at 120°C yields a thermal output of 1.8 MW_{th} or an electric potential of 0.09 MW_e and a remaining thermal potential of 0.9 MW_{th}.

4.18.3.6 The Litlaland well field

One production well, LL-1, has been drilled at Litlaland, it is 2,183 m deep, see Fig. 79. It found 190°C at 2,065 m. It delivered only 1 kg/s (Kristmannsdóttir et al., 1976).

Adding up the potential of the fields within the Bakki System one obtains a thermal potential of at least 12.0 MW_{th} or an electric potential of 0.5 MW_e and a remaining thermal potential of 7.2 MW_{th}.

5 Presentation and Analysis of the Results

5.1 Criteria for selection of data

To obtain an overview of medium enthalpy geothermal systems in Iceland we have selected well fields where a maximum temperature above 100°C has been found in wells. We have also considered several hot spring areas where SiO_2 concentration in springs indicates a formation temperature above 100°C although no wells have yet been drilled. High temperature fields with 200°C above 1,000 m depth are not included but some of the medium enthalpy systems are former high temperature systems with a formation temperature near or above 200°C. The fields we have selected are 81 and grouped in 37 medium enthalpy systems. The total number of exploratory and production wells drilled in these systems is 655. Of those we count 289 as production wells. Many of the wells did not find hot water or high formation temperatures. We have selected 193 production wells that found maximum temperatures above 90°C for further analysis. They are listed in the Table of Appendix 1. Data on shallow wells are incomplete, especially for wells drilled with percussion drill rigs before 1950. To investigate whether that affects the results we made the analysis also for the subgroup of the 172 of these 193 production wells that were deeper than 300 m. We define production wells successful for electric generation if they yield discharge at temperatures above 95°C. As the effluent water from the electric generation is assumed to be 80°C we define production wells with a discharge temperature above 80°C successful for space heating. The wells are located in the 37 medium enthalpy systems analysed in this report. Production wells yielding water above 80°C are abundant in low enthalpy systems throughout the country but they are a subject of a separate report.

5.2 All wells

5.2.1 Drilled depth

The 655 exploratory and production wells were drilled in the medium enthalpy systems in the years 1928-2014. Before 1950 most of wells were drilled with percussion drill rigs but after that rotary drill rigs took over. Most of the wells were drilled vertically. The depth is known in 639 wells. It ranges from 3–3,085 meters, average 335.5 m. Fig. 80 shows the drilled depth of these wells through years of drilling.

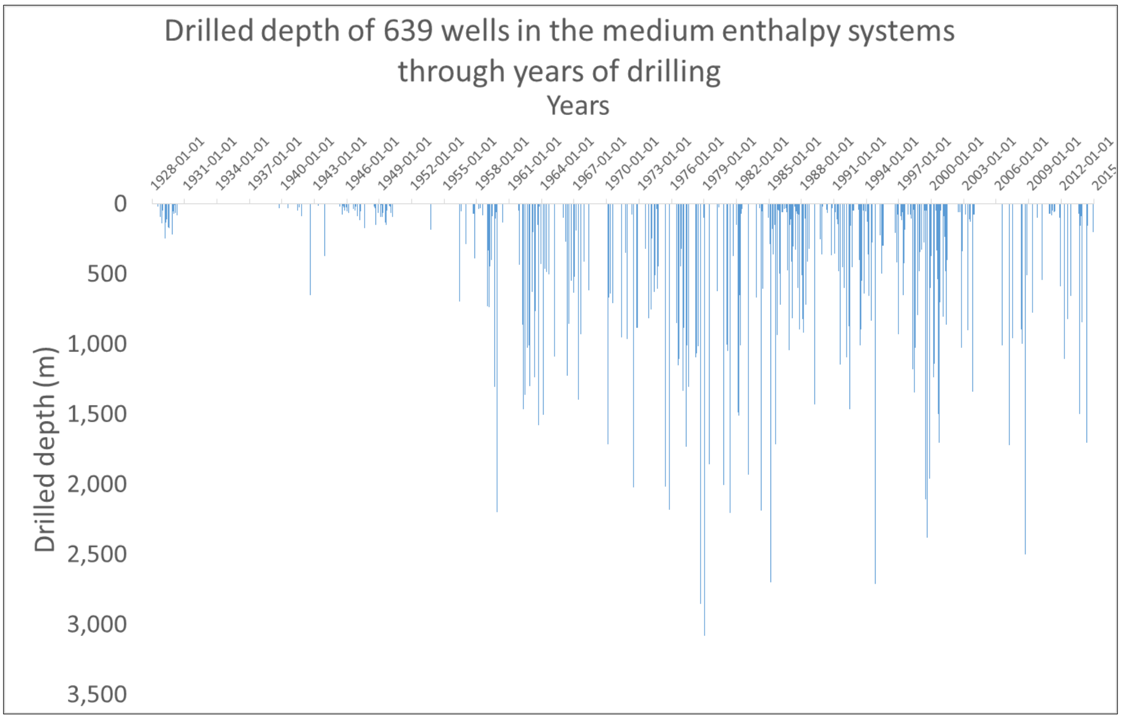

Figure 80. *Drilled depth of 639 exploration and production wells in the medium enthalpy systems through years of drilling.*

5.3 Production wells

5.3.1 Drilled depth

Out of the drilled 655 wells 289 are filed as production wells. Drilled depth is known in 283 of those wells. They range between 10–3,085 m in depth, average 650.4 m. Fig. 81 shows the distribution of drilled depth of these production wells. About 39% of the wells are shallower than 300 m, 45% are between 300 and 1,200 m in depth and 16% are deeper than 1,200 m. Fourteen wells are deeper than 2,000 meters, the deepest one 3,085 m.

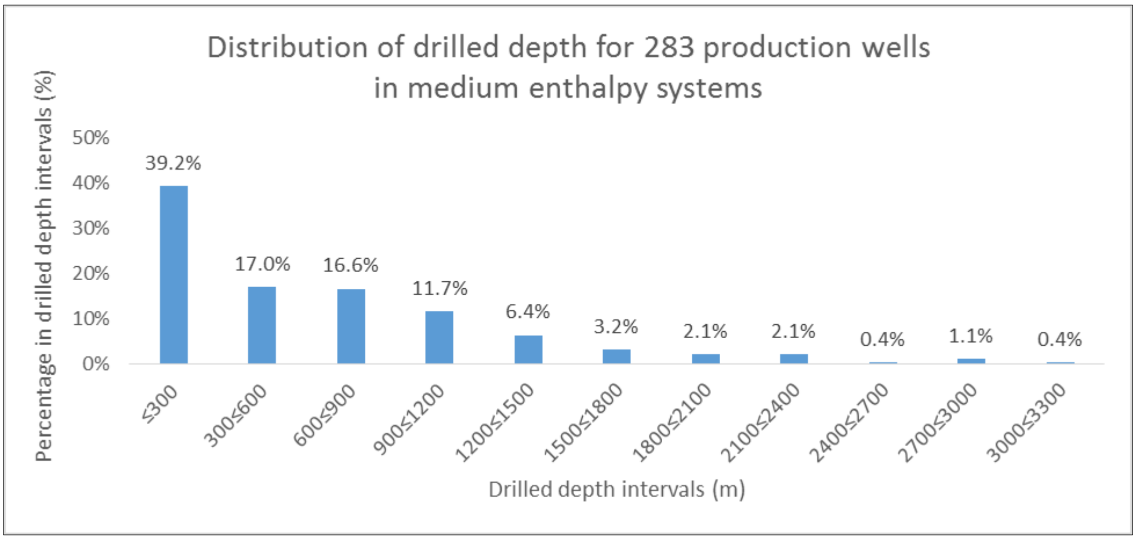

Figure 81. *Distribution of drilled depth for 283 production wells in medium enthalpy systems.*

As data on wells shallower than 300 m are incomplete the distribution for wells deeper than 300 m is regarded more reliable. Fig. 82 shows that distribution for 172 production wells that are deeper than 300 m.

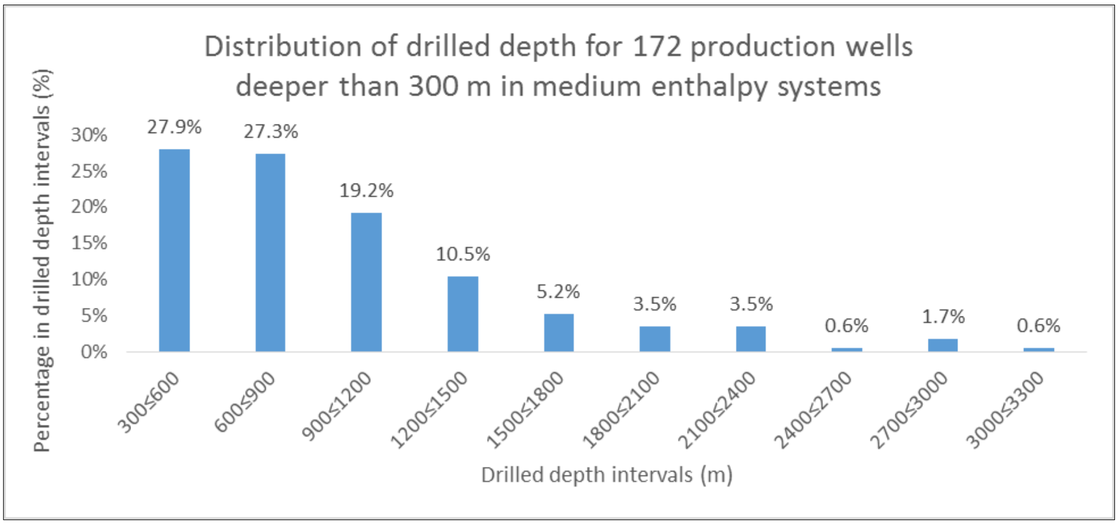

Figure 82. *Distribution of drilled depth for 172 production wells deeper than 300 m in medium enthalpy systems.*

Fig. 83 shows the drilled depth through years of drilling from 1928 to 2014 for the 274 of the 289 production wells for which date of completion is available.

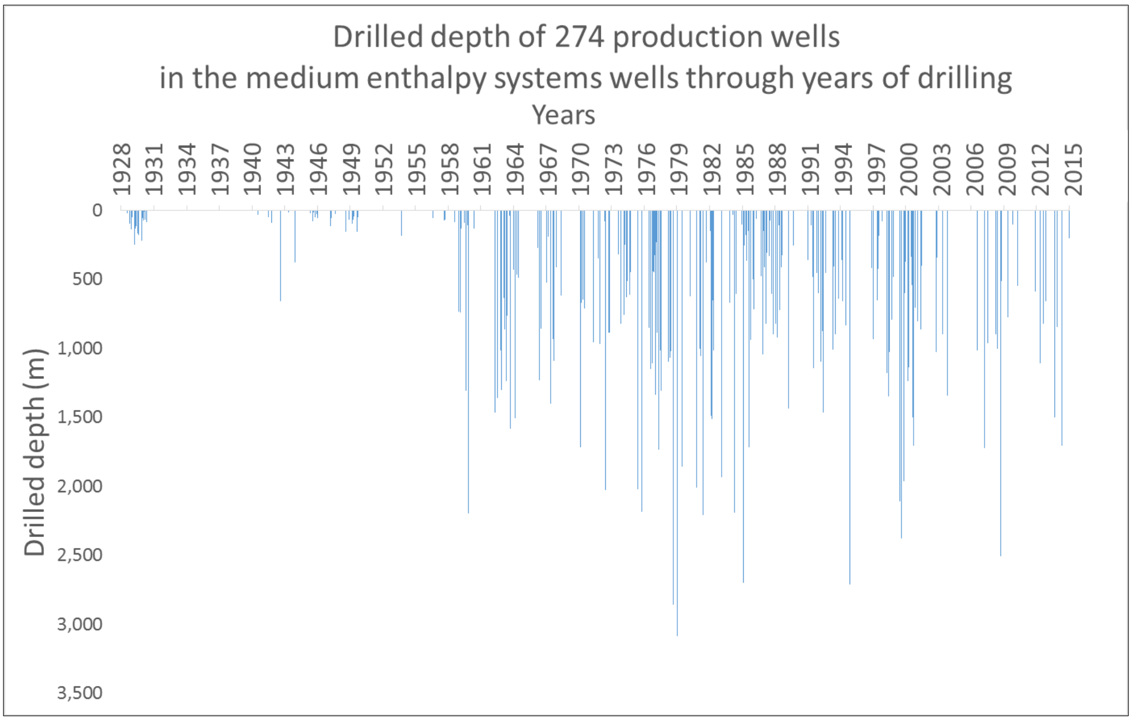

Figure 83. *Drilled depth of 274 production wells in the medium enthalpy systems through years of drilling.*

Fig. 84 shows a closer view for 223 production wells drilled in the period 1958–2014.

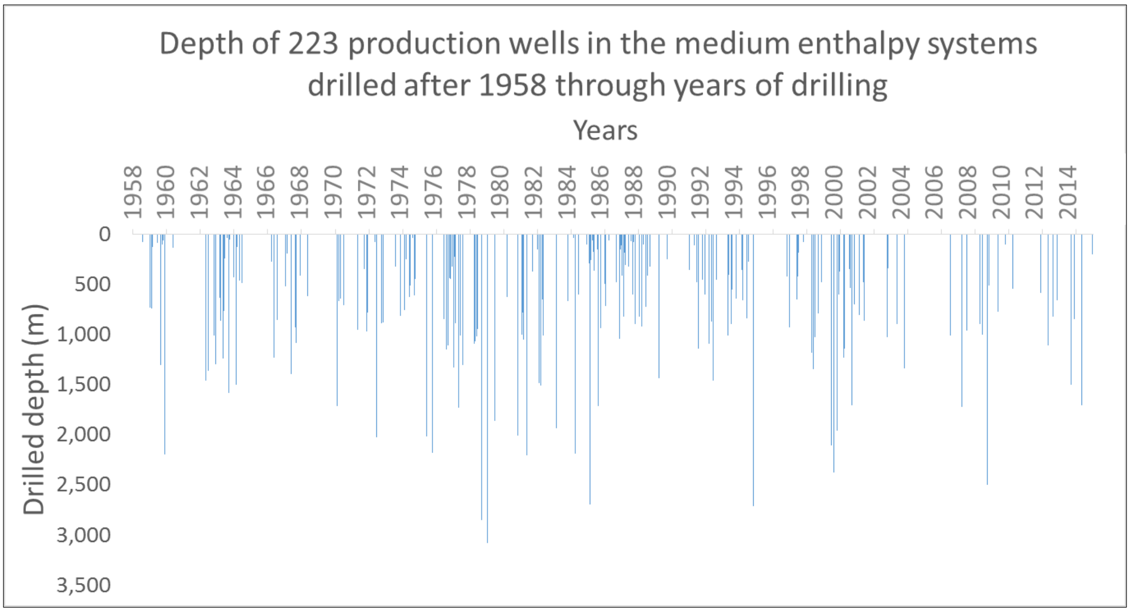

Figure 84. *Depth of 223 production wells in the medium enthalpy systems drilled after 1958.*

5.3.2 Productivity and flow

Of the 289 drilled production wells 173 were found to be productive after drilling, 54 were not productive but records are not available for 62 wells, see Fig. 85.

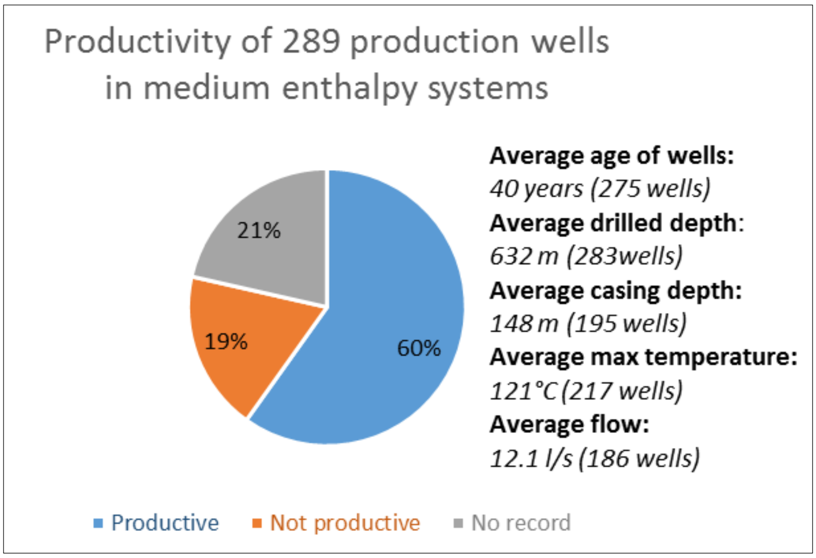

Figure 85. *Productivity of 289 production wells in medium enthalpy systems.*

Reasons for not productive wells are primarily low formation temperatures and poor permeability. Drilling problems are rarely the cause of a dry well. Of the 173 productive wells 108, or 62% are still in use, see Fig. 86.

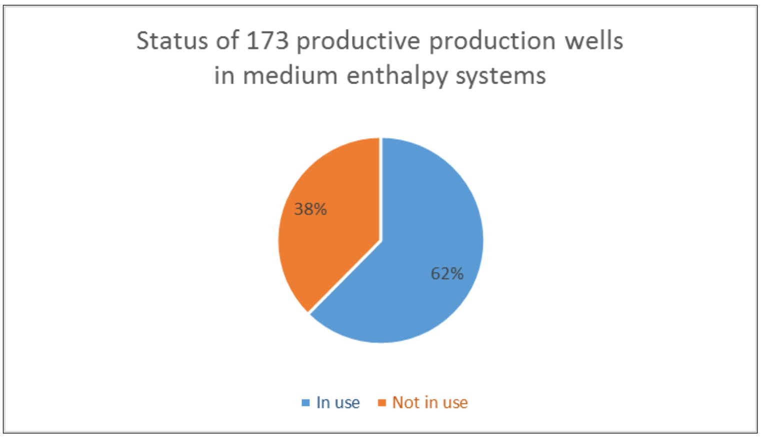

Figure 86. *Status of 173 productive wells in medium enthalpy systems.*

Information on flow is available for 132 of the productive wells. The flow of those wells averages 17.3 l/s but 12.1 l/s for the total of 132 productive wells with known flow and 54 not productive wells.

5.4 Production wells with measured temperatures above 90°C

Many of the production wells did not find hot water or high formation temperatures. Of the total of 289 drilled production wells, 193 wells found measured temperature above 90°C and were considered of interest for further analysis from the viewpoint of medium enthalpy utilization.

5.4.1 Drilled depth

Drilled depth is known in all the 193 wells. They range between 52–3,085 m in depth, average 861 m. Information on production casing depth is available in 176 wells. It averages 151 m.

Fig. 87 shows the frequency distribution of drilled depth of those 193 wells in 300 m depth intervals.

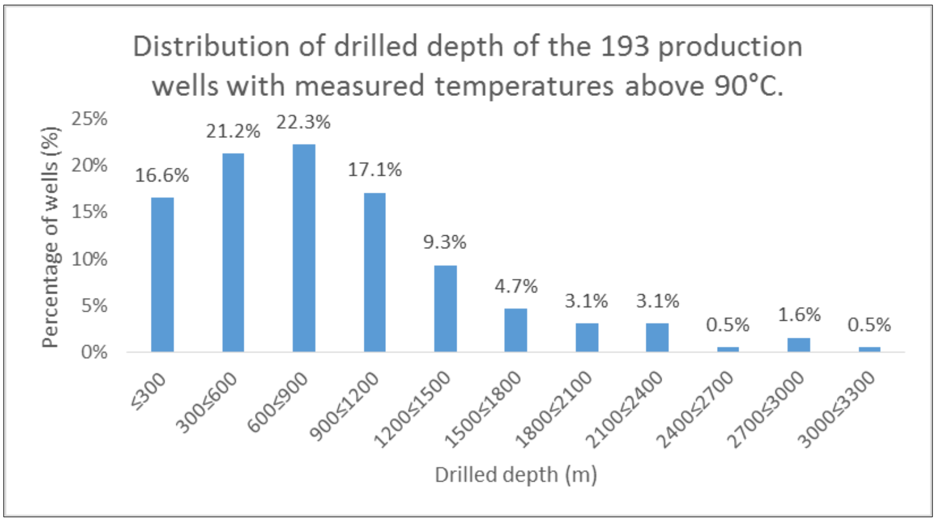

Figure 87. *Distribution of drilled depth of the 193 production wells with measured temperatures above 90°C*

About 17% are shallower than 300 m, 61% are between 300 and 1,200 m and 22% deeper than 1,200 m. Fourteen wells are deeper than 2,000 meters, the deepest one 3,085 m.

Information on date of drilling is available for all these wells. The average age in 2016 is 33 years.

Fig. 88 shows the drilled depth of these wells during the period 1942 to 2014.

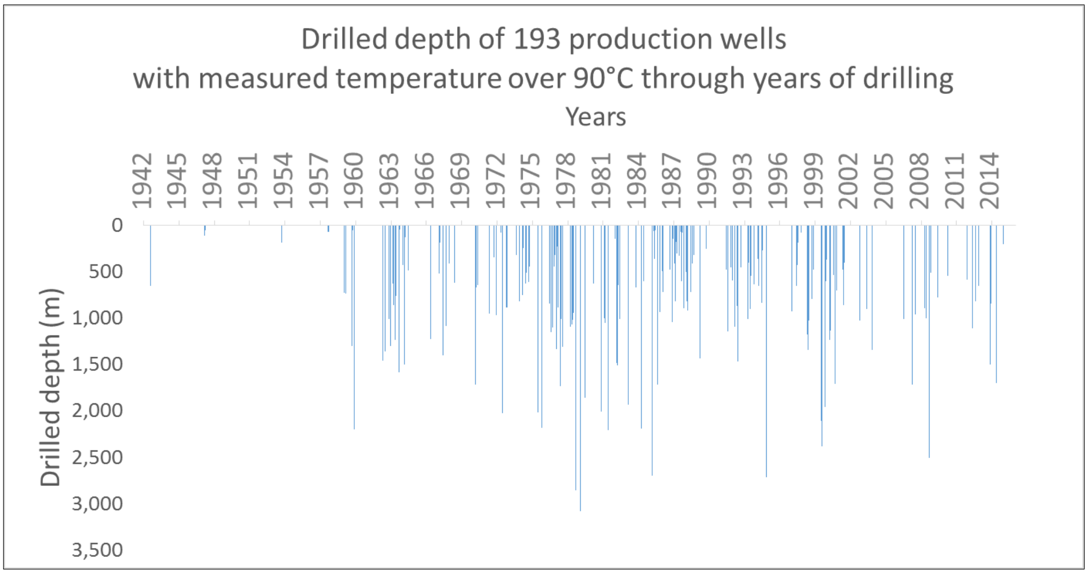

Figure 88. *Depth of 193 production wells with measured temperatures above 90°C, plotted against time when drilling/deepening finished.*

5.4.2 Maximum temperature

Data on maximum temperatures in the 193 production wells are available in 189 of the wells. Average maximum temperatures is 126°C.

Fig. 89 shows the distribution of maximum temperatures in intervals of 10°C.

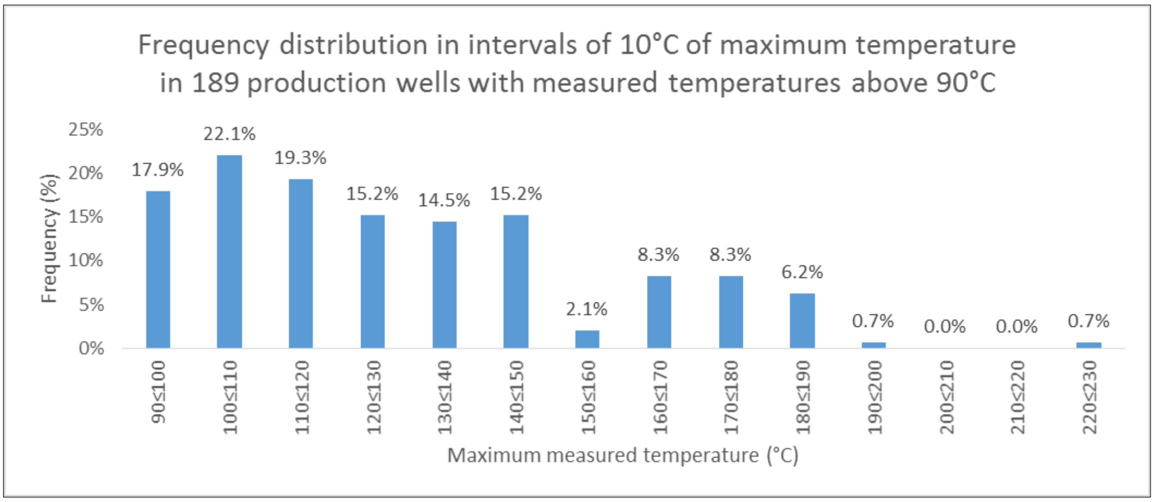

Figure 89. *Frequency distribution in intervals of 10°C of maximum temperatures in production wells with measured temperature above 90°C.*

5.4.3 Productivity and flow

Of the 193 production wells in this group 149 wells or 77% were productive after drilling, 44 or 23% not productive, see Fig. 90.

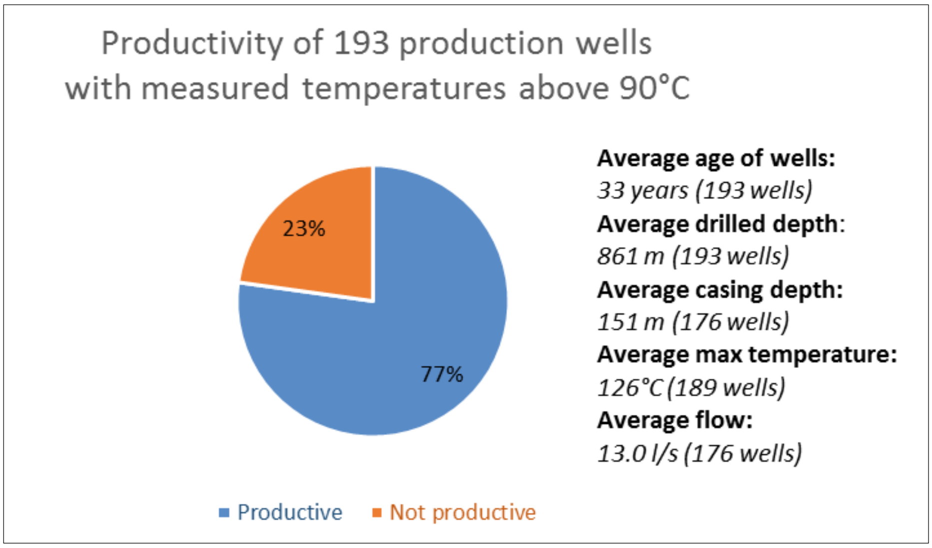

Figure 90. *Productivity of 193 production wells with measured temperatures above 90°C.*

In use today are 104 or 70% of the 149 productive wells, see Fig. 91.

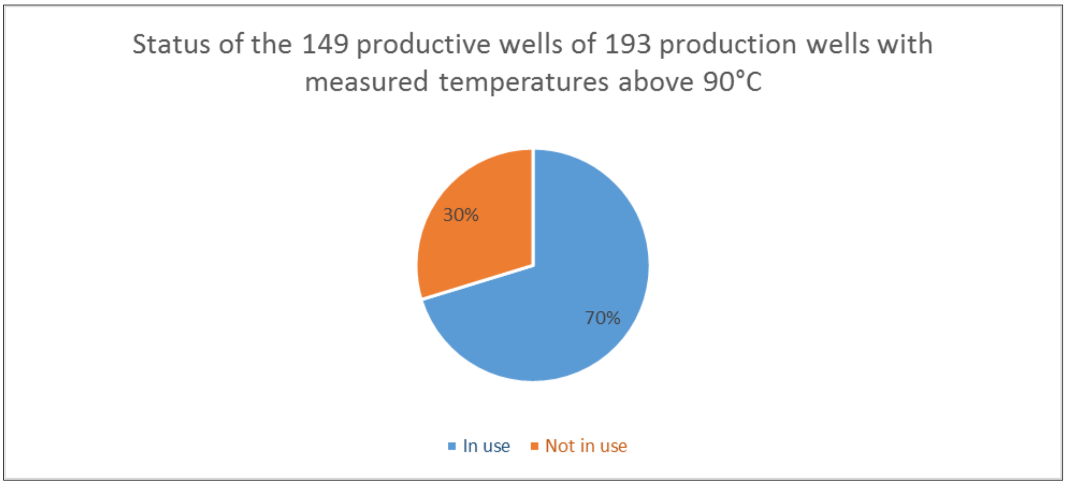

Figure 91. *Status of 149 productive production wells with measured temperatures above 90°C.*

Data on flow are available from 132 of the 149 productive wells. The average flow from these 132 wells is 17.5 l/s but 13.0 l/s for the total of the 132 productive and the 44 not productive wells.

Fig. 92 shows the distribution of flow from wells in 10 l/s intervals. Flow values of 0-10 and 10-20 l/s dominate with a frequency of 47.0% and 27.3%, respectively. Only 2 wells have a flow above 62 l/s, one 100 l/s, the other 110 l/s.

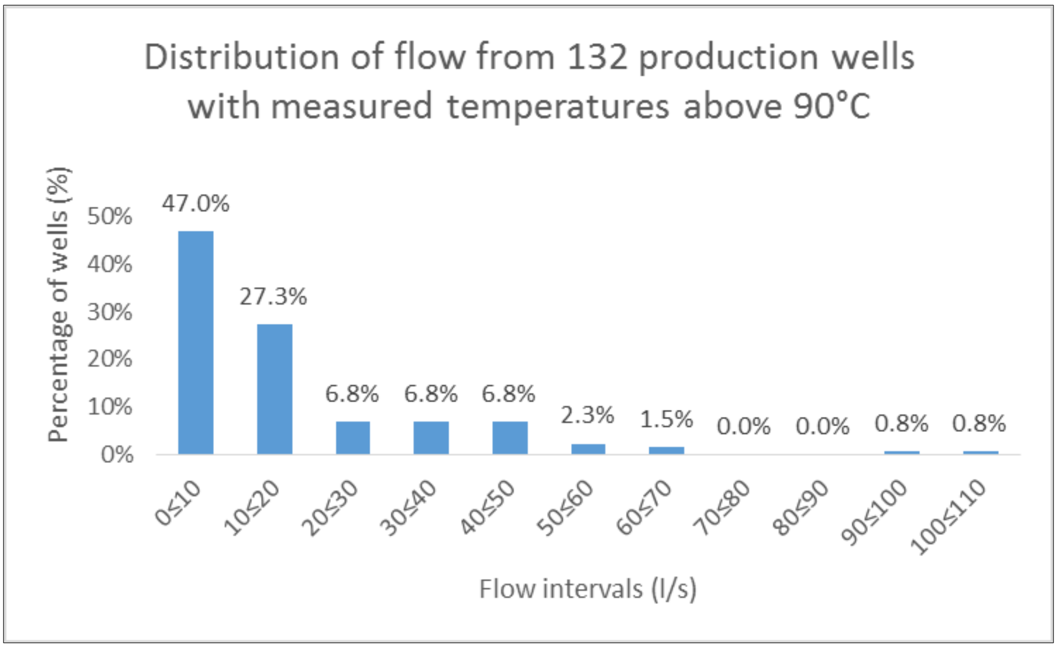

Figure 92. *Distribution of flow from 132 production wells with measured temperatures above 90°C.*

5.4.4 Main feeders

Data on the depth of the main feeder are available in 127 wells. The depth of the feeder is drawn against the drilled depth in Fig. 93. It is not surprising that in many wells drilling is stopped shortly after a good feeder has been found. This is especially apparent for wells shallower than 1,000 m. Often the owners may not have had financial capacity to drill deeper or used smaller drill rigs that did not have the technical capacity to drill deeper than 1,000 meters.

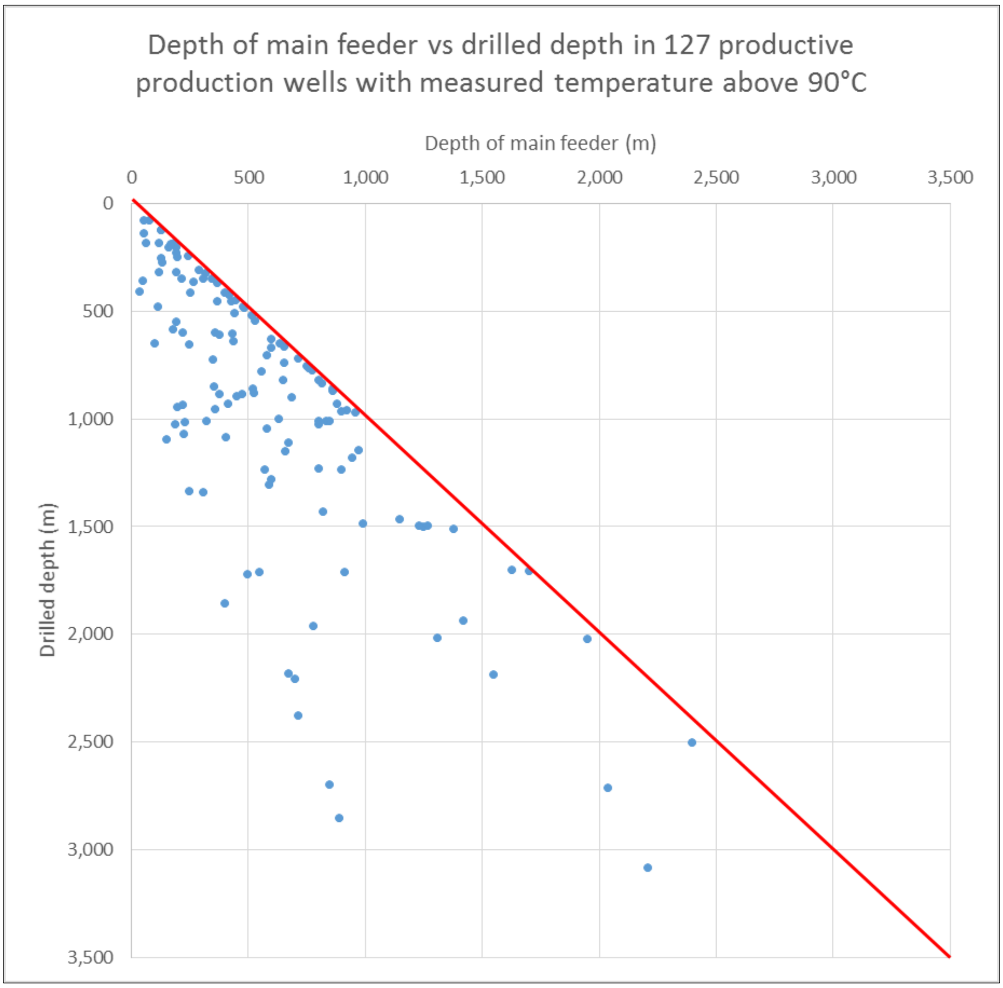

Figure 93. *Depth of main feeder versus drilled depth in 127 productive wells with measured temperatures above 90°C.*

Fig. 94 shows the depth distribution of the main feeder in 100 m intervals. About 89% of the feeders are shallower than 1,000 m.

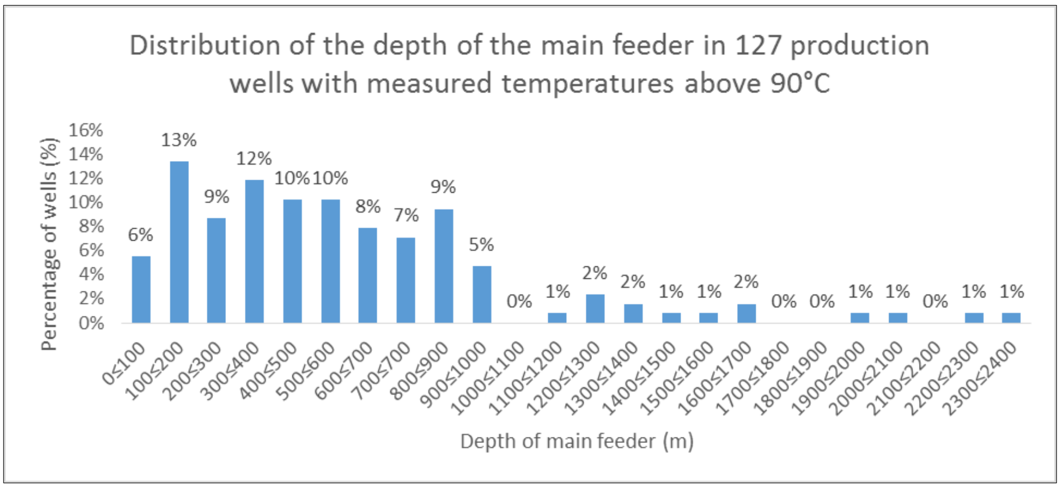

Figure 94. *Depth distribution of the main feeder in 127 production wells with measured temperatures above 90°C.*

Fig. 95 correlates flow against depth of main feeder in 123 of the 148 productive wells. Wells with feeders in the uppermost 1,000 meters have a broad range in flow values, up to 62 l/s, and one well of 110 l/s. Feeders below 1,000 meters give a more limited flow, generally within 20 l/s. Only 3 wells have a flow above 18 l/s, one 40 l/s, another 62 l/s and third 100 l/s.

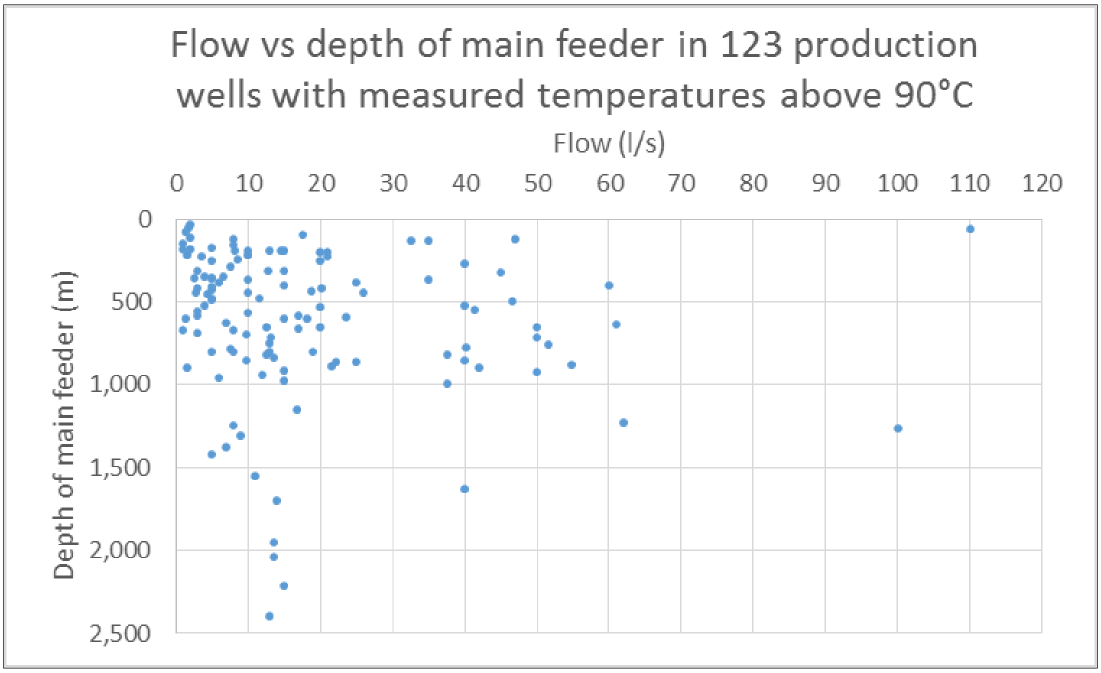

Figure 95. *Flow against depth of main feeder in 123 production wells with measured temperatures above 90°C.*

Fig. 96 plots flow from wells against the discharge temperatures in the 126 wells with available information. There is no correlation to be seen.

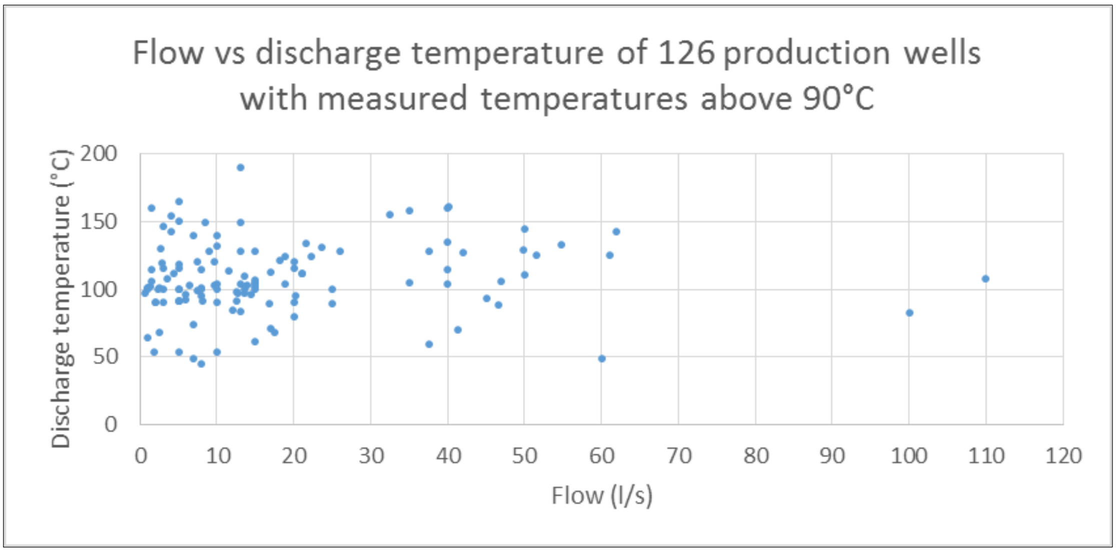

Figure 96. *Flow and discharge temperature of 126 production wells with measured temperatures above 90°C.*

5.4.5 Success of wells for space heating

Wells with a discharge temperature above 80°C are considered successful for space heating. Fig. 97 shows the success ratio for production wells with measured temperatures above 90°C. Successful wells are 131 out of 193 or 68%.

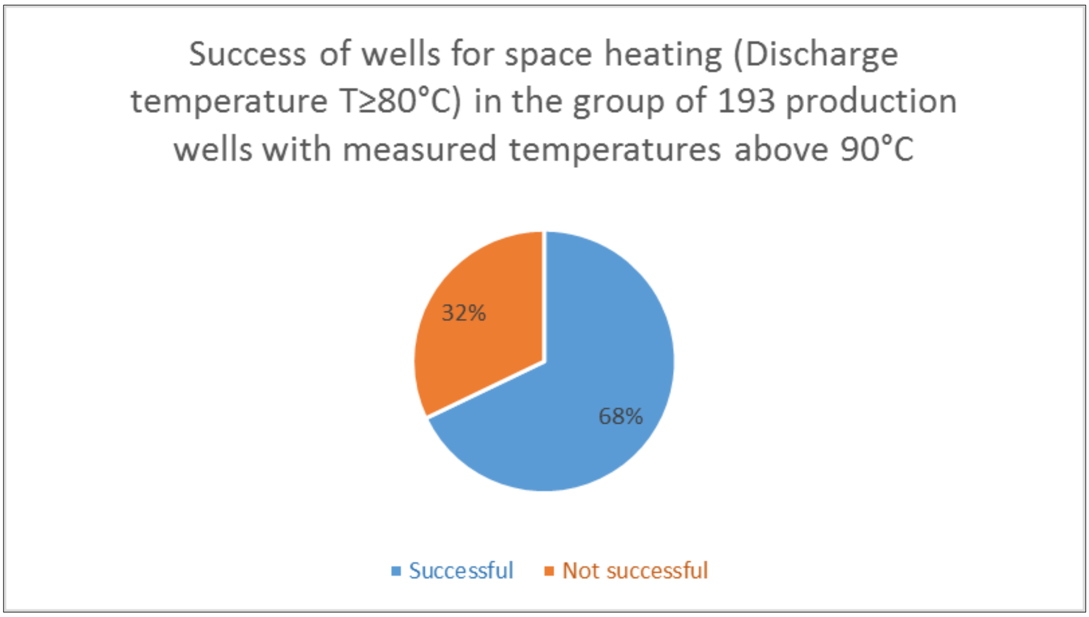

Figure 97. *Success of wells for space heating (Discharge temperature above 80°C) in the group of 193 production wells with measured temperatures above 90°C.*

5.4.6 Success of wells for electric generation

Wells with a discharge temperature above 95°C are considered successful for electric generation. Fig. 98 shows the success ratio for production wells with measured temperatures above 90°C. Successful wells are 109 out of 193 or 56.5%.

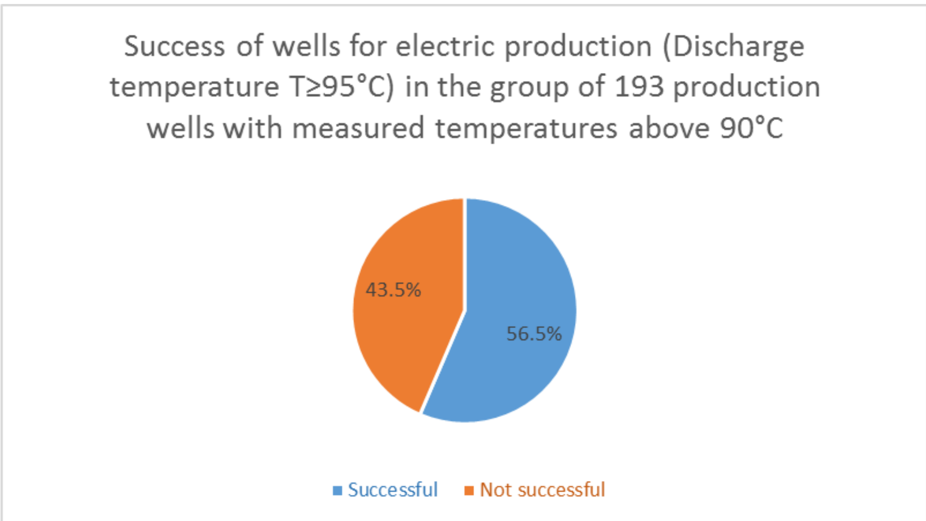

Figure 98. *Success of wells for electric generation (Discharge temperature above 95°C) in the group of 193 production wells with measured temperatures above 90°C.*

5.5 Production wells with measured temperatures above 90°C and deeper than 300 m

5.5.1 Drilled depth

Of the 193 production wells with measured temperatures above 90°C there is 161 well deeper than 300 m, ranging from 305–3,085 m in depth. Average age of these wells (in 2016) is 31 years. Average depth is 1,003 m and the average length of casing 165 m. The distribution of the drilled depth of these 161 wells is shown in Fig. 99 for 300 m intervals.

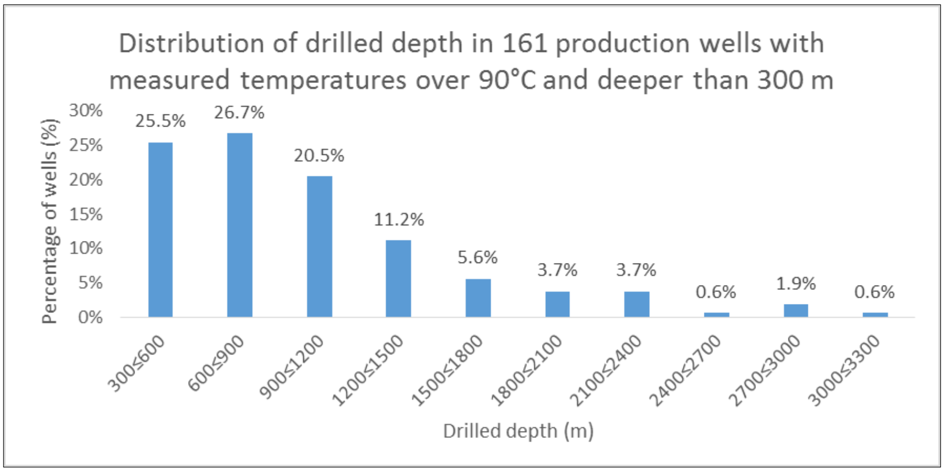

Figure 99. *Distribution of the drilled depth of 161 production wells deeper than 300 m with measured temperatures above 90°C.*

About 73% of these wells have a depth between 300 and 1,200 m and 27% are deeper than 1,200 m. As in the former group 14 wells are deeper than 2,000 meters, the deepest one 3,085 m.

Fig. 100 shows drilled depth of these wells versus date of drilling.

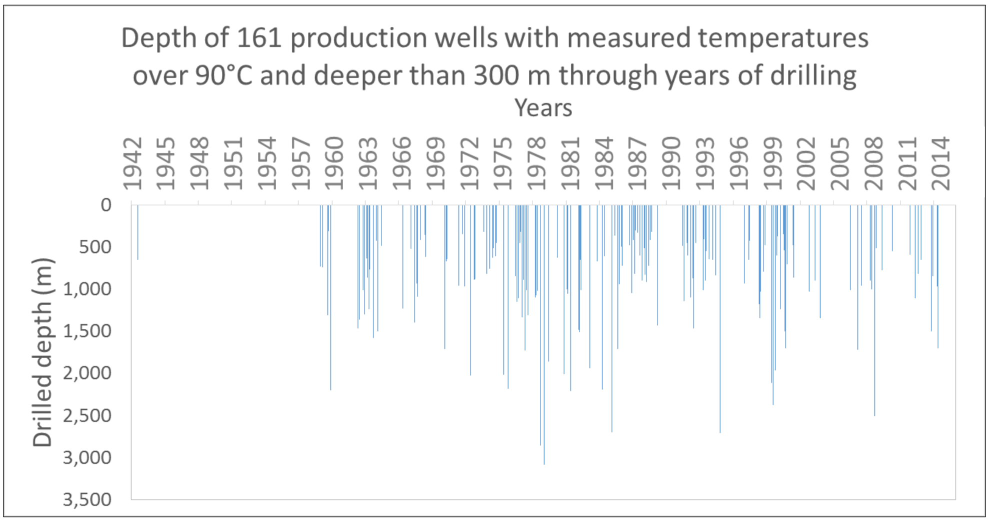

Figure 100. *Drilled depth versus date of drilling for the 161 production wells that were deeper than 300 m with measured temperatures above 90°C.*

5.5.2 Maximum temperature

Data on maximum measured temperature in these 159 of 161 production wells are available. Fig. 101 shows the distribution of maximum temperatures in intervals of 10°C. Average maximum temperature is 131°C.

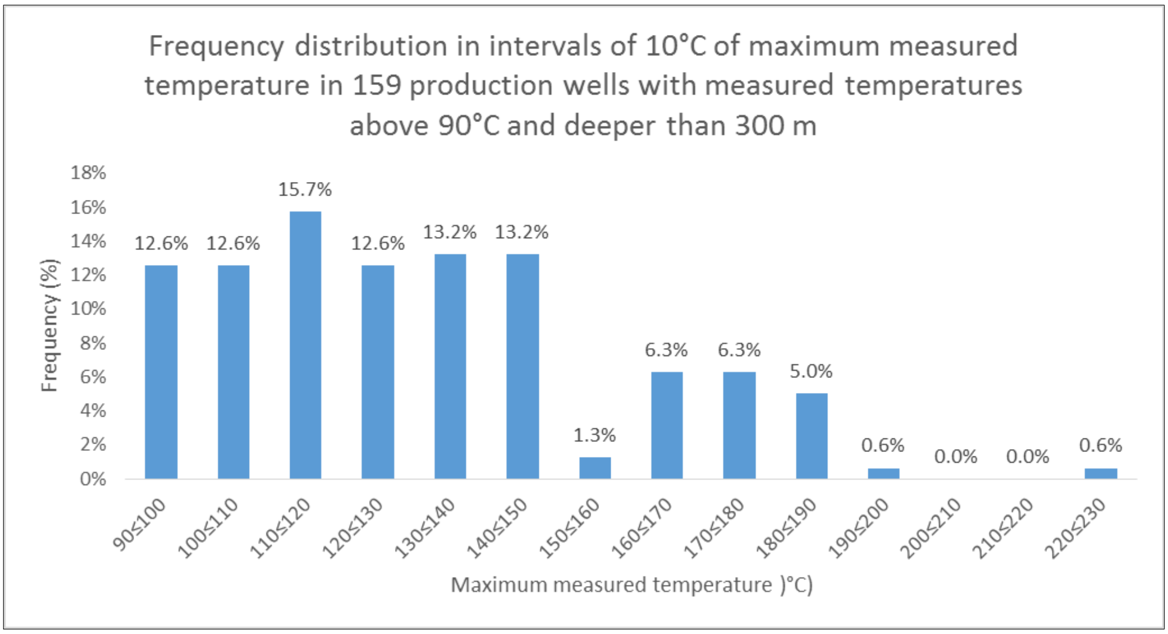

Figure 101. *Frequency distribution of maximum temperatures found in 159 production wells deeper than 300 m and with measured temperatures above 90°C.*

5.5.3 Productivity and flow

Of the 161 wells deeper than 300 m and with measured temperatures above 90°C, 127 or 78.9% were productive after drilling, 34 or 21.1% not productive, see Fig. 102.

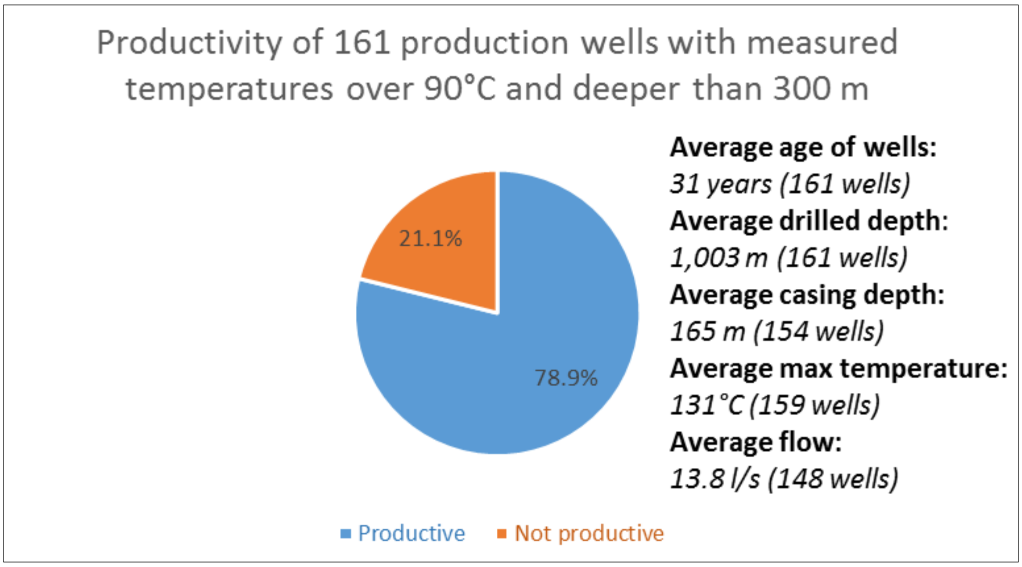

Figure 102. *Productivity of wells deeper than 300 m and with measured temperatures above 90°C.*

In use today are 93 or 73.2% of the 127 productive wells, see Fig. 103.

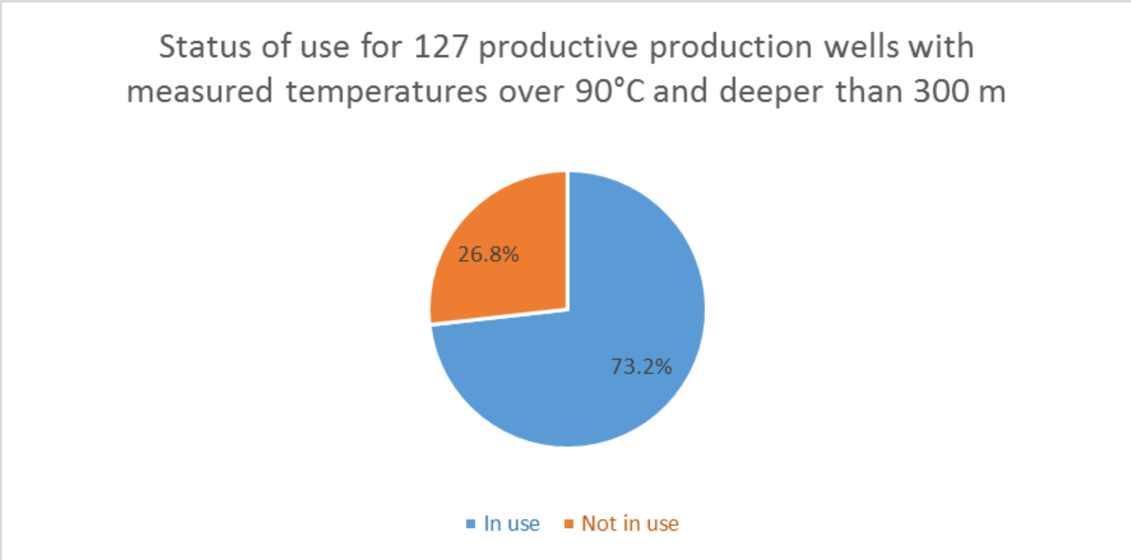

Figure 103. *Status of 127 productive wells deeper than 300 m and with measured temperatures above 90°C.*

Data on flow are available from 113 of the 127 productive wells. The average flow from these 113 wells is 18.0 l/s but 13.8 l/s for the total of the 113 productive and the 34 not productive wells.

Fig. 104 shows the distribution of flow from wells in 10 l/s intervals. Flow values of 0-10 and 10-20 l/s dominate with a frequency of 43.4% and 29.2%, respectively. Only one well has a flow above 62 l/s, i.e. 100 l/s.

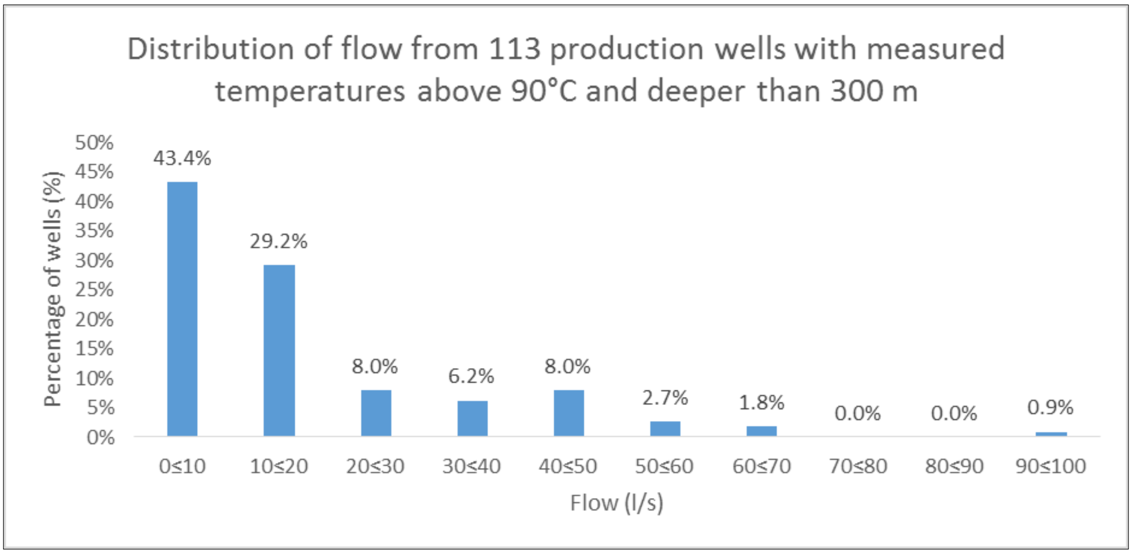

Figure 104. *Distribution of flow from 113 production wells with measured temperatures above 90°C and deeper than 300 m.*

5.5.4 Main feeders

Data on the depth of the main feeder are available in 113 of 161 wells. The depth of the feeder is drawn against the drilled depth in Fig. 105. As in the former group drilling is stopped in many wells shortly after a good feeder has been found.

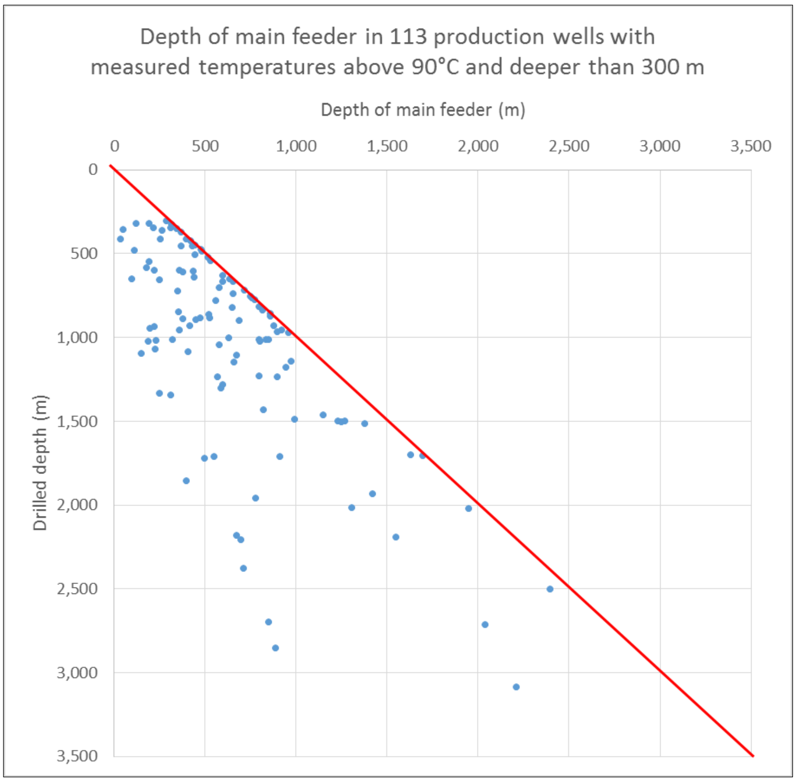

Figure 105. *Depth of main feeder in 113 production wells with measured temperatures above 90°C and deeper than 300 m.*

Fig. 106 shows the depth distribution of the main feeder in 100 m intervals. About 86% of the feeders are shallower than 1,000 m. This group has relatively fewer feeders above 300 m depth than the former group discussed in 5.4, probably with the reason that drilling is continued beyond 300 m if no good feeder has been found.

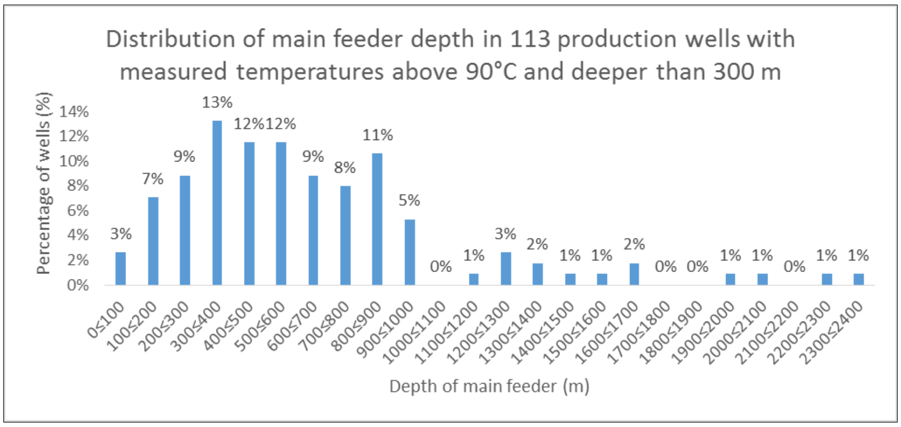

Figure 106. *Depth distribution of the main feeder in 100 m intervals for 113 production wells with measured temperatures above 90°C and deeper than 300 m.*

Fig. 107 correlates flow against depth of main feeder in 111 wells. Wells with feeders in the uppermost 1,000 meters have a broad range in flow values, up to 62 l/s. Feeders below 1,000 meters give a more limited flow, generally within 20 l/s. At those depths only 3 wells have a flow above 18 l/s, one 40 l/s, another 62 l/s and third 100 l/s.

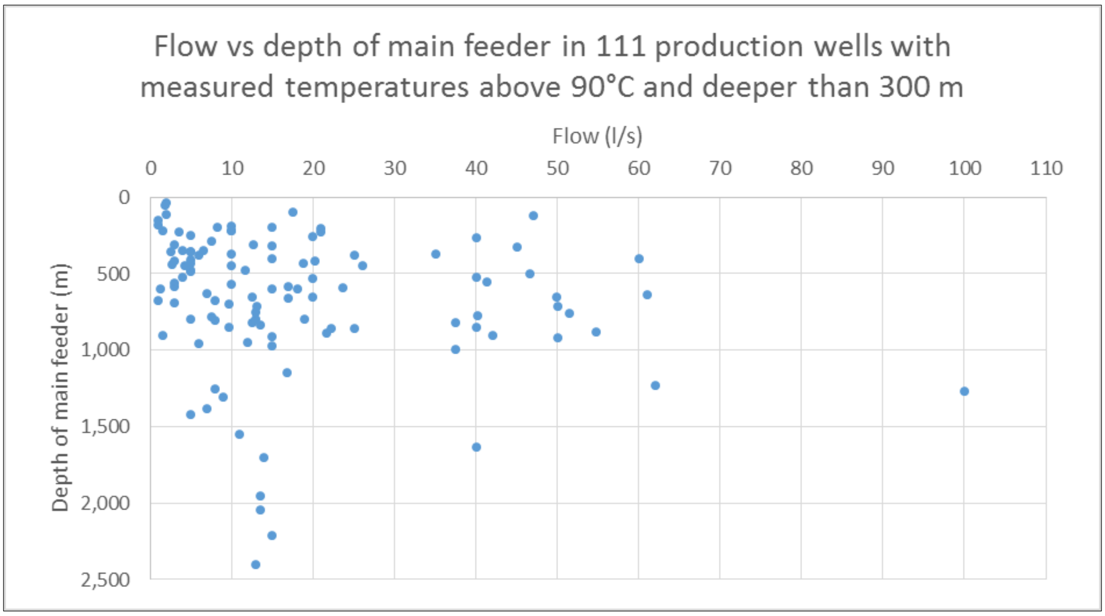

Figure 107. *Flow versus depth of main feeder in 111 production wells with measured temperatures above 90°C and deeper than 300 m.*

Fig. 108 plots flow from 107 wells against wellhead temperatures or the discharge temperatures of the well. There is no correlation to be seen.

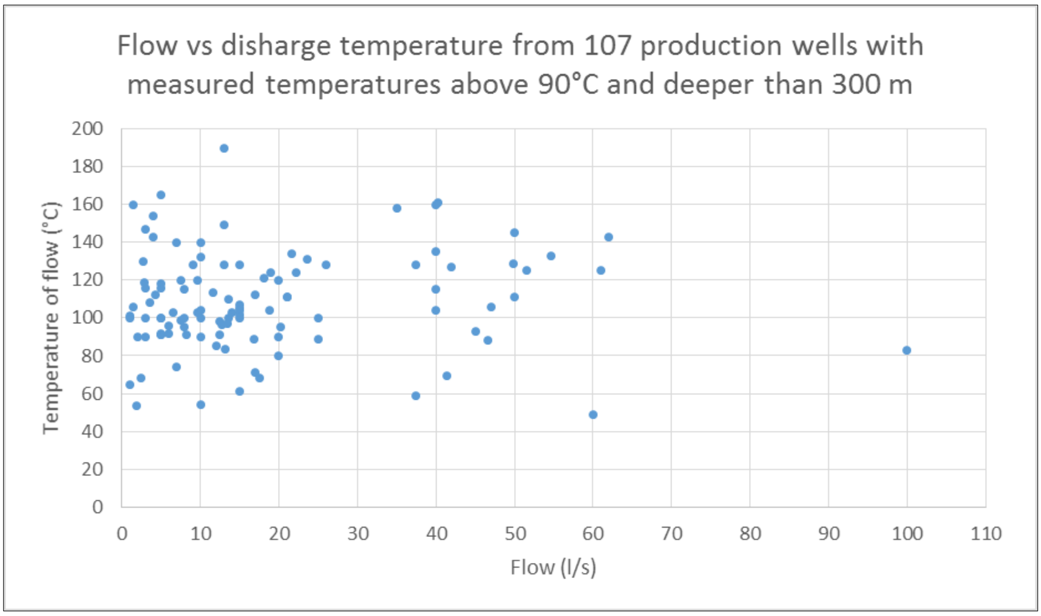

Figure 108. *Flow from 107 production wells against wellhead temperatures or the discharge temperatures of the well. The wells have measured temperatures above 90°C and are deeper than 300 m.*

5.5.5 Success of wells for space heating

Wells with discharge temperatures above 80°C are considered successful for space heating. Fig. 109 shows the success ratio for production wells that are deeper than 300 m and with maximum temperatures above 90°C. Successful wells are 113 out of 161 or 70.2%.

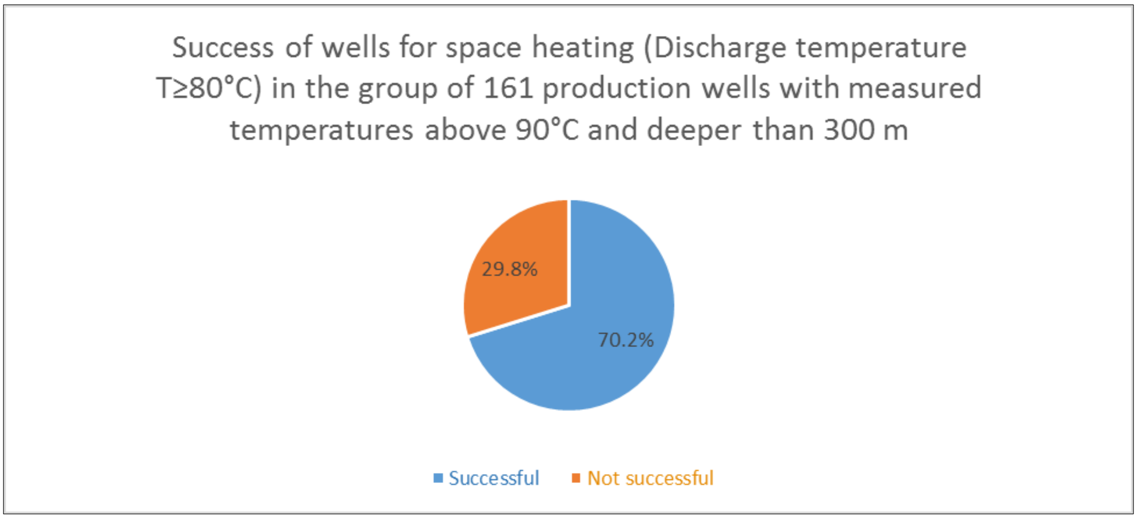

Figure 109. *Success of wells for space heating (discharge temperatures above 80°C) in the group of 193 production wells with measured temperatures above 90°C and deeper than 300 m.*

5.5.6 Success of wells for electric generation

Wells with a discharge temperature above 95°C are considered successful for electric generation. Fig. 110 shows the success ratio for production wells that are deeper than 300 m and with maximum temperatures above 90°C. Successful wells are 91 out of 161 or 56.5%.

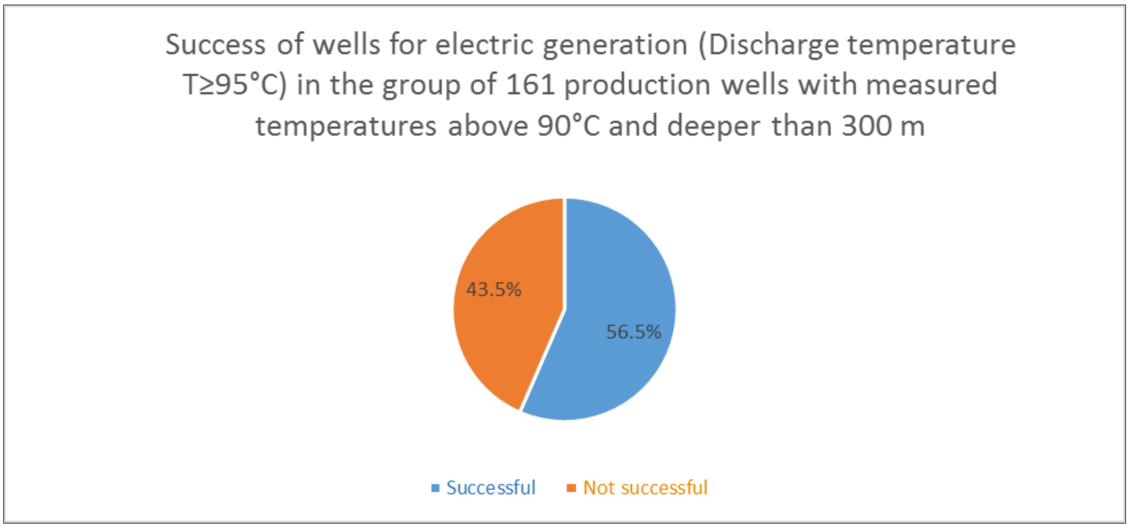

Figure 110. *Success of wells for electric generation (discharge temperatures above 95°C) in the group of 161 production wells with measured temperatures above 90°C and deeper than 300 m.*

5.6 Statistical difference between groups

As already pointed out in chapter 5.1 data on shallow wells are incomplete, especially for wells drilled with percussion drill rigs before 1950. To evaluate in which degree this might affect the statistical analysis of wells we did the analysis both for all the 193 production wells that found temperatures above 90°C and for the 161 wells of that group that were deeper than 300 m.

For the 193 production wells with measured temperatures above 90°C we found a productivity of 77%, still in use are 70% of them, average flow of productive and not productive wells 13.0 l/s, success for space heating 68% and success for electric production 56.5%.

For the 161 wells of this group that were deeper than 300 m we found a productivity of 78.9%, still in use are 73.2% of them, average flow of productive and not productive wells 13.8 l/s, success for space heating 70.2% and success for electric production 56.5%.

The difference between the groups is not significant.

5.7 Thermal and electric potential

Table 2 shows the proven and possible thermal and electric potential of the main medium enthalpy geothermal systems in Iceland as they were calculated in chapter 4. The thermal potential is calculated above an outlet temperature of 35°C. The electric potential is calculated under the assumption that the total flow is used to generate electricity in a binary cycle with effluent water at 80°C and efficiency of 11%. The remaining thermal potential of the effluent water above 35°C is also evaluated. The proven potential refers to verified production tests of the wells. The possible potential refers to estimates of capacity beyond what has yet been realized.

Table 2. *Proven and possible thermal potential above 35°C, electric potential and remaining thermal potential of the 80°C effluent water, of the main medium enthalpy geothermal systems and fields in Iceland.*

System/*well field*		Thermal and electric power potential of fields and systems					
		Thermal power above 35°C		Electric power in binary above 80°C		Remaining thermal power after binary from 80 to 35°C	
		Proven	Possible	Proven	Possible	Proven	Possible
(no)	(name)	(MW_{th})	(MW_{th})	(MW_e)	(MW_e)	(MW_{th})	(MW_{th})
1	**Laugarnes**	**132.4**		**7.40**		**63.9**	
-	*Laugarnes*	*44.2*		*2.51*		*21.3*	
-	*Lækjarhvammur*	*65.3*		*3.71*		*31.5*	
-	*Rauðarárholt*	*8.2*		*0.45*		*4.1*	
-	*Hátún*	*14.7*		*0.83*		*7.1*	
2	**Seltjarnarnes**	**14.2**	**28.5**	**0.60**	**1.06**	**8.7**	**18.8**
-	*Bakki*	*0.0*		*0.00*		*0.0*	
-	*Nes*	*0.0*		*0.00*		*0.0*	
-	*Nýibær*	*3.5*		*0.19*		*1.8*	
-	*Bygggarður*	*6.5*		*0.22*		*4.4*	
-	*Ráðagerði*	*4.2*		*0.19*		*2.5*	
3	**Fremri-Háls**	**5.7**		**0.00**			
4	**Möðruvellir**	**20.6**		**0.98**		**7.5**	
5	**Hvammsvík**	**5.7**		**0.00**			
6	**Miðsandur**	**3.1**		**0.19**		***1.3***	
7	**Leirá-Geldingaá**	**3.5**		**0.20**		**1.7**	
-	*Leirá*	*3.5*		*0.20*		*1.7*	
-	*Geldingaá*	*0.0*		*0.00*			
8	**Stillholt**	**0.0**		**0.00**			
9	**Brautartunga-England**	**8.4**		**0.00**			
-	*England*	*0.7*		*0.00*			
-	*Stóra-Drageyri*	*3.3*		*0.00*			
-	*Hvammur*	*2.3*		*0.00*			
-	*Snartarstaðir*	*2.1*		*0.00*			
10	**Bær-Varmaland**	**21.2**	**50.7**	**0.42**	**1.74**	**6.0**	**34.8**
-	*Hellur*	*0.0*		*0.00*			
-	*Bær*	*5.5*		*0.25*		*3.2*	
-	*Laugarholt*	*11.3*		*0.00*			
-	*Varmaland/Laugaland*	*4.4*		*0.17*		*2.8*	
11	**Reykholt. Borgarfjörður**	**115.8**		**4.03**		**79.1**	
12	**Eiðhús-Dalur**	**7.8**		**0.29**		**5.0**	
-	*Eiðhús*	*5.9*		*0.22*		*3.8*	
-	*Dalur*	*1.9*		*0.07*		*1.2*	
13	**Reykhólar. Barðaströnd**	**16.8**		**0.71**		**10.4**	
14	**Ytri-Reykir. Laugarbakki**	**12.6**		**0.38**		**9.4**	
15	**Reykjarhóll Varmahlíð**	**10.1**		**0.31**		**7.5**	
16	**Reykjarhóll on Bakkar in Fljót**	**2.6**		**0.00**			
17	**Langhús in Fljót**	**2.5**		**0.09**		**1.7**	
18	**Laugaland. Þelamörk**	**4.0**		**0.15**		**2.6**	
19	**Hveravellir. Reykjahverfi**	**86.1**		**4.39**		**46.2**	
20	**Húsavík**	**2.2**		**0.07**		**1.5**	
21	**Ytribakki**	**17.9**	**35.3**	**0.93**	**2.78**	**9.4**	**9.4**
22	**Ærlækjarsel**	**18.1**	**20.4**	**0.80**	**1.20**	**10.8**	**9.4**

Table 2. (*Continued.*)

System/*well field*		Thermal power above 35°C		Electric power in binary above 80°C		Remaining thermal power after binary from 80 to 35°C	
		Proven	Possible	Proven	Possible	Proven	Possible
(no)	(name)	(MW_{th})	(MW_{th})	(MW_e)	(MW_e)	(MW_{th})	(MW_{th})
23	**Reykjaból**	**36.7**		**2.27**		**15.6**	
-	*Reykjaból*	*6.3*		*0.41*		*2.4*	
-	*Þórarinsstaðir*	*1.4*		*0.05*		*0.9*	
-	*Reykjadalur*	*0.8*		*0.03*		*0.6*	
-	*Kópsvatn*	*28.2*		*1.78*		*11.7*	
-	*Kotlaugar*	*0.0*		*0.00*			
-	*Jata*	*0.0*		*0.00*			
-	*Haukholt*	*0.0*		*0.00*			
24	**Flúðir**	**65.1**		**2.91**		**40.9**	
-	*Hellisholt*	*31.4*		*1.49*		20.2	
-	*Grafarbakki*	*33.7*		*1.42*		20.7	
25	**Laugaland in Holt**	**9.1**		**0.29**		**6.6**	
26	**Haukadalur**	**0.0**		**0.00**			
-	*Gýgjarhóll*	*0.0*		*0.00*			
-	*Kjarnholt*	*0.0*		*0.00*			
-	*Neðridalur*	*0.0*		*0.00*			
-	*Helludalur*	*0.0*		*0.00*			
27	**Bergstaðir in Eystritunga**	**1.5**		**0.00**			
28	**Reykholt. Stórafljót**	**37.3**		**1.31**		**22.3**	
-	*Stórafljót*	*14.7*		*0.62*		*5.3*	
-	*Reykjavellir*	*0.0*		*0.00*			
-	*Laugarás*	*22.6*		*0.69*		*17.0*	
29	**Efri-Reykir**	**42.9**		**2.35**		**21.3**	
-	*Efri-Reykir*	*29.7*		*1.89*		*12.1*	
-	*Syðri-Reykir*	*10.1*		*0.31*		*7.5*	
-	*Böðmóðsstaðir*	*3.1*		*0.15*		*1.7*	
30	**Laugarvatn**	**10.9**	**28.2**	**0.37**	**2.22**	**7.5**	**7.5**
31	**Eyvík**	**2.4**		**0.14**		**1.1**	
32	**Klausturhólar**	**40.6**		**2.93**		**13.7**	
-	*Hallkelshólar*	*0.0*		*0.00*			
-	*Klausturhólar*	*8.6*		*0.68*		*2.4*	
-	*Hæðarendi*	*32.0*		*2.25*		*11.3*	
33	**Öndverðarnes**	**15.9**		**0.71**		**9.4**	
34	**Þorleifskot/Laugardælir**	**59.6**		**2.54**		**37.6**	
-	*Ósabotnar*	*23.9*		*0.69*		*18.8*	
-	*Þorleifskot*	*35.7*		*1.85*		*18.8*	
35	**Árbær**	**0.0**		**0.00**			
36	**Hveragerði**	**89.9**		**5.71**		**37.6**	
-	*Hverasvæðið*	*38.8*		*2.58*		*15.1*	
-	*Reykir*	*0.0*		*0.00*			
-	*Reykir - Fagrihvammur*	*0.0*		*0.00*			
-	*Reykir – NLFÍ*	*23.3*		*1.55*		*9.0*	
-	*Reykir – Ölfusborgir (ASÍ)*	*2.6*		*0.19*		*0.9*	
-	*Gljúfurárholt*	*13.4*		*0.65*		*7.5*	
-	*Vellir*	*0.0*		*0.00*			
-	*Öxnalækur*	*0.8*		*0.06*		*0.3*	
-	*Kröggólfsstaðir*	*4.4*		*0.27*		*1.9*	
-	*Núpar*	*6.6*		*0.41*		*2.8*	
37	**Bakki**	**12.0**		**0.50**		**7.2**	
-	*Þóroddsstaðir*	*0.0*		*0.00*			
-	*Eystribakki*	*1.0*		*0.05*		*0.5*	
-	*Bakki*	*3.8*		*0.18*		*2.2*	
-	*Hjallakrókur*	*5.4*		*0.21*		*3.5*	
-	*Vindheimar*	*1.8*		*0.09*		*0.9*	
-	*Litlaland*	*0.0*		*0.00*			
SUM PROVEN		**935.3**		**44.0**		**493.5**	
SUM POSSIBLE			**1,016,0**		**49.9**		**531.0**

The data in Table 2 are presented in Figs. 111–113 for the 37 medium enthalpy systems. The wells in these systems have a proven aggregate capacity of 935 MW_{th} or 44 MW_e using an organic Rankine cycle, yielding aggregate 494 MW_{th} of remaining thermal potential of 80°C effluent water for cascade direct use and a possible capacity of 1,016 MW_{th} and 49.9 MW_e yielding aggregate 531 MW_{th} of remaining thermal potential of 80°C effluent water for cascade direct use. Ten systems have a thermal potential in the range of 37-132 MW_{th} and an electric potential of 1.0-7.4 MW_e. The largest systems are already in use for district heating but they have not been used for generation of electricity. Five systems have may have considerably greater potential than presently proven. This applies especially to Laugarvatn where 200°C water may be found but no wells have yet been drilled.

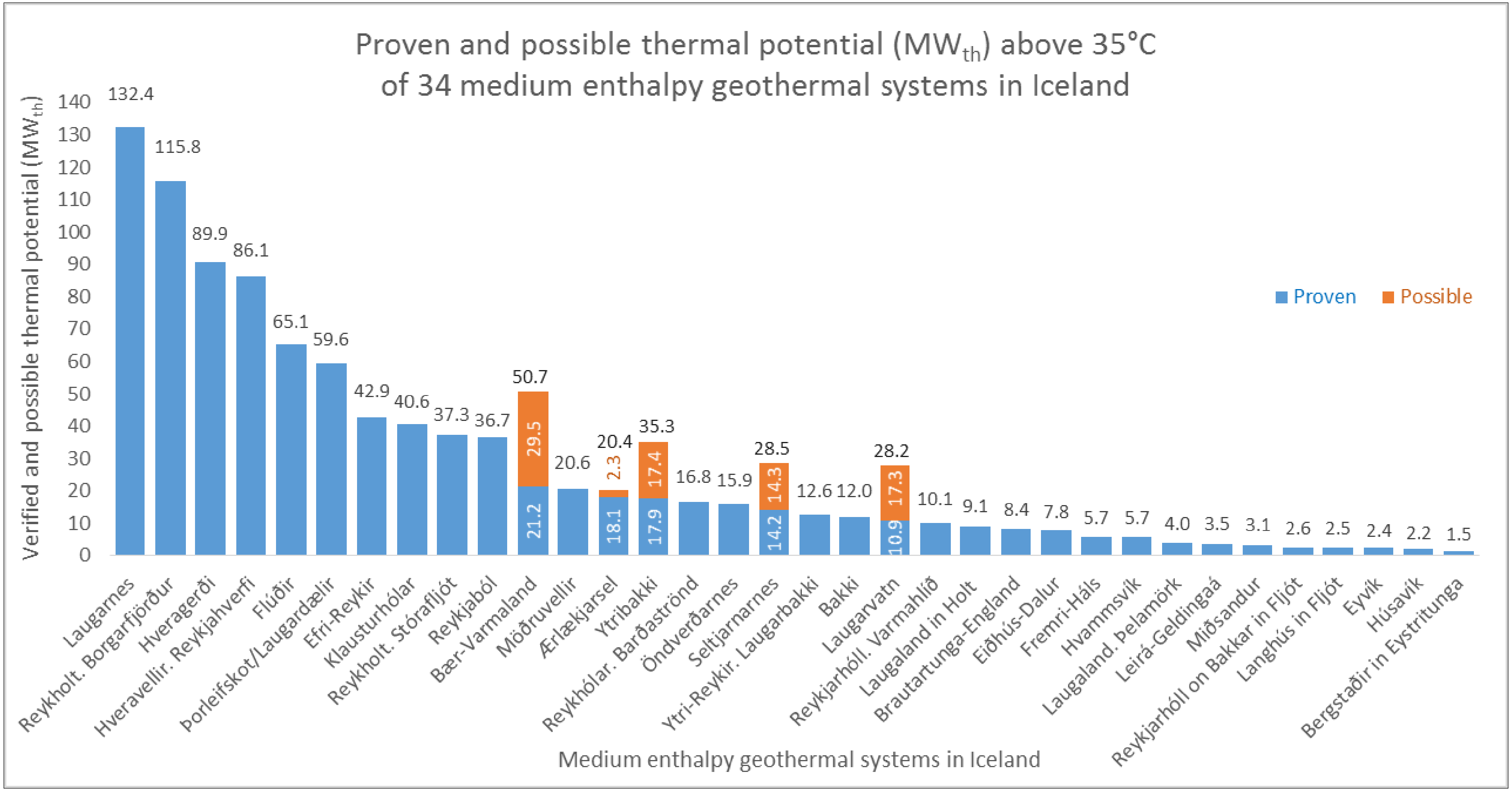

Figure 111. *Proven and possible thermal potential (MW$_{th}$) above 35°C of 34 medium enthalpy geothermal systems in Iceland.*

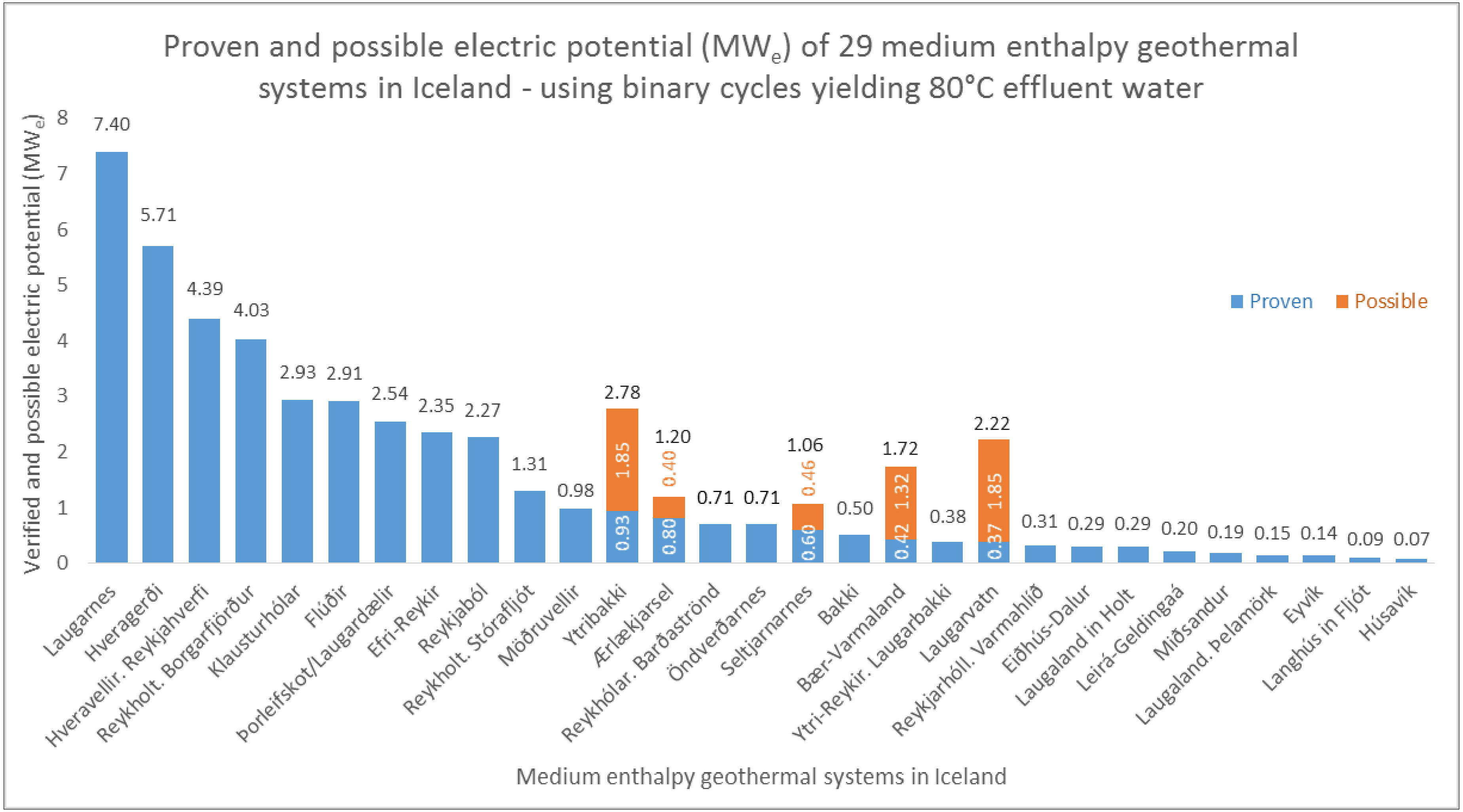

Figure 112. *Proven and possible electric potential (MW_e) of 29 medium enthalpy geothermal systems in Iceland using binary cycles and 80°C of effluent water.*

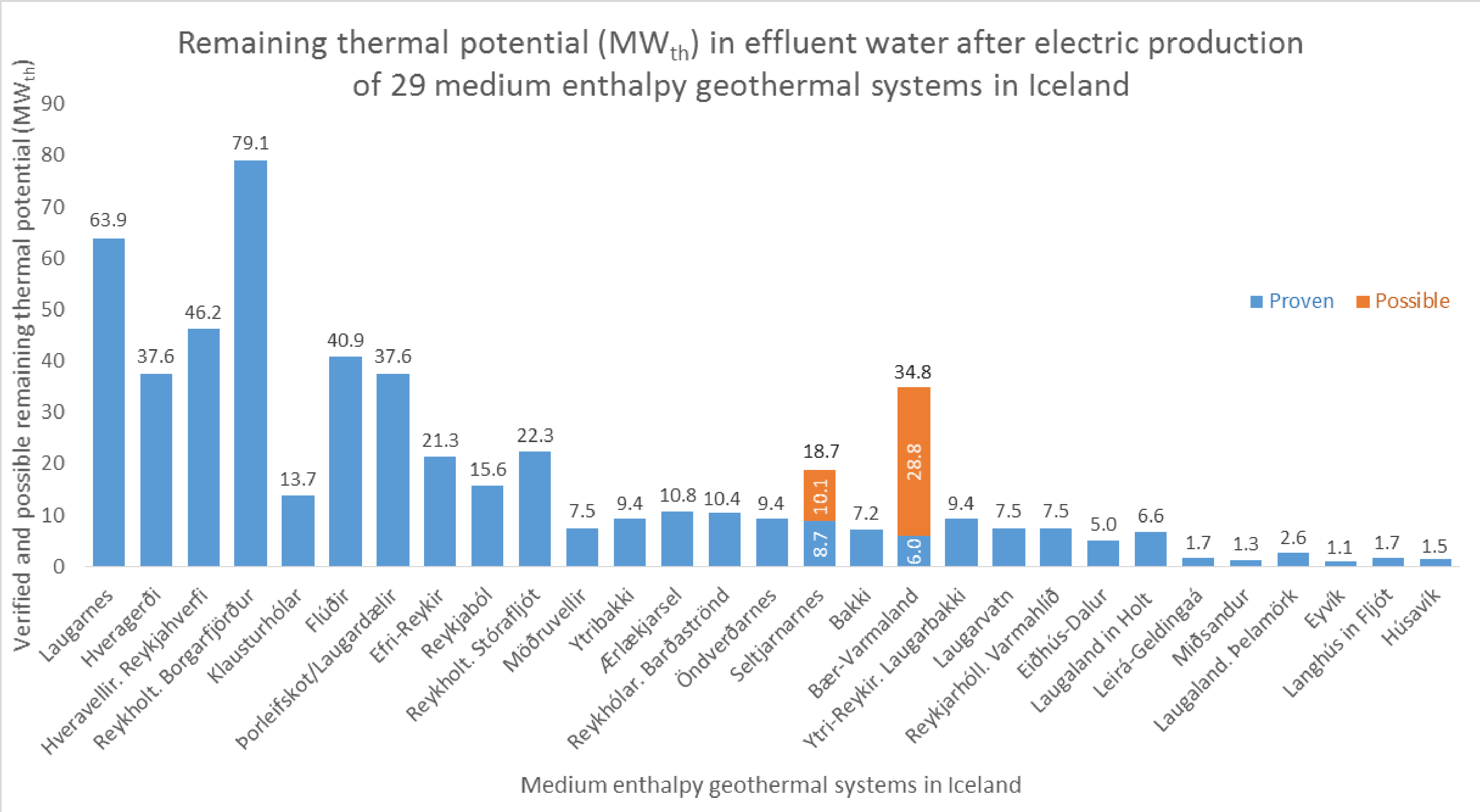

Figure 113. *Remaining thermal potential (MWth) in effluent water from 80 to 35°C after electric generation of 29 medium enthalpy systems in Iceland.*

6 Key Findings

6.1 All wells

- There were 655 exploratory and production wells drilled in the medium enthalpy systems in the years 1928-2014. Most of the wells were drilled vertically. The depth is known in 639 wells. It ranges from 3-3,085 meters, average 335.5 m.
- Out of the 655 wells drilled 289 are filed as production wells. Drilled depth is known in 283 of those wells. They range between 10-3,085 m in depth, average 650.4 m.
- Of the 289 production wells about 39% of the wells are shallower than 300 m, 45% are between 300 and 1,200 m in depth and 16% deeper than 1200 m. Fourteen wells are deeper than 2,000 meters, the deepest one 3,085 m.
- Productive production wells are 172 or 60% of the drilled production wells, 106 or 62% of them are still in use. Data on flow are available from 132 productive wells and 54 not productive wells. The average yield for these 186 wells is 12.1 l/s.

6.2 Production wells

- Of the total of 289 drilled production wells, 193 wells found measured temperature above 90°C and were considered of interest for further analysis from the viewpoint of medium enthalpy utilization.
- Drilled depth is known in all the 193 wells. They range between 52-3,085 m in depth, average 861 m. About 16.6% are shallower than 300 m, 60.6% are between 300 and 1,200 m and 22.8% deeper than 1,200 m. Fourteen wells are deeper than 2,000 meters, the deepest one 3,085 m.
- Productive wells of this group were 149 or 77%. Of them 104 or 70% are still in use. Data on flow are available from 132 of the productive wells. The average flow from 132 productive and the 44 not productive wells is 13 l/s.
- Flow values of 0-10 and 10-20 l/s dominate with a frequency of 47.0% and 27.3%, respectively. Only 2 wells have a flow above 62 l/s, one 100 l/s, the other 110 l/s.
- About 89% of the main feeders are in the uppermost 1,000 meters. Wells with feeders in the uppermost 1,000 meters have a broad range in flow values, up to 62 l/s, and one well 110 l/s. Feeders below 1,000 meters give a more limited flow, generally within 20 l/s. At those depths only 3 wells have a flow above 18 l/s; one 40 l/s, another 62 l/s and third 100 l/s.
- There are no indications of variance in the total flow within the discharge temperature range of 50-160°C.
- Wells with a discharge temperature above 80°C are considered successful for space heating. Successful wells are 131 out of 193 or 68%.
- Wells with a discharge temperature above 95°C are considered successful for electric generation. Successful wells are 109 out of 193 or 56.5%

6.3 Production wells with measured temperature above 90°C and deeper than 300 m

- Of the 193 wells that found measured temperature above 90°C, 161 well was deeper than 300 m.
- Drilled depth is known in all the 161 wells. They range between 305-3,085 m in depth, average 1,003 m. About 73% are between 300 and 1,200 m and 27% deeper than 1,200 m. Fourteen wells are deeper than 2,000 meters, the deepest one 3,085 m.
- Productive wells of this group were 126 or 78%. In use today are 92 or 73% of those wells. Data on flow are available from 113 of the productive wells. The average flow from these 113 wells is 18.0 l/s but 13.8 l/s for the total of the 113 productive and the 35 not productive wells.
- Flow values of 0-10 and 10-20 l/s dominate with a frequency of 43.4% and 29.2%, respectively. Only one well has a flow above 62 l/s, i.e. 100 l/s.
- About 89% of the main feeders are in the uppermost 1,000 meters. Wells with feeders in the uppermost 1,000 meters have a broad range in flow values, up to 62 l/s. Feeders below 1,000 meters give a more limited flow, generally within 20 l/s. At those depths only 3 wells have a flow above 18 l/s; one 40 l/s, another 62 l/s and third 100 l/s.
- There are no indications of variance in the total flow within the discharge temperature range of 50-160°C.
- Wells with a discharge temperature above 80°C are considered successful for space heating. Successful wells, deeper than 300 m, are 112 out of 161 or 69.6%
- Wells with a discharge temperature above 95°C are considered successful for electric generation. Successful wells, deeper than 300 m, are 91 out of 161 or 56.5%.

6.4 Statistical difference between groups

- Comparison of the results obtained for all production wells that found temperature above 90°C and the subgroup of wells that were deeper than 300 m showed insignificant differences. Despite incomplete data on wells shallower than 300 m this deficiency does not affect the results severely.

6.5 Potential

- The 37 medium enthalpy systems analyzed have an aggregate thermal potential above 35°C of 935 MW_{th} or an electric potential of 44 MW_e, using an organic Rankine cycle, yielding aggregate 494 MW_{th} of remaining thermal potential of 80°C effluent water for cascade direct use
- The ten largest systems have a range of 37 to 132 MW_{th} and 1.3 to 7.4 MW_e.
- Five systems may have considerably greater potential than presently proven. This applies especially to Laugarvatn where 200°C water may be found but no wells have yet been drilled.

7 Addendum

7.1 The Ölfusdalur System

The Ölfusdalur System is in the farmland of Reykjakot and Vorsabær, just north of the Town Hveragerði, see Fig. 114.

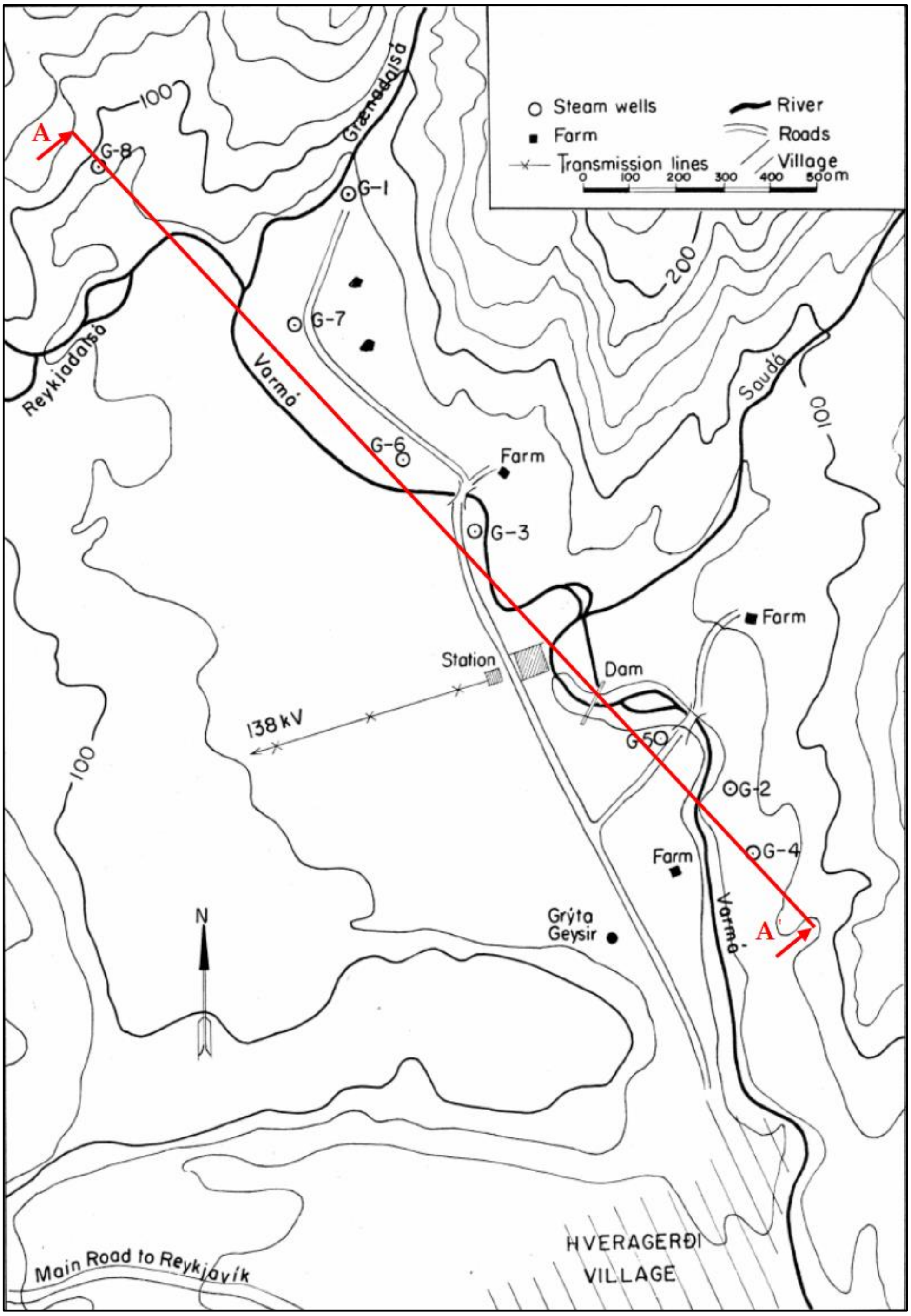

Figure 114. *Overview of the Ölfusdalur System. (From Einarsson, 1961.)*

The system lies between the high enthalpy system Grændalur in the North and the medium enthalpy system Hveragerði in the South. Eight production wells (G-1 to G-8) were drilled in the Ölfusdalur valley in the years 1958-1962. Their location is shown on Fig. 114. The wells found 197-232°C at 250-700 m depth. The temperature distribution along the cross section A-A′ in Fig. 114 is shown in Fig. 115. This distribution strongly suggests that the reservoir fluid is an ascending outflow from the Grændalur high enthalpy system.

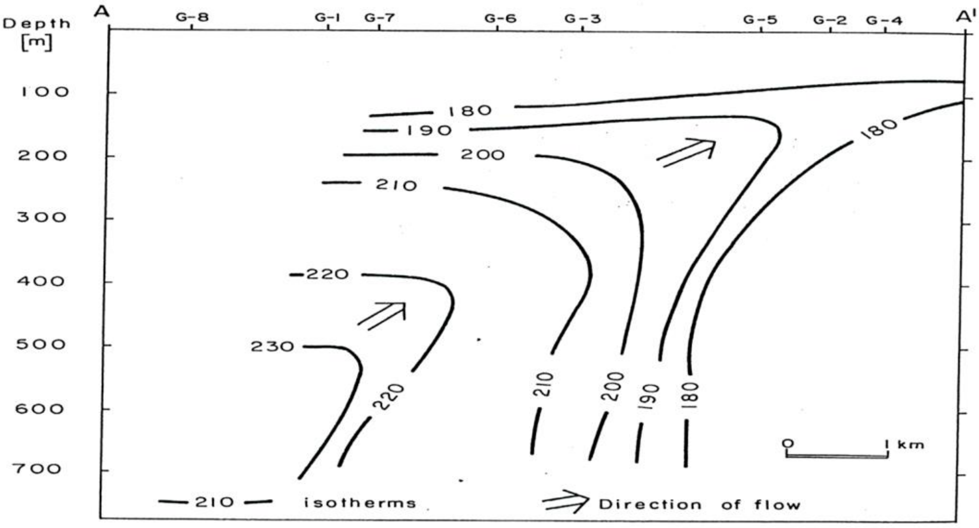

Figure 115. *Temperature distribution in the cross section A-A' of Fig. 114. (From Steingrímsson, 1991, adapted from Xi-Xiang, 1980).*

In the well registry there are registered twenty-five wells in the Ölfusdalur System, eleven drilled shorter than 100 m for hot water, three exploration wells, shorter than 300 m, the eight production wells drilled in the years 1958-1962 ranging 346 to 1,206 m in depth, two additional steam wells, one for tourist attraction and the other drilled into a steam cap (Geyser) and at last one well for which the purpose is not defined. Fig. 116 shows the wells in the Ölfusdalur System. The main production wells G-1 to G-8 are marked as wells HV-1 to HV-8 in the well registry.

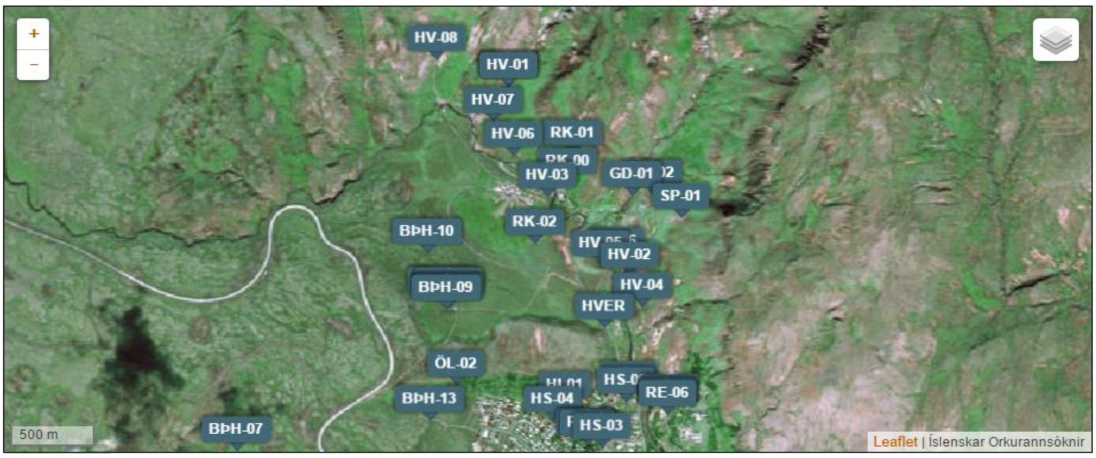

Figure 116. *Overview of the wells at the Ölfusdalur System. (NEA's well registry.)*

The Ölfusdalur system is intermediate between a high enthalpy and a medium enthalpy system. It was not included in the report on success of high temperature geothermal wells in Iceland (Sveinbjörnsson, 2014) and is not classified as one of the medium enthalpy systems in this report. For the sake of completeness it is however included here as an addendum.

Wells HV-1 to HV-8 were drilled to appraise the feasibility of generating electricity with the geothermal steam (Einarsson, 1961). Despite positive results the project was not realized as the energy industry preferred a 210 MW_e hydroelectric plant to meet the demands of the first aluminium plant in Iceland.

Well HV-1 reached 982 m depth and found a maximum temperature of 232°C. Due to drilling problems the well had to be abandoned with a stuck drill stem pipe and is not usable. Well HV-4 has been used to heat houses in the valley since 1961 and both HV-2 and HV-4 have served the District Heating of Hveragerði since 1973. HV-3 has been used for heating houses in its vicinity since about 1990 (Jónasson, 2008). Well HV-5 was drilled as a reference well for temperature and pressure. All feeders were cemented and the well has not been induced to produce.

All the wells except HV-1 and HV-5 were subjected to a 4 months' flow test in 1961 and 6 months in 1962-1963. In the flow tests water and steam were separated. The measurements of water flow were considered reliable but difficulties in recording the steam flow may have led to overestimates in some cases. To avoid such errors the results of 1961-1963 reported in Tables 3 and 4 are calculated from the observed water flow and the estimated inflow enthalpy of reservoir water at the respective formation temperature (Björnsson, 1975). Over the 54 years since 1961 the wells have been subjected to a number of flow tests. The results of those are summarized and compared in Table 4.

Table 3. *Results of flow tests of production wells in Ölfusdalur 1961–2008.*

Well	Date of flow tests	Duration of tests	Pressure		Enthalpy	Q_{tot}	Q_{steam}	Reference
			Wellhead	Steam				
			(bar-a)	(bar-a)	(kJ/kg	(kg/s)	(kg/s)	
HV-2	1961-1963	10 months	7	6	795	93.4	5.8	Björnsson, 1975
	1961-1963	10 months	5	1	795	100.3	16.8	Björnsson, 1975
	Nov/Dec 1971	2 x 4 days	5.5	1	850	97.9	23.9	Arnórsson, 1972
HV-3	1961-1963	10 months	8.5	6	925	75.3	9.3	Björnsson, 1975
	1961-1963	10 months	8.5	1	925	74.7	16.7	Björnsson, 1975
HV-4	1961-1963	10 months	6	6	782	37.7	2.1	Björnsson, 1975
	1961-1963	10 months	3	1	782	62.0	10.0	Björnsson, 1975
HV-6	1961-1963	10 months	6	6	929	65.6	8.3	Björnsson, 1975
	1961-1963	10 months	6	1	929	65.9	14.9	Björnsson, 1975
	Oct. 1979	1 month	6	6	1,000	59	9	Ragnars et al., 1979
	Oct. 1979	1 month	9	9	1,050	41	6	Ragnars et al., 1979
	May 2003	12 hours		7	920-930	32.6	3.6	Sigurðsson, 2003
HV-7	1961-1963	10 months	6	6	971	54.7	8.0	Björnsson, 1975
	1961-1963	10 months	6	1	971	53.6	13.1	Björnsson, 1975
	June 2003	12 hours		7	980-986	47.7	6.6	Sigurðsson, 2003
HV-8	1961-1963	10 months	7	6	883	128	13.3	Björnsson, 1975
	1961-1963	10 months	7	1	883	128	26.4	Björnsson, 1975
	August 1984	5 days	9	7	900	87	8.6	Elefsen and Hauksson, 1984
	August 1984	5 days	9	1	900	87	18.6	Elefsen and Hauksson, 1984
	July 2003	12 hours		7	884-890	84	7.7	Sigurðsson, 2003
	Sept. 2008	1 day	7.8	5	875	70.8	7.9	Björnsson et al., 2009
	Sept. 2008	1 day	7.8	7	875	70.8	6.1	Björnsson et al., 2009

There is no significant change in the downhole temperatures and discharge enthalpy of the wells through this period but well HV-8 shows a clear decline in output after 1979. One reason for that may be scaling of calcite and aragonite in the well (Björnsson et al., 2009). It was cleaned and deepened by 20 m in 2003 but that did not bring the output up to former values (Sigurðsson, 2003).

Pressure records in HV-5 and other wells indicate a general decline in reservoir pressure by about 2 bars after 1990 or even after 1994. The reason for this decline is not known but changes due to tectonic stresses and earthquake activity are considered more likely than drawdown by utilization (Steingrímsson et al., 2000).

Regarding duration and simultaneous flow test of all wells the results obtained in 1961-1963 are still regarded the best representation of the potential of the system. The interpretation that the inflow into wells is only reservoir water is on the conservative side for the steam flow as boiling of the inflowing reservoir fluid might have led to an inflow of water and steam and a higher inflow enthalpy than that of the reservoir water.

Table 4. *Results of flow tests of production wells in Ölfusdalur 1961-1963 (Björnsson, 1975).*

Well	Depth	Max temp.	Depth of max temp.	Separation pressure at 6 bar-a		Enthalpy	Thermal potential above 35°C	Electric potential in binary cycles	Remaining thermal potential above 35°C
				Q_{total}	Q_{steam}				
	(m)	(°C)	(m)	(kg/s)	(kg/s)	(kJ/kg)	(MW_{th})	(MW_e)	(MW_{th})
HV-1	982	232	612	-	-	-	-	-	-
HV-2	407	193	204	93.4	5.8	795	60.6	4.72	17.6
HV-3	654	218	408	75.3	9.3	925	58.6	4.38	14.2
HV-4	692	185	100	37.7	2.1	782	24.0	1.86	7.1
HV-5	1,206	197	250	-	-	-	-	-	-
HV-6	661	218	612	65.6	8.3	929	51.3	3.81	12.4
HV-7	831	230	357	54.7	8.0	971	45.1	3.36	10.3
HV-8	314	217	201	128.0	13.3	883	94.3	7.23	24.1
Total							**333.9**	**25.4**	**85.7**

Adding the potential of the wells one obtains a thermal potential above 35°C of 333.9 MW_{th} or an electric potential using binary cycles of 25.4 MW_e and a remaining thermal potential of 85.7 MW_{th}. This potential is much larger than in any of the medium enthalpy systems discussed in the chapters above.

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Appendix:

CD-disc with analyzed dataset of 193 medium enthalpy geothermal wells and an evaluation of the Ölfusdalur System in Iceland