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Geothermal Development in Iceland 2010-2014

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ABSTRACT

Utilization of geothermal energy has played a major role in the energy supply of Iceland for many decades. The country's geological characteristics related to its location on the Mid-Atlantic Ridge have endowed the country with an abundant supply of geothermal resources. The share of geothermal energy in the primary energy supply of Iceland is about 68%. The utilization of geothermal water for house heating and other direct uses started early in the twentieth century. Space heating is by far the most important direct utilization, covering 90% of all energy used for house heating in the country. Other sectors of direct use are swimming pools, snow melting, industry, greenhouses and fish farming. The total annual direct use of geothermal energy is estimated to be about 26,700 TJ (7,417 GWh). Geothermal electricity generation started 45 years ago and after a rapid growth during the last 15 years, mainly due to increased demand in the energy intensive industry, it has now reached 29% of the total electricity generation in the country. The total installed capacity is now 663 MWe and the annual generation about 5,245 GWh. After a brief description of the geological background of geothermal utilization in Iceland and the main characteristics of the geothermal resources the paper discusses each of the utilization sectors as well as ongoing research activities and prospects for future development.

1. INTRODUCTION

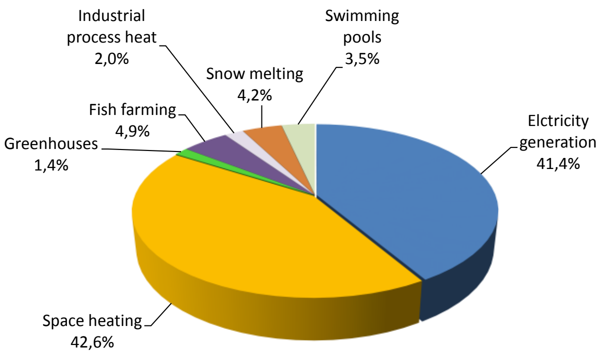
Iceland has a huge geothermal potential based on the location of the country on the Mid-Atlantic Ridge. The country is mountainous and volcanic, with much precipitation, making hydropower resources abundant. The population of Iceland is 325,000, of which almost two third live in the capital area. During the course of the 20th century, Iceland went from what was one of Europe’s poorest countries, dependent upon peat and imported coal for its energy, to a country with a high standard of living where practically all stationary energy, and roughly 86% of the primary energy comes from indigenous renewable sources (68% geothermal, 18% hydropower). The rest comes from imported fossil fuel used for the transport sector and fishing fleet. Iceland´s energy use per capita is among the highest in the world and the proportion provided by renewable energy sources exceeds most other countries.

The geothermal resources in Iceland are used to a great extend for both electricity generation and direct uses. In the high-temperature (>200°C) fields geothermal steam is utilized for electricity generation and to an increasing extend also for hot water production in so-called co-generation plants. Thus, the energy efficiency is improved considerably. The low-temperature (<150°C) fields are used mainly to supply hot water for district heating. The current utilization of geothermal energy for heating and other direct uses is considered to be only a small fraction of what this resource can provide. A master plan assessing the economic feasibility and the environmental impact of proposed power development projects has been adopted by the Icelandic Parliament.

It has been the policy of the government of Iceland to increase the utilization of renewable energy resources even further for the power intensive industry, direct use and the transport sector. A broad consensus on conservation of valuable natural areas has been influenced by increased environmental awareness. Thus, there has been opposition against large hydropower and some geothermal projects. The ownership of energy resources in Iceland is based on the ownership of land. However, exploration and utilization is subject to licensing.

2. OVERVIEW OF THE GEOTHRMAL UTILIZATION

Figure 1 gives a breakdown of the estimated utilization of geothermal energy in Iceland for 2014. Direct use of geothermal energy that year, i.e. for heating, was in total about 26,700 terajoules (TJ), which corresponds to 7,417 GWh of used energy. This is based on estimated inlet and outlet water temperature for each category (e.g. 35°C outlet temperature for space heating). In addition, electricity production by geothermal amounted to 5,245 GWh in 2013 and is expected to be similar in 2014. The 42.6% share of space heating was by far the greatest direct use sector while electricity production accounted for 41.4%. Several sources of information have been used to estimate the geothermal utilization. As a basis describing the status a few years back previous country update papers presented by the author have been used as well as a report published by Orkustofnun in 2010 (Haraldsson and Ketilsson, 2010). Orkustofnun has not been able to provide access to categorized information about the uses by district heating systems and other geothermal statistics during the last few years. Thus, the author has mainly relied on other sources like published papers, websites, power company annual reports and personal communication.



	Installed power	Energy consumption	
	MW	TJ/year	GWh/year
Space heating	1,550	19,400	5,389
Greenhouses	45	660	183
Fish farming	85	2,230	619
Industrial process heat	70	910	253
Snow melting	195	1,900	528
Swimming pools	90	1,600	444
Direct uses total	2,035	26,700	7,417
Elctricity generation	663	18,882	5,245
Geothermal utilization total	2,698	45,582	12,662

Figure 1: Geothermal utilization in Iceland 2014.

3. GEOLOGICAL BACKGROUND

Iceland is a geologically young country located in the North Atlantic astride the Mid-Atlantic Ridge, which is the boundary between the North American and Eurasian tectonic plates. The two plates are moving apart at a rate of about 2 cm every year. Due to this position geological and tectonic processes are extraordinary rapid and easily observed in Iceland. Some 20-30 volcanic eruptions occur every century on average, producing lava in the order of 45 km^3 every 1000 year. Some 400 km are exposed of the Mid-Atlantic ridge which makes it possible to observe a variety of tectonic processes such as volcanism and associated features (University of Iceland, 2014). A large number of volcanoes and hot springs are found in the country and earthquakes are frequent. The volcanic zone is running from the southwest to the northeast. More than 200 volcanoes are located within this zone and at least 30 of them have erupted since the country was settles over 1100 years ago. Associated with the volcanoes are numerous geothermal systems, ranging from freshwater to saline in composition and from warm to supercritical temperatures. At least 20 high-temperature areas exist within the volcanic zone with temperatures reaching 200°C within 1000 m depth. About 250 separate low-temperature areas with temperatures not exceeding 150°C in the uppermost 1000 m are mostly in the areas flanking the active volcanic zone. Over 600 hot spring areas (temperature over 20°C) have been located (Figure 2).

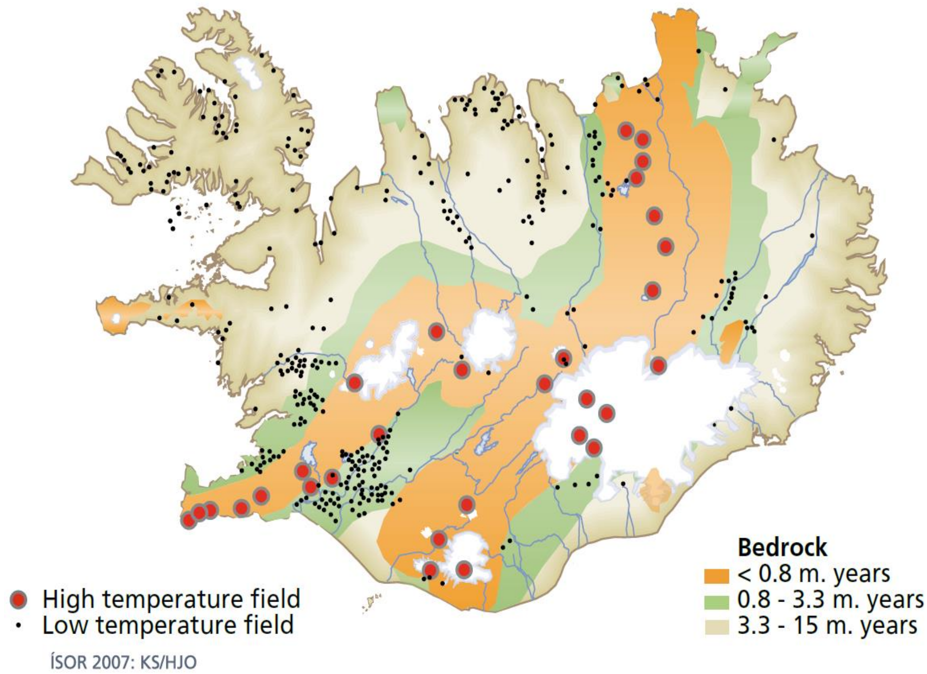


Figure 2: Volcanic zones and geothermal areas in Iceland.

4. SPACE HEATING

Different from most other geothermal countries, direct uses and especially space heating play a predominant role in the geothermal utilization in Iceland. The pioneer was a farmer at Sudur-Reykir in the vicinity of Reykjavík who started using geothermal water for heating his house in 1908 by transporting water from a hot spring through a pipeline over a distance of about 500 m. Utilization of geothermal energy for space heating on a large scale began with the laying of a 3 km long hot water pipeline from the hot springs of Laugardalur in Reykjavík in 1930. The formal operations of Reykjavík District Heating (now Reykjavík Energy) began in 1946. Following the oil price hikes of the 1970s, the government took the initiative in expanding district heating, with the result that the share of geothermal energy increased from 43% in 1970 to the current level of about 90%. This development is illustrated in Figure 3. About 30 separate geothermal district heating systems are operated in towns and villages in the country and additionally some 200 small systems in rural areas. These smaller systems supply hot water to individual farms or a group of farms as well as summerhouses, greenhouses and other users. Geothermal space heating has enabled Iceland to import less fossil fuel, and has resulted in a very low heating cost compared to most other countries. Using geothermal energy, which is classified as a renewable energy source, for space heating has also benefited the environment. Although most of the towns and villages in Iceland with the possibility of geothermal heating have already such a system in operation, exploration activities are ongoing with the aim to develop geothermal heating in new areas.

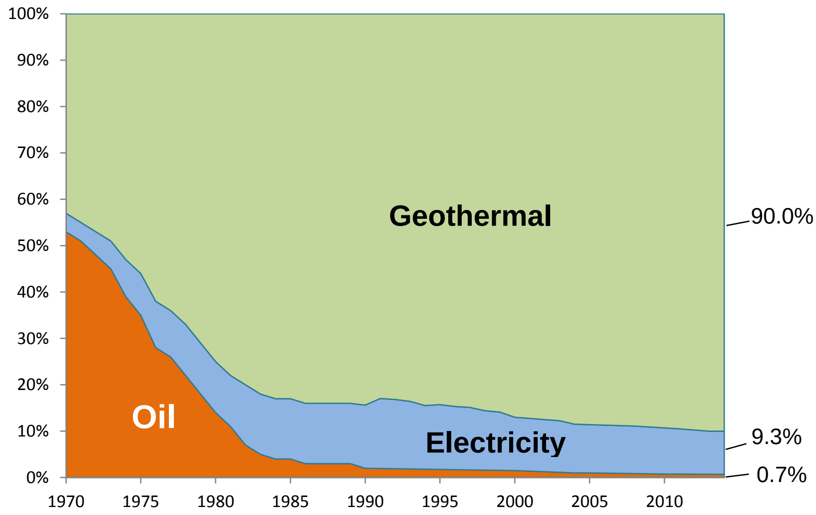


Figure 3: Energy sources used for space heating in Iceland 1970-2014.

4.1 District heating in Reykjavík

Reykjavík Energy (Orkuveita Reykjavíkur) is a public utility responsible for distribution and sale of both hot water and electricity as well as the city's waterworks and sewage system. The total number of employees is about 420 and the turnover in 2013 was 38,600 million ISK (322 million US$ based on the average 2013 exchange rate). Reykjavík Energy is by far the largest geothermal district heating utility in Iceland. It serves in total over 200,000 people or about 67% of the Icelandic population, the entire population of Reykjavík, plus neighboring communities as well as some additional villages in separate smaller systems.

District heating in Reykjavík began in 1930 when some official buildings and about 70 private houses received hot water from geothermal wells, located close to the old thermal springs in Reykjavík. In 1943 delivery of hot water from the Reykir field, 18 km from the city, started. The district heating system was expanded gradually over the years to the whole greater Reykjavik area. Today Reykjavík Energy utilizes low-temperature areas within and in the vicinity of Reykjavík as well as the high-temperature fields at Nesjavellir, about 27 km away, since 1990 and Hellisheidi since 2010. At Nesjavellir and Hellisheiði fresh water is heated in co-generation power plants, producing both electricity and hot water. A few years back Reykjavík Energy took over several district heating systems in operation outside the capital area. Some are small systems in rural areas, but others are among the largest geothermal district heating systems in the country. The total installed capacity of Reykjavik Energy district heating system is about 1,100 MWt and the total annual hot water production is over 80 million m^3 per year.

On 1 January 2014 the provision of the Icelandic Electricity Act dealing with electric energy market restructuring came into effect that obliges companies to segregate the licensed part from the competitive market operations. Then the company Our Nature (ON, Orka náttúrunnar) began operating on the competitive electricity market as a subsidiary, wholly-owned by Reykjavik Energy. Our Nature is responsible for the competitive part of the operation, which is generation and sale of electricity, while distribution of electricity and operations of the district heating systems, which are licensed activities, continue under Reykjavik Energy.

4.2 HS Orka and HS Veitur

The privately owned company HS Orka is responsible for production and sale of electricity and heat in the Reykjanes Peninsula. They are the only energy company in Iceland that has been fully privatized. HS Orka was previously a part of Hitaveita Sudurnesja (Sudurnes Regional Heating) which at the time of privatization was split in 2008 into HS Orka for generation and HS Veitur for distribution. Hitaveita Sudurnesja was a pioneer in building the co-generation power plant at Svartsengi in 1977. It is located about 50 km SW of Reykjavík. The plant utilizes 240°C geothermal brine from the Svartsengi field to heat fresh water for district heating (150 MWt, expected to increase by 25% in early 2015), and to generate electricity (74 MWe). HS Orka has a 100 MWe geothermal plant on Reykjanes that was commissioned in 2006 for electricity generation only. The company HS Veitur, which has a majority public ownership, takes care of the non-competitive distribution of energy from HS Orka. They serve four communities on the

Reykjanes peninsula with totally about 20,000 inhabitants with hot water, electricity and water. They also serve about 30,000 inhabitants in Hafnarfjordur and neighboring communities with electricity.

4.3 Nordurorka – District heating in Akureyri

Akureyri is a town of 18,000 inhabitants located in the central N-Iceland. It has been heated by geothermal energy since the end of the seventies. Hot water is pumped to Akureyri from five different geothermal fields. In addition to this, two 1.9 MWt heat pumps have supplied a small part of the annual energy production most of the time since 1984, but their contribution has been insignificant for the last decade or so. During the last few years several small district heating systems in neighboring communities have merged with Nordurorka. Thus, the total number of people served is now about 23,000. The total installed capacity is 103 MWt and the annual hot water consumption about 8.1 million m^3.

5. OTHER DIRECT UTILIZATION

5.1 Swimming and bathing

For centuries natural hot springs were mainly used for bathing in Iceland, but since early in the last century outdoor swimming pools as we know them today have been gaining popularity and they are today a part of the daily life of a large part of the nation. There are about 165 recreational swimming centers in the country, 140 of which use geothermal heat to keep the water temperature at 28-30°C year round. The combined surface area of the geothermally heated pools is about 34,000 m^2. Most of the swimming pools are open to the public throughout the year. They serve for recreational purposes and are also used for swimming lessons, which are compulsory in schools. Swimming is very popular in Iceland and swimming pool attendance has increased in recent years. In the greater Reykjavík area alone there are fourteen public outdoor pools and a few indoor ones. The largest of these is Laugardalslaug with 1,500 m^2 outdoor pools, 1,250 m^2 indoor pool and five hot tubs where the tub temperature ranges from 35 to 42°C. Other health uses for geothermal energy are the Blue Lagoon, the bathing facility at Bjarnarflag close to Lake Mývatn and the Health Facility in Hveragerdi, comprising geothermal clay baths and water treatments. Typically, about 220 m^3 of water or 40,000 MJ of energy is needed annually for heating one m^2 of pool surface area. This means that a new, mid-sized outdoor swimming pool uses as much hot water as heating 80-100 single-family dwellings. The total geothermal energy used for heating swimming pools in Iceland is estimated to be 1,600 TJ per year.

The Blue Lagoon mentioned above is a 5,000 m^2 surface pond that receives effluent brine from the Svartsengi power plant (42 l/s). At the start of operations of the power plant in 1977 the effluent water was discharged into the surrounding lava field, which was to absorb the water due to its high permeability. People started bathing in the pond and psoriasis patients discovered that the water had a beneficial effect on their skin. Later, showering facilities were added and in 1999 a man-made lagoon with a temperature of 37-39°C was created along with improved facilities for visitors. The Blue Lagoon contains about 6 million liters of brine and the hydraulic retention time is about 40 hours. The salt content is 2.5%, close to 70% of sea water. (Haraldsson and Cordero, 2014). In addition to the bathing facilities there are other important activities of the Blue Lagoon company. They operate a clinic for psoriasis patients that takes advantage of the therapeutic effects of the geothermal brine and produce skin care products that contain unique natural ingredients, silica, minerals and algae. The number of Blue Lagoon visitors has increased rapidly during the past years and reached 700,000 in 2014, making it one of Iceland's most popular tourist attractions.

5.2 Snow Melting

For a long time, geothermal water has been used to some extent in Iceland to heat sidewalks and pavements to melt snow during the winter. These uses have been gradually increasing and today almost all new buildings in areas with geothermal heating have snow melting systems. Iceland´s total area of snow melting systems is around 1,200,000 m^2, mostly in the capital area. Spent water from the houses, at about 35°C, is thus used for de-icing sidewalks and parking spaces. Most of the larger systems have the possibility to mix spent water from the houses with hot supply water from the district heating system (80°C) when the load is high. The main purpose is often to prevent icing or to make removal of the snow easier, rather than directly melt the snow. In downtown Reykjavík, a snow-melting system has been installed under most sidewalks and some streets, covering an area of 70,000 m^2. This system is designed for a maximum heat output of 180 W/m^2 surface area and the annual energy consumption is estimated to be 430 kWh/m^2. About two thirds of that energy comes from spent water from the space heating systems and one third directly from hot supply water. The total geothermal energy used for snow melting in Iceland is estimated to be 1,900 TJ per year.

5.3 Industrial Uses

The largest industrial user of geothermal energy in Iceland is the seaweed drying plant Thorverk, located at Reykhólar in West Iceland. It uses geothermal heat directly in its production. The company harvests seaweed found in the shallow waters of Breidafjordur bay using specially designed harvester crafts. Once landed, the seaweed is chopped and dried on a belt dryer that uses large quantities of air heated to 85°C by geothermal water. The plant has been in operation since 1975, and produces about 4,000 tonnes of rockweed and kelp meal annually using 36 l/s of 112°C water for the drying process. The 70°C hot return water from the seaweed drying plant is now utilized by a new table-salt factory, Nordursalt.

Since 1986, a facility at Haedarendi in Grímsnes, South Iceland, has produced commercial liquid carbon dioxide (CO_2) derived from the geothermal fluid of two gas rich wells. The Heidarendi geothermal field has an intermediate temperature (160°C) and a very high gas content (1.4% by weight). The gas discharged by the wells is nearly pure carbon dioxide with a hydrogen sulphide concentration of only about 300 ppm. Upon flashing, the fluid from the Haedarendi well would produce large amounts of calcium carbonate scaling. Scaling in the well is avoided by a 250 long downhole heat exchanger made of two coaxial steel pipes. Cold water is pumped down through the inner pipe and back up the annulus. Through this process, the geothermal fluid is cooled to arrest boiling and rapid degassing and the solubility of calcium carbonate is increased sufficiently to prevent scaling (reverse solubility). The plant uses approximately 6 l/s of fluid and produces some 3,000 tonnes CO_2 annually, which is a large share of the Icelandic gas market. The production is used in greenhouses to enrich the atmosphere, for manufacturing carbonated beverages and in other food industries.

Geothermal energy has been used in Iceland for drying fish for about 35 years. The main application has been the drying of salted fish, cod heads, small fish, stockfish and other products. Cod heads were traditionally dried by hanging them on outdoor stock racks. Because of Iceland´s variable weather conditions, indoor drying is preferred. Hot air is blown over the fish in batch dryers. Today about 10 companies dry cod heads indoors and all of them use geothermal hot water. The annual export of dried cod heads is about 10-12,000 tonnes. The product is shipped mainly to Nigeria where it is used for human consumption. Among the largest Icelandic producers of dried cod heads is the company Haustak. They buy about 1.3 kg/s of steam at 18 bar (220°C) from the nearby Reykjanes power plant to produce annually 2,500 tonnes of dried product from 12,000 tonnes of raw material. The steam is used to heat water up to 70°C for the drying process.

The Icelandic-American company Carbon Recycling International (CRI) has since 2012 operated a plant that uses CO_2 emissions of the Svartsengi geothermal power plant of HS Orka to produce methanol to blend with gasoline to fuel cars. Hydrogen used in the process is produced locally by electrolysis of water. The current production capacity is 1.7 million liters of methanol per year. Output from the plant is currently used directly as a blend component for standard petrol or as a feedstock for biodiesel from esterified vegetable oil or animal fats. CRI and HS Orka have signed an expanded Power Purchase agreement which guarantees the availability of sufficient power for CRI to expand the annual fuel production plant up to 5 million liters per year from about 6,000 tonnes CO_2.

Two salt factories that utilize geothermal energy in their production have recently been established in Iceland. The focus is on producing “gourmet” table salt. One of them is Nordursalt that has been in operation since 2013. They use 30 l/s of 70°C hot waste water from the nearby Thorverk seaweed plant, which was until then discharged to the sea. This water, together with 115°C water from a geothermal well that is useful for regulating the heat, is used for the evaporation process and to dry the salt. The other salt factory is Saltverk at Reykjanes in Northwestern Iceland. They started operation in 2011 and utilize about 10 l/s of 90-95°C hot water from a geothermal well that is cooled down to 70°C in the salt production process. The annual production is 70-80 tonnes of salt.

Several other industrial processes utilizing geothermal energy have been operated in Iceland in the past. Among them is the Kisilidjan diatomite plant at Lake Mývatn, which was among the largest industrial users of geothermal steam in the word until the plant was closed down in 2004 after almost 40 years of operation. Examples of other industrial applications that have been realized but are no longer in operation are a salt production plant on the Reykjanes peninsula utilizing geothermal brine and seawater, drying of imported hardwood in Húsavík by geothermal water, retreading of car tires and wool washing in Hveragerdi. Among smaller ongoing activities using geothermal energy are laundry processes and steam baking of bread at several locations and a concrete block plant with steam heated autoclaves. The total geothermal energy used as process heat in industry in Iceland is estimated to be 910 TJ per year.

5.4 Greenhouse Heating

Heating of greenhouses is one of the oldest and most important uses of geothermal energy in Iceland after space heating. Naturally warm soil had been used for outdoor growing of potatoes and other vegetables for a long time when geothermal heating of greenhouses started in Iceland in 1924. The majority of the greenhouses are located in the south, and most are enclosed in glass. The heating installations are of unfinned steel pipes hung on the walls and over the plants. Under table or floor heating is also common. It is also common to use inert growing media (volcanic scoria, rhyolite) on concrete floors with individual plant watering. By using electric lighting the growing season is extended to year round, which improves the utilization of the greenhouses and increases the annual production per square meter of greenhouse area. Artificial lighting, which also produces heat, has contributed to a diminishing demand for hot water supply to greenhouses. As a consequence of the lengthening of the growing season the need for new constructions is less than before. CO_2 enrichment in greenhouses is common, primarily by using CO_2 produced in the geothermal plant at Haedarendi (see Chapter 5.3). Outdoor growing at several locations is enhanced by soil heating with geothermal water, especially during early spring (Ragnarsson, 2013).

The total surface area of greenhouses in Iceland was about 194,000 m^2 in 2012 including plastic tunnels for bedding and forest plants. Of this area, 50% is used for growing vegetables (tomatoes, cucumbers, paprika etc.) and the rest mainly for growing cut flowers and potted plants. The total production of vegetables in 2011 was about 18,000 tonnes. The share of domestic production in the total consumption of tomatoes in Iceland is about 75% and for cucumbers about 90%.

Most of the greenhouses in Iceland have automatic control of the indoor climate and thus, for example, the temperature can be adjusted to the optimum temperature for different kinds of crops, ranging from 10-15°C in nurseries up to 20-25°C for roses. Also, the temperature is commonly adjusted to follow the optimum daily variations. The main parameters that influence the heat loss from greenhouses and thereby the heating demand are the outdoor temperature, wind speed, greenhouse cover material, indoor temperature, artificial lighting, heating system arrangement and opening of the windows. A study made on energy consumption for heating a group of typical greenhouses in Iceland resulted in an average energy consumption of 3.67 GJ/m^2 in greenhouses with artificial lighting and 5.76 GJ/m^2 in greenhouses without artificial lighting (Haraldsson and Ketilsson, 2010). The total geothermal energy used in Icelandic greenhouses is estimated to be 660 TJ per year.

5.5 Aquaculture

Fish farming has been a slowly growing sector in Iceland for a number of years. After a rapid growth from 2002 the total production reached about 10,000 tonnes in 2006, mainly salmon. The dominating species are now salmon and arctic char followed by trout. There are about 70 fish farms in Iceland and the total production was about 7,000 tonnes in 2013. Of these fish farms between 15 and 20 utilize geothermal water. Initially, Iceland’s fish farming was mainly in shore-based plants. Geothermal water, commonly 20-50°C, is used to heat fresh water, either in heat exchangers or by direct mixing, typically from 5 to 12°C for juvenile production. The beginning of the 21st century saw growing interest in developing sea cage farming of salmon in the sheltered fjords on Iceland’s east coast. Two large farms were established and remained in operation for a few years, but today only two small cage farms are in operation. The main use of geothermal energy in the fish farming sector in Iceland is for juvenile’s production (char and salmon). In land-based char production geothermal energy is also used for post-smolt rearing. Geothermal utilization in the fish farming sector is expected to increase in the coming years (Ragnarsson, 2013). The total geothermal energy used in the fish farming sector in Iceland is estimated to be 2,230 TJ per year.

A fish farming plant owned by the company Stolt Sea Farm started breeding warm-water Senegalese sole at Reykjanes peninsula, Iceland, in 2013. It is the first stage of a large indoor land-based plant that is planned. The 22,500 m^2 plant is located close to a 100 MWe geothermal power plant owned by the energy company HS Orka. The power plant uses a large amount of sea water for the tubular power plant condensers which is at the outlet at a temperature of 35°C, flows by gravity to the sea and a part of it goes to the fish farm. There it is mixed with sea water that is pumped from wells and used in the rearing tanks at about 21°C, which is the optimum temperature for the fish. The water temperature can be kept constant throughout the year without any influences from the environment. In mid-2014 there were about 1.2 million juveniles in the plant and that number is increasing. They are grown to about 400 g before the Senegalese sole is slaughtered and transported fresh to markets in Europe. The production capacity of the first stage is 500 tonnes per year, but the planned production after reaching the final stage is 2,000 tonnes per year. In mid-2014 the number of employees was 14 and it is expected to increase to 60-70 in the final stage.

6. ELECTRIC POWER GENERATION

Geothermal power accounts for a significant share of the electricity generation in Iceland which mainly results from a relatively rapid development during the past 15 years. Figure 4 gives an overview of the individual plants and Figure 5 shows how the generation has developed during the period 1970-2013. The total installed capacity of geothermal generating plants is now 663 MWe. The total production in 2013 was 5,245 GWh, which is 29% of the total electricity production in the country. The production in 2014 is expected to be similar to the production in 2013.

Plant name	Pland size MW	Year	Unit size MW	No of units	Type	Temp. °C	Pressure bar	Flow rate t/h	Estimated production GWh/yr
Krafla	60	1978	30	1	DF	172/122	7.2/1.1	400/130	480
		1997	30	1	DF				
Svartsengi	74.4	1977	1	2	SF	159	5	166	611
		1981	6	1	SF	155	4.5		
		1989-1993	1.2	7	B	103	0.12	131	
		1999	30	1	SF	163	5.5	275	
		2007	30	1	DS	198	15	288	
Bjarnarflag	3.2	1969	3.2	1	SF	182	9.5	45	26
Nesjavellir	120	1998	30	2	SF	188	12	432	960
		2001	30	1	SF	192	12	198	
		2005	30	1	SF	192	12	198	
Húsavík	2	2000	2	1	B	122		324	16
Reykjanes	100	2006	50	2	SF	210	18	288	800
Hellisheiði	303	2006	45	2	SF	178	8.5	600	2,400
		2007	33	1	SF	124	1.05	315	
		2008	45	2	SF	178	8,5	600	
		2010	45	2	SF	178	8,5	600	
Total	662.6			29				4,460	5,293

Figure 4: Geothermal power plants in Iceland.

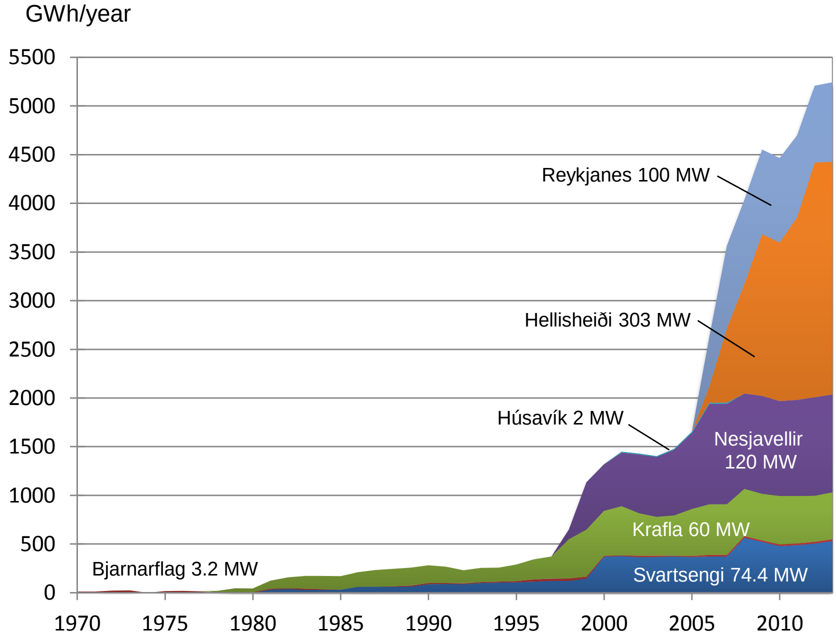


Figure 5: Electricity generation by geothermal energy in Iceland 1970-2013.

The oldest geothermal power plant in Iceland is in **Bjarnarflag** where a 3 MWe back pressure unit started operation in 1969. The turbine installed was bought second hand from a sugar refinery, but it was later refurbished. The plant is using steam from a well in the Namafjall geothermal field within the lake Mývatn area in North Iceland. The same well has been used to supply heat for industrial applications, district heating and a geothermal spa. The power plant has been operated successfully ever since the beginning except for three years in 1985-1987 when the plant was closed, partly due to volcanic activity in the area. Exploration drilling has been performed in preparation of further development of the Namafjall field by a new 90 MWe power plant in two stages.

The **Krafla** power plant is located near the lake Mývatn in North Iceland (about 10 km from the Bjarnarflag plant) and has been operating since 1977. Two 30 MWe double flash condensing turbine units were purchased when the plant started, but due to unexpected difficulties with steam supply the plant was run with only one installed turbine for the first 20 years. The shortfall of steam was due to volcanic activity that injected volcanic gases into the most productive part of the geothermal reservoir. Volcanic eruptions occurred only about two kilometers away from the power plant, posing a serious threat to its existence. Initially the power generation was 8 MWe, but reached 30 MWe in 1982. The capacity of the Krafla power plant was expanded in 1997 from 30 to 60 MWe by commissioning the second turbine, and further expansion is being considered. Totally, 33 wells have been drilled in the area, including 17 high pressure and 5 low-pressure production wells. The plant uses 110 kg/s of 7.7 bar saturated high-pressure steam and 36 kg/s of 2.2 bar saturated low-pressure steam.

The **Svartsengi** co-generation power plant of HS Orka has been producing both hot water and electricity since it started operation in 1977. It is located on the Reykjanes peninsula, about 40 km from Reykjavík, and serves about 20,000 people. The reservoir fluid is a brine at 240°C and with a salinity of about two thirds of sea water. The total production from the reservoir is about 400 kg/s. Of that between 50 and 75% is reinjected. Geothermal heat is transferred to freshwater in several heat exchangers. After expanding the plant in several steps the total installed capacity in Svartsengi is now 150 MWt for hot water production (expected to increase further by 25% in early 2015) and 74 MWe for electricity generation. Of that 8.4 MWe come from Ormat binary units using low-pressure waste steam. A part of the effluent brine from Svartsengi (40 l/s) goes the Blue Lagoon (see Chapter 5.1).

HS Orka started operation of a new 100 MWe geothermal power plant at **Reykjanes** in May 2006 (two 50 MWe steam turbines with sea cooled condensers). An expansion of the plant has been under preparation for some time, totally by 80 MWe of which 30 MWe are planned to be produced by using brine from high pressure separators. These plans are now being reconsidered.

Reykjavík Energy has been operating a co-generation power plant at **Nesjavellir** high temperature field north of the Hengill volcano since 1990. A mixture of steam and geothermal brine is transported from the wells to a central separator station at 200°C and 14 bars. The primary purpose of the plant is to provide hot water for the Reykjavík area, 27 km away. Freshwater is heated by geothermal steam and hot water in heat exchangers, first by preheating within the turbine condensers and thereafter by utilizing the heat from the liquid brine from the separators. After deaeration a small amount of geothermal steam containing hydrogen sulfide is injected into the water to remove any remaining oxygen and thereby preventing corrosion and scaling. The hot water is pumped to a large storage tank at an elevation of 400 m from where it flows by gravity to smaller tanks in Reykjavík. The capacity of the plant is about 300 MWt which corresponds to 1,800 l/s of district heating water at 83°C. The power plant started generating electricity in 1998 when two 30 MWe steam turbines were put into operation. In 2001, a third turbine was installed and the plant enlarged to a capacity of 90 MWe, and to 120 MWe in 2005.

Reykjavík Energy started operation of a new 90 MWe geothermal power plant at **Hellisheidi** in the southern part of the Hengill area in October 2006. It was expanded by a 33 MWe low pressure unit in 2007 and further by installing two 45 MWe units in late

2008 and additionally two 45 MWe units in 2011, increasing the total installed capacity of the plant to 303 MWe. Hot water production for district heating in Reykjavík started at Hellisheidi in 2010. Due to increased demand for steam connecting of additional wells drilled in 2007 and 2008 to the plant is now being done. Originally these wells were planned for a new power plant that was expected to be built (Hverahlid), but it was decided to transport the steam over a distance of 5 km to the Hellisheidi plant.

At **Húsavík**, in Northeast Iceland, the generation of electricity using geothermal energy began in 2000 when a 2 MW binary-fluid power plant, based on Kalina cycle technology, was put into service. Due to operational problems the plant has not been in operation since January 2008. It was one of the first of its kind in the world. The plant utilized about 90 kg/s of 120°C hot geothermal water from wells located about 20 km south of Husavík. This water was used as an energy source to heat a mixture of water and ammonia, which in closes circuit acts as a working fluid for the heat exchangers and a turbine. The Kalina cycle gains efficiency by the ability of the working fluid to closely parallel the temperature of the heat source and the heat sink. Part of the hot water leaving the generating plant at 80°C was used for the town´s district heating, as well as the local swimming pool and other direct uses.

7. OTHER GEOTHERMAL ACTIVITIES

Drilling activities. The development of geothermal drilling activities in Iceland in the period 1970 to 2013 is shown in Figure 6 as the total well depth drilled annually. As can be seen there have been substantial variations in the drilling activity in this period. Before the economic crisis hit Iceland in late 2008 the geothermal industry had grown rapidly over a number of years. This resulted in an increase of total installed capacity for power generation of a factor of almost three in a five years period. In 2009 the Icelandic energy companies reduced considerably their geothermal activities compared to their previous plans. As a result of these delayed projects there has been a drastic reduction in the geothermal drilling activity from a high of 28 high-temperature wells drilled in 2008 to no high-temperature well drilled in 2014. As a consequence of this most of the larger Icelandic drill rigs are working on overseas projects.

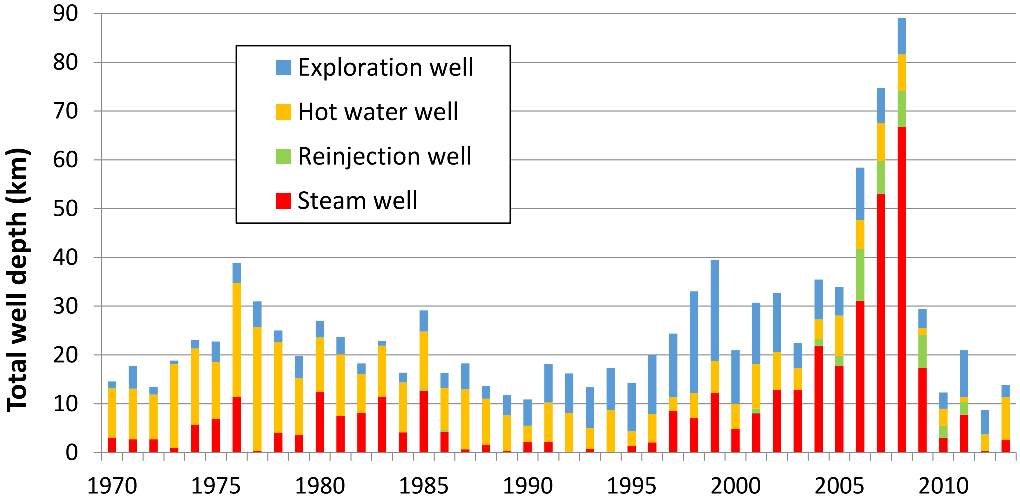


Figure 6: Total depth of geothermal wells drilled annually in Iceland 1970-2013.

CarbFix and Sulfix projects. Reykjavík Energy, in cooperation with Icelandic and foreign scientists, has for several years been working on projects aiming at reducing the gas emission from geothermal power plants. The process is based on dissolving the gases in water before injection into the bedrock where minerals will be formed in the same way as happens in the nature. Experiments have been performed at Hellisheidi power plants. A gas separation plant is used to separate different streams of gases. The carbon dioxide is then diverted to 400-800 m deep drillholes (CarbFix project) where the liquid will react with calcium from the basalt and form calcite. This process occurs naturally and the mineral calcite is stable for thousands of years in geothermal systems. The hydrogen sulfide is re-injected into the geothermal reservoir (SulFix project). The main difference between the SulFix project and the CarbFix project is that the sulphides and the carbonate minerals are stable at different temperature. For this reason the hydrogen sulphide has to be injected deep into the reservoir.

Iceland Deep Drilling Project (IDDP). A consortium of Icelandic energy companies and international organizations has for about 15 years been working on a project aiming at drilling 4-5 km deep wells into high-temperature hydrothermal systems in Iceland to reach 400-600°C hot supercritical fluid. The main purpose of the IDDP project is to find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. Drilling of the first well started in the Krafla field in late 2008 and continued in 2009. Drilling of IDDP-1 at Krafla had to be abandoned short of target depth when magma was intersected by the drill bit at 2114 m depth. Due to this the IDDP postponed the planned drilling of two additional wells in other geothermal fields in Iceland. Meanwhile the Krafla well has been flow-tested and further research projects carried out. The plan is now to drill an IDDP well at the Reykjanes geothermal field in the near future.

Geothermal clusters. The Iceland Geothermal Cluster (http://www.icelandgeothermal.is) is an industry-driven cooperation that was established a few years back with the aim to promote Iceland’s qualities as the land of geothermal energy and geothermal energy production. The membership is composed of 55 companies and institutions that all are somehow involved in the geothermal industry. The purpose of the organization is to stimulate competitiveness among it´s members, add value in the sector, and improve the utilization of Iceland’s geothermal energy. Among the group's aims is to increase the number of products and services within geothermal, increase domestic and foreign investments, and increase exports of goods and services in the field of geothermal energy. GEORG (GEOthermal Research Group, http://georg.hi.is) is a research-driven geothermal cluster cooperation joining efforts in geothermal research and innovations. It is supported by the Icelandic Centre for Research (Rannís) and has 22 members from Icelandic and international organizations, research centers and universities. GEORG is cooperating with the Iceland Geothermal Cluster mentioned above to maximize the added value of the projects organized by the individual platforms.

UNU-GTP. The Geothermal Training Programme of the United Nations University (UNGTP) has operated in Iceland since 1979 with six months annual courses for training geothermal professionals from developing countries. In 2014 a total number of 29 fellows attend the training course. Specialized training is offered in different geothermal disciplines. Most of the candidates receive scholarships financed by the Government of Iceland and the UNU, although the number of cases where the study is financed by the candidate's employer in the homeland has increased in recent years. UNU-GTP has supported it´s fellows to continue their education and a MSc. programme was started in 2000 and a PhD programme in 2008 at the University of Iceland. Also, annual workshops/short courses are held in Africa, Central America, and Asia. From the beginning a total number of 583 scientists and engineers from 58 countries have completed the six month courses and 40 have completed the MSc. Programme. The first fellow defended his PhD degree in yearly 2013 and additional two are expected to finish their PhD studies in 2015.

8. DISCUSSION

The Icelandic energy companies have plans for expansion of their geothermal electricity generation. New developments did slow down considerably after the financial crisis in 2008 which resulted in delays in projects that were planned. The most developed project by the end of 2014 is in the Theistareykir geothermal field in North Iceland, not far from the Krafla geothermal field. There, Landsvirkjun (The National Power Company) plans to build a 45 MWe power plant in the first phase. Seven deep wells have already been drilled in the area and construction work has started. If the plans for full development to 200 MWe will be realized it is expected that a total number of 40 wells will be needed.

The use of heat pumps for space heating in areas of Iceland where geothermal heating is not available (about 10% of the total) has been very limited. However, during the last few years a number of heat pumps, mainly heat pumps that extract heat from the outside air, have been installed with financial support from the government. Geothermal heat pumps are also becoming more common and it has been estimated that 60-70 such systems are in operation in Iceland, most of them of horizontal ground loop type.

There is a large potential for increased utilization of geothermal energy in Iceland and geothermal electricity generation is expected to increase in the coming years, but direct uses will most likely only grow at a moderate rate.

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TABLE 1. PRESENT AND PLANNED PRODUCTION OF ELECTRICITY

	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables[1]		Total	
	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr	Capacity MWe	Gross Prod. GWh/yr
In operation in December 2014	663	5245	114	3	1986	12863			2	5	2765	18116
Under construction in December 2014												
Funds committed, but not yet under construction in December 2014	45	369									45	369
Estimated total projected use by 2020	738	5854	114	3	2079	13582			20	60	2951	19499

[1] Wind power

TABLE 2. UTILIZATION OF GEOTHERMAL ENERGY FOR ELECTRIC POWER GENERATION AS OF 31 DECEMBER 2014

1) N = Not operating (temporary), R = Retired. Otherwise leave blank if presently operating.

2) 1F = Single Flash B = Binary (Rankine Cycle)
2F = Double Flash H = Hybrid (explain)
3F = Triple Flash O = Other (please specify)
D = Dry Steam

3) Data for 2014.

Locality	Power Plant Name	Year Commissioned	No. of Units	Status1)	Type of Unit2)	Total Installed Capacity MWe*	Total Running Capacity MWe*	Annual Energy Produced 2013 3) GWh/yr	Total under Constr. or Planned MWe
Bjarnarflag	Bjarnarflag	1969	1		1F	3.2		18	
Krafla	Krafla	1978/97	2		2F	60		482	
Svartsengi	Svartsengi	1977/99	2		1F	36		253	
Svartsengi	Svartsengi	1989/93	7		B	8.4		61	
Svartsengi	Svartsengi	2007	1		D	30		218	
Nesjavellir	Nesjavellir	1998/05	4		1F	120		1005	
Húsavík	Húsavík	2000	1		B	2		0	
Hellisheidi	Hellisheidi	2006/11	7		1F	303		2390	90
Reykjanes	Reykjanes	2006	2		1F	100		818	80
Theistarey	Theistareykir								90
Total			25			662.6		5245	260

* Installed capacity is maximum gross output of the plant; running capacity is the actual gross being produced.

TABLE 3. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 2014 (other than heat pumps)

1) I = Industrial process heat
C = Air conditioning (cooling)
A = Agricultural drying (grain, fruit, vegetables)
F = Fish farming
K = Animal farming
S = Snow melting
H = Individual space heating (other than heat pumps)
D = District heating (other than heat pumps)
B = Bathing and swimming (including balneology)
G = Greenhouse and soil heating
O = Other (please specify by footnote)

2) Enthalpy information is given only if there is steam or two-phase flow

3) Capacity (MWt) = Max. flow rate (kg/s)[inlet temp. (^{o}C) - outlet temp. (^{o}C)] x 0.004184 (MW = 10^6 W)
or = Max. flow rate (kg/s)[inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

4) Energy use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (^{o}C) - outlet temp. (^{o}C)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.03154

5) Capacity factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171
Note: the capacity factor must be less than or equal to 1.00 and is usually less,
since projects do not operate at 100% of capacity all year.

Note: please report all numbers to three significant figures.

Locality	Type[1)]	Maximum Utilization					Capacity[3)]	Annual Utilization		
		Flow Rate	Temperature (^{o}C)		Enthalpy[2)] (kJ/kg)			Ave. Flow	Energy[4)]	Capacity
		(kg/s)	Inlet	Outlet	Inlet	Outlet	(MWt)	(kg/s)	(TJ/yr)	Factor[5)]
Reykjavík	DBGISF	5842	80	35			1100	2409	14300	0,41
Seltjarnarnes	DBIS	159	80	35			30	56	335	0,35
Mosfellsbær	DBGIS	156	80	35			29	79	470	0,51
Sudurnes	DBISF	693	82	35			136	369	2290	0,53
Akranes and Borgarfj.	DBGF	36	78	35			7	12	70	0,34
Akranes	DBGIS	182	78	35			33	62	350	0,34
Borgarnes	DBGIS	50	82	35			10	23	145	0,47
Stykkishólmur	DB	41	80	35			8	19	110	0,46
Dalabyggd	D	24	65	35			3	11	45	0,48
Reykholar	DBG	17	95	35			4	3	26	0,19
Sudureyri	DB	22	70	35			3	10	45	0,44
Drangsnes	DB	10	60	35			1	24	80	2,54
Hvammstangi	DB	31	77	35			5	11	60	0,35
Blönduós	DB	58	64	35			7	25	95	0,43
Skagafjordur	DBGIS	174	72	35			27	88	430	0,51
Siglufjordur	DBI	45	70	35			7	17	80	0,39
Ólafsfjordur	DBI	89	62	35			10	38	135	0,43
Dalvík	DBISF	135	64	35			16	42	160	0,31
Hrísey	DB	24	79	35			4	8	45	0,33
Akureyri	DBIS	521	78	35			94	175	990	0,33
Húsavík	DBIF	139	80	35			26	54	320	0,39
Reykjahlíd	DB	24	99	35			7	11	90	0,44
Eskifjordur	DB	39	82	35			8	9	55	0,23
Egilsstadir	DBGIS	96	73	35			15	26	130	0,27
Rangæinga	DBI	100	74	35			16	33	170	0,33
Flúdir	DBGI	133	98	35			35	39	320	0,29
Blaskogabyggd	DBGI	156	85	35			33	83	545	0,53
Selfoss	DBI	358	75	35			60	102	540	0,29
Hveragerdi	DBGI	254	82	35			50	61	380	0,24
Thorlákshofn	DBIF	49	94	35			12	24	190	0,50
Reykhólar	I	46	112	70			8	36	200	0,79
Other users	DGBSIF	1381	80	35			260	590	3500	0,43
TOTAL		11083					2064	4549	26700	0,41

TABLE 4. GEOTHERMAL (GROUND-SOURCE) HEAT PUMPS AS OF 31 DECEMBER 2014

This table should report thermal energy used (i.e. energy removed from the ground or water) and report separately heat rejected to the ground in the cooling mode as this reduces the effect of global warming.

1) Report the average ground temperature for ground-coupled units or average well water or lake water temperature for water-source heat pumps

2) Report type of installation as follows: V = vertical ground coupled (TJ = 10^{12} J)
H = horizontal ground coupled
W = water source (well or lake water)
O = others (reserve power based on heat from DH return water)

3) Report the COP = (output thermal energy/input energy of compressor) for your climate

4) Report the equivalent full load operating hours per year, or = capacity factor x 8760

5) Thermal energy (TJ/yr) = flow rate in loop (kg/s) x [(inlet temp. (^{o}C) - outlet temp. (^{o}C)] x 0.1319
or = rated output energy (kJ/hr) x [(COP - 1)/COP] x equivalent full load hours/yr

Note: please report all numbers to three significant figures

Locality	Ground or Water Temp. (^{o}C)[1)]	Typical Heat Pump Rating or Capacity (kW)	Number of Units	Type[2)]	COP[3)]	Heating Equivalent Full Load Hr/Year[4)]	Thermal Energy Used (TJ/yr)	Cooling Energy (TJ/yr)
	0-10°C	10 (tot. 50)	4	V	3-4		1	
	0-10°C	10 (tot. 700)	60	H	3-5		13	
	0-10°C	10 (tot. 150)	5	W	3-6		3	
Akureyri	30	1900	2	O	4		0	
TOTAL		4.700					17	

TABLE 5. SUMMARY TABLE OF GEOTHERMAL DIRECT HEAT USES AS OF 31 DECEMBER 2014

1) Installed Capacity (thermal power) (MWt) = Max. flow rate (kg/s) x [inlet temp. (^oC) - outlet temp. (^oC)] x 0.004184
or = Max. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg)] x 0.001

2) Annual Energy Use (TJ/yr) = Ave. flow rate (kg/s) x [inlet temp. (^oC) - outlet temp. (^oC)] x 0.1319 (TJ = 10^{12} J)
or = Ave. flow rate (kg/s) x [inlet enthalpy (kJ/kg) - outlet enthalpy (kJ/kg) x 0.03154

3) Capacity Factor = [Annual Energy Use (TJ/yr)/Capacity (MWt)] x 0.03171 (MW = 10^6 W)
since projects do not operate at 100% capacity all year

Note: please report all numbers to three significant figures.

Use	Installed Capacity[1] (MWt)	Annual Energy Use[2] (TJ/yr = 10^{12} J/yr)	Capacity Factor[3]
Individual Space Heating[4]			
District Heating [4]	1550	19400	0,40
Air Conditioning (Cooling)			
Greenhouse Heating	45	660	0,47
Fish Farming	85	2230	0,83
Animal Farming			
Agricultural Drying[5]			
Industrial Process Heat[6]	70	910	0,41
Snow Melting	195	1900	0,31
Bathing and Swimming[7]	90	1600	0,56
Other Uses (specify)			
Subtotal	2035	26700	0,42
Geothermal Heat Pumps	5	17	0,11
TOTAL	2040	26717	0,42

4) Other than heat pumps
5) Includes drying or dehydration of grains, fruits and vegetables
6) Excludes agricultural drying and dehydration
7) Includes balneology

TABLE 6. WELLS DRILLED FOR ELECTRICAL, DIRECT AND COMBINED USE OF GEOTHERMAL RESOURCES FROM JANUARY 1, 2010 TO DECEMBER 31, 2014 (excluding heat pump wells)

1) Include thermal gradient wells, but not ones less than 100 m deep

Purpose	Wellhead Temperature	Number of Wells Drilled				Total Depth (km)
		Electric Power	Direct Use	Combined	Other (specify)	
Exploration[1]	(all)		47			10
Production	>150^o C	7				13
	150-100^o C					
	<100^o C		23			18
Injection	(all)	6				5
Total		13	70			46

TABLE 7. ALLOCATION OF PROFESSIONAL PERSONNEL TO GEOTHERMAL ACTIVITIES (Restricted to personnel with University degrees)

(1) Government
(2) Public Utilities
(3) Universities
(4) Paid Foreign Consultants
(5) Contributed Through Foreign Aid Prograi
(6) Private Industry

Year	Professional Person-Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
2010	60	75	15			90
2011	60	75	15			90
2012	60	75	15			90
2013	60	75	15			90
2014	60	75	15			90

TABLE 8. TOTAL INVESTMENTS IN GEOTHERMAL IN (2014) US$

Period	Research & Development Incl.	Field Development Including Production	Utilization		Funding Type	
			Direct	Electrical	Private	Public
	Million US$	Million US$	Million US$	Million US$	%	%
1995-1999	13	76	20	174		100
2000-2004	37	72	10	80		100
2005-2009	58	881	37	925		100
2010-2014	20	40	10	260	25	75