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Geothermal Development in Iceland 2015-2019

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ABSTRACT

Geothermal resources play a major role in the energy supply of Iceland. They are utilized both for electricity generation and direct heat application. The share of geothermal energy in the nation's primary energy supply is 62%. Space heating is the most important direct utilization of geothermal energy in Iceland, covering over 90% of all energy used for house heating in the country. Other sectors of direct use are swimming pools, snow melting, industrial process heat, greenhouses, aquaculture and soil warming. The geothermal fluid is also a source of silica and salts for skin care products and liquid carbon dioxide (CO_2) for soft drinks, greenhouses and industry. The total direct use of geothermal energy in 2019 is estimated to have been 9,328 GWh_{th} (33,600 TJ). Generation of electricity by geothermal energy has been increasing during the past two decades, mainly due to increased demand in the energy intensive industry. The total installed capacity is now 755 MW_e and the total generation in 2018 was 6,010 GWh_e, which is 30% of the electricity produced in the country.

1. INTRODUCTION

Iceland has a huge geothermal potential based on the location of the country on a hot spot on the Mid-Atlantic Ridge. The country is mountainous and volcanic, with much precipitation, making hydropower resources also abundant. The population of Iceland is about 360,000, of which almost two third live in the Reykjavik capital area. During the course of the 20th century, Iceland went from being one of Europe's poorest countries, dependent upon peat, dung and imported coal for its energy, to a country with a high standard of living where practically all stationary energy, and roughly 81% of the primary energy supply comes from indigenous renewable sources (62% geothermal (referenced to 15°C), 19% hydropower (generated electricity)). 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.

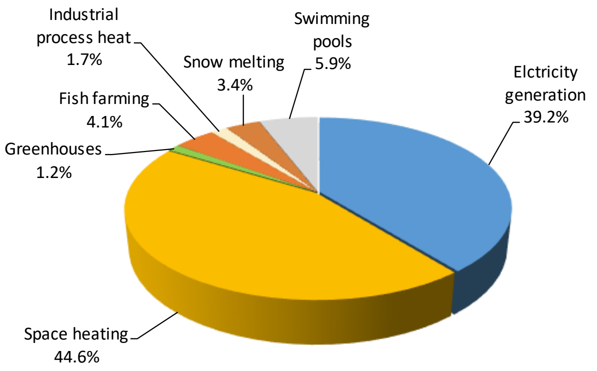
The geothermal resources in Iceland are used for both electricity generation and direct uses. In the high-temperature (>200°C) fields the geothermal steam fraction is utilized for electricity generation at eight sites. The brine fraction is used for hot water production for district heating in so-called co-generation plants at three of the sites. 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.

It has been the policy of the Government of Iceland to increase the utilization of renewable energy resources even further for power generation, direct uses 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 hydropower and some geothermal projects. The ownership of energy resources in Iceland is based on the ownership of land. However, exploration and utilization are subject to licensing.

A master plan assessing the economic feasibility and the environmental impact of selected power development projects was adopted by the Icelandic Parliament about 20 years ago. It is a tool to reconcile the often competing interests of nature conservation and energy utilization on a national scale and at the earliest planning stages. The Master Plan is currently in its fourth phase, which is due to be completed in 2021 (Bjornsson et al., 2012), (The Master Plan for Nature Protection and Energy Utilization).

2. OVERVIEW OF GEOTHERMAL UTILIZATION

Figure 1 shows a breakdown of the utilization of geothermal energy in Iceland for 2019, both for direct uses and for power generation (Orkustofnun A and B, 2019). Direct uses of geothermal energy, i.e. for heating, was estimated in total to be 33,579 terajoules (TJ), which corresponds to 9,328 GWh_{th} of used energy. Calculation of the used energy is based on estimated inlet and outlet water temperature for each category (e.g. 35°C outlet temperature for space heating) and the corresponding annual flow. In addition, electricity production by geothermal amounted to 21,636 terajoules or 6,010 GWh_e. The 44.6% share of space heating was the largest geothermal use sector while electricity production accounted for 39.2%.



	Installed power	Energy consumption	
	MW	TJ/year	GWh/year
Space heating	1,650	24,603	6,834
Greenhouses	57	668	186
Fish farming	110	2,264	629
Industrial process heat	80	922	256
Snow melting	260	1,889	525
Swimming pools	210	3,232	898
Direct uses total	2,367	33,579	9,328
Elctricity generation	755	21,636	6,010
Geothermal utilization total	3,122	55,215	15,338

Figure 1: The sectoral share of geothermal utilization in Iceland 2019. Source of energy consumption: Orkustofnun, OS-2019 T007-01 and OS-2019 T006-01 for utilization in 2018. Assume electricity generation in 2019 unchanged from previous year and 2% annual increase in direct use for 2019.

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. 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 on land a variety of tectonic processes such as volcanism and associated features. Numerous volcanoes and hot springs are found in the country and earthquakes are frequent. The volcanic zone crosses the island 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 settled over 1100 years ago. Associated with the volcanoes are numerous geothermal systems, ranging from freshwater to saline in composition and from warm to supercritical in temperature. At least 25 high-temperature areas exist on land within the volcanic zone with temperatures reaching 200°C above 1000 m depth and several HT-fields are expected to be (a few are known) in ocean ridges southwest and north of Iceland. About 250 separate low-temperature areas with temperatures not exceeding 150°C in the uppermost 1000 m have been identified, mostly in the areas flanking the active volcanic zone. Over 600 hot spring areas (temperature over 20°C) have been located (Figure 2).

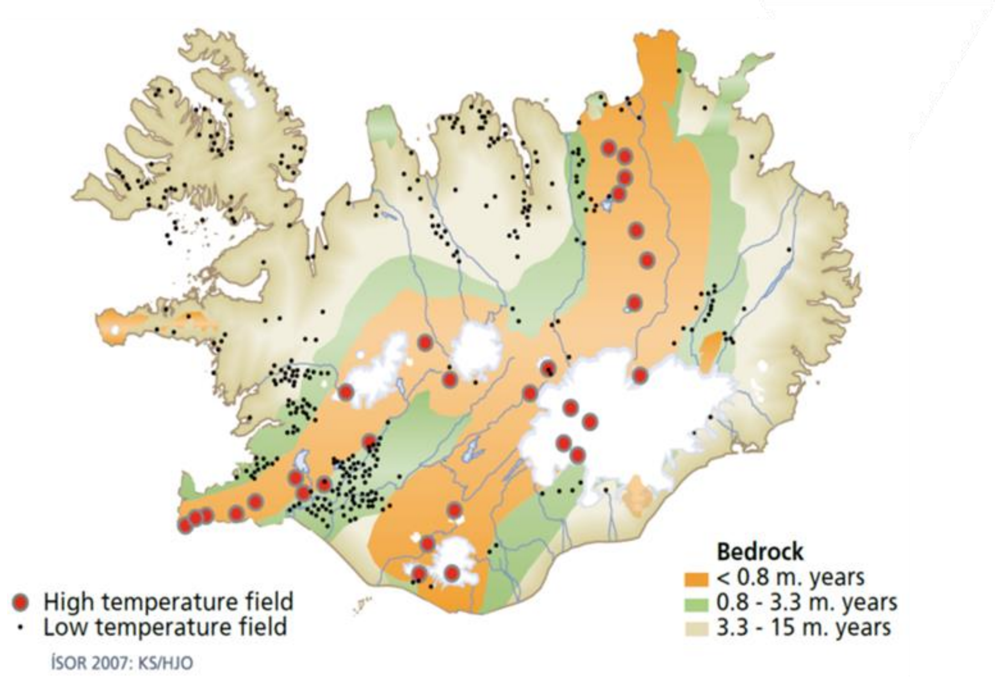


Figure 2: Volcanic zones and geothermal fields in Iceland.

4. SPACE HEATING

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 establishment of Reykjavík Municipal District Heating Service (now Reykjavík Energy) was in 1946. Following the oil price hikes of the 1970s, the Government took the initiative in eliminating oil from district heating, replacing it with geothermal energy, with the result that the share of geothermal energy increased from 43% in 1970 to the current level of about 90%. Buildings outside geothermal regions have electrical heating. 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 for the remaining villages and rural areas. Recently, the construction of a 20 km hot water transmission pipeline from the geothermal field at Hoffell to the town Höfn in Southeast Iceland started after many years of exploration in the area. The geothermal water will replace electricity as an energy source for the already existing district heating system and will serve a population of about 1,800 people.

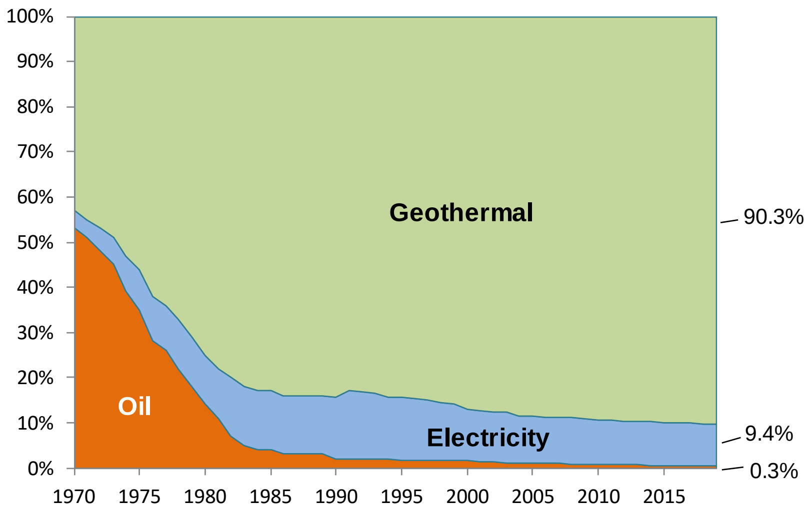


Figure 3: Energy sources used for space heating in Iceland 1970-2019.

4.1 District Heating in Reykjavík

Reykjavík Energy (Orkuveita Reykjavíkur) is a public utility responsible for production, distribution and sale of both hot water and electricity as well as the city's waterworks and sewage system and fibre optic cables. The principal owner is the City of Reykjavík, and since 2014 it provides its services through three subsidiaries; Veitur Utilities, ON Power and Reykjavík Fibre Network. The total number of employees is about 570 and the turnover in 2018 was about 46,000 million ISK (425 million US$ based on the average 2018 exchange rate). Reykjavík Energy is by far the largest geothermal district heating utility in Iceland. It serves in total about 240,000 people or about 65% of the Icelandic population, the entire population of Reykjavík and neighboring towns.

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 Hellisheidi cold ground water is heated in co-generation power plants. In the past a number of district heating systems were either bought or merged with Reykjavík Energy. Some are small systems in rural areas, but others are among the largest geothermal district heating systems in the country serving towns with population of several thousand people. The total installed capacity of Reykjavik Energy's district heating system is about 1,200 MW_{th} and the total hot water production is about 90 million m^3 per year.

4.2 HS Orka and HS Veitur

Hitaveita Sudurnesja (Sudurnes Regional Heating) was a pioneer in building the co-generation power plant at Svartsengi in 1976. It is located about 50 km SW of Reykjavík. In 2000, the operation was privatized and following changes in electricity legislation in 2008 the company was divided up into HS Veitur hf. and HS Orka hf. The plant in Svartsengi utilizes 240°C geothermal brine from the Svartsengi field to heat fresh water for district heating (190 MW_{th}), and to generate electricity (76.4 MW_e). HS Orka also has a 100 MW_e geothermal plant on Reykjanes that was commissioned in 2006 for electricity generation only.

4.3 Nordurorka – District heating in Akureyri

Akureyri is a town of about 19,000 inhabitants located in the north of Iceland. It has been heated by geothermal energy since the end of the 19-seventies. Hot water is pumped to Akureyri from six different geothermal fields. In addition to this, two 1.9 MW_{th} heat pumps supplied a small part of the annual energy production after their installation in 1984, but their contribution has been insignificant for the last decade or so. During the last few years, several small geothermal district heating systems in neighboring communities have merged with Nordurorka. Thus, the total number of people served is now about 24,000. The total installed capacity is 100 MW_{th} and the annual hot water consumption about 9 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 now a part of the daily life all year round. There are about 170 recreational swimming centers in the country, 145 of which use geothermal heat to keep the water temperature at 28-30°C. The combined surface area of the geothermally heated pools is about 35,000 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 as well. 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. The number of people visiting Laugardalslaug annually is about 800 thousand. Among other balneological uses for geothermal energy are the Blue Lagoon, the bathing facility Mývatn Nature Bath at Bjarnarflag close to Lake Mývatn, the Laugarvatn Fontana geothermal baths, the Secret Lagoon at Flúdir and the NLFI Spa and Medical Clinic in Hveragerdi, comprising geothermal clay baths and water treatments. In recent years several new geothermal spas have been established like Vök baths at Urridavatn, Geosea sea baths at Húsavík and Krauma spa in Reykholtsdalur

Typically, about 220 m^3 of geothermal 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 (50 m long) 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 in 2019 is estimated to be 3,232 TJ.

The Blue Lagoon mentioned above is a 8,700 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 1976 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 9 million liters of brine and the hydraulic retention time is about 40 hours. The salt content is 2.5%, close to 70% of seawater salinity. (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 a line of 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 was 1.3 million in 2018, making it one of Iceland's most popular tourist attractions.

5.2 Snow melting

Geothermal water is used 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 used for de-icing sidewalks and parking spaces. Most of the larger systems have the possibility to add 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, consisting of loops of buried plastic pipes, 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 in 2019 is estimated to be 1,889 TJ.

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. The company harvests seaweed found in the shallow sea waters of Breidafjordur bay using specially designed harvester crafts. Once landed, the seaweed is chopped and dried in 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. It uses 112°C hot geothermal water that is cooled down to 45°C in the drying process.

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 Haedarendi geothermal field has an intermediate temperature (160°C) and a very high gas content in the total flow (1.4% by weight). The gas discharged by the wells is nearly pure carbon dioxide. Upon flashing, the fluid from the Haedarendi well would deposit large amounts of calcium carbonate scaling. Scaling in the well is, however, avoided by installing 250 m and 300 m long downhole heat exchangers made of two coaxial stainless 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. The solubility of calcium carbonate increases sufficiently at lower temperatures to prevent scaling (inverse solubility). The plant extracts approximately 15 l/s of water from the wells and produces some 10,000 tonnes of CO_2 annually, which practically covers the needs of the Icelandic 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 (bacalao), cod heads, fish bones, 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 exported 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 geothermal steam at 18 bar (210°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 fresh water up to 70°C for the drying process.

The Icelandic-American company Carbon Recycling International (CRI) has since 2012 operated a pilot plant that uses CO_2 emissions of non-condensable gas in the steam from 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 4,000 tonnes of methanol per year from about 5,500 tonnes of CO_2. Output from the plant is exported and used directly as a blend component for standard petrol or as a feedstock for biodiesel from esterified vegetable oil or animal fats.

Two small salt factories that utilize geothermal energy in their production have been established in Iceland in the last decade. The focus is on producing "gourmet" table salt. One of them is Nordursalt at Reykhólar in West Iceland, which has been in operation since 2013. They use over 100°C hot geothermal water to boil seawater at 51°C under sub-atmospheric conditions 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.

Several other industrial processes utilizing geothermal energy have been operated in Iceland in the past. Among them was the Kísilidjan diatomite plant at Lake Mývatn, which was among the largest industrial users of geothermal steam in the word. The plant used about 13 kg/s of steam at 180°C (9 bar) and produced about 28,000 tonnes of diatomaceous earth filter aids for export annually. Kísilidjan was commissioned in 1968 and was operated until the plant was closed down in 2004 after 36 years of operation. Examples of other industrial applications that have been realized but are no longer in operation are: a salt production plant at the Reykjanes field utilizing geothermal brine and seawater, drying of imported hardwood in Húsavík by geothermal water, rethreading of car tires, and wool washing in Hveragerdi. Among smaller ongoing activities using geothermal energy are a hospital laundry and steam baking of bread at several locations and a plant for curing concrete blocks in a steam heated autoclave. The total geothermal energy used as process heat in industry in Iceland in 2019 is estimated to be 922 TJ.

The Icelandic company GeoSilica, which started as a university spin-off project, was founded in 2012. It produces silica health products from the mineral rich brine from the Hellisheidi power plant in cooperation with ON Power, the operator of the plant. The company's first product was released in late 2014, a liquid silica supplement made from 100% natural silica. Today the product line consists of five different types of food supplements. GeoSilica has plans for expansion and export of their products.

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. 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 diminished. 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.

The total surface area of greenhouses in Iceland is about 200,000 m^2 including plastic tunnels for bedding and forest plants. Of this area, which has not changed much in the past few years, 50% is used for growing vegetables (tomatoes, cucumbers, paprika etc.) and the rest mainly for growing cut flowers and potted plants. The total annual production of vegetables in Iceland is about 18,000 tonnes. The share of domestic production in the total consumption of tomatoes in Iceland is about 50% and for cucumbers almost 100%.

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 per year in greenhouses with artificial lighting and 5.76 GJ/m^2 per year in greenhouses without artificial lighting (Haraldsson and Ketilsson, 2010). The total geothermal energy used in Icelandic greenhouses in 2019 is estimated to be 668 TJ.

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 and Senegalese sole. Production of all these species is expected to increase rapidly in the coming years. There are about 60 fish farms in Iceland and the total annual production is about 20,000 tonnes. Of these fish farms between 15 and 20 utilize geothermal water. 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 main use of geothermal energy in the fish farming sector in Iceland is for juvenile's production (char and salmon). Further rearing of salmon to full marketable size is made in sea cages where geothermal water is not used.

However, in land-based char production geothermal energy is used for post-smolt rearing to marketable size. Geothermal utilization in the fish farming sector is expected to increase in the coming years. The total geothermal energy used in the fish farming sector in Iceland in 2019 is estimated to be 2,264 TJ.

A fish farm 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 operation that is planned. The 22,000 m^2 plant is located close to the 100 MW_e Reykjanes geothermal power plant owned by 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. From there the warm sea water 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 shallow wells and used in the rearing tanks at about 21°C, which is the optimum temperature for the fish. The juveniles are grown to about 500 g weight 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, and plans have been made for 2,000 tonnes per year.

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 20 years. Figure 4 gives an overview of the power plants and Figure 5 shows how the generation has developed during the period 1970-2018. The total installed capacity of geothermal generating plants is now 755 MW_e. The total production in 2018 was 6,010 GWh_e, which is 30% of the total electricity production in the country (Orkustofnun B, 2019).

The first geothermal power plant in Iceland is in Bjarnarflag where a 3,2 MW_e back pressure unit started operation in 1969. The turbine was bought second hand from a sugar refinery. It was later refurbished and operated successfully until early 2018 except for two periods when it was out of service, 1978-1980 due to damage of production wells caused by volcanic activity, the Krafla Fire, in the area, and 1985-1988 due to rehabilitation of the power plant. In 2018-2019 the plant was totally refurbished and the old turbine and generator replaced by a new 5 MW back pressure unit, which started full production in late 2019. The new turbine uses the same amount of steam as the old one. The Bjarnarflag plant is using steam from a well in the Námafjall geothermal field within the lake Mývatn area in North Iceland. The same field has been used to supply heat for industrial applications (Kísilidjan diatomite plant, closed down in 2004), district heating for the community and the Mývatn Nature Bath. Exploration drilling has been carried out in preparation of further development of the Námafjall field for a new 90 MW_e 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 1978. Two 30 MW_e double flash condensing turbine units were purchased, 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, the Krafla Fire, 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 security. Initially, the power generation was only 8 MW_e, but reached 30 MW_e in 1984. The capacity of the Krafla power plant was expanded in 1997 from 30 to 60 MW_e by commissioning the second turbine, which reached full capacity in 1999. Further expansion is being considered. In total, about 40 wells have been drilled in the area. The plant uses 110 kg/s of 6.7 bar-g saturated high-pressure steam and 36 kg/s of 1.2 bar saturated low-pressure steam.

Plant name	Plant size MW_e	Year	Unit size MW_e	No of units	Type	Temp. °C	Press. bar-g	Flow rate t/h	Estimated production GWh_e/yr
Krafla	60	1978	30	1	DF	172/122	6.7/1.2	400/130	480
		1997	30	1	DF				
Svartsengi	76.4	1978-1880	8	2	SF	155	4.5	124	611
		1989-1993	1.2	7	B	103	0.12	131	
		1999	30	1	SF	162	5.5	275	
		2007	30	1	DS	201	15	288	
Bjarnarflag	5	1969	5	1	SF	182	9.5	45	42
Nesjavellir	120	1998	30	2	SF	192	12	432	960
		2001	30	1	SF	192	12	198	
		2005	30	1	SF	192	12	198	
Reykjanes	100	2006	50	2	SF	210	18	576	800
Hellisheidi	303	2006	45	2	SF	178	8.5	600	2,400
		2007	33	1	SF	124	1.25	315	
		2008	45	2	SF	178	8.5	600	
		2011	45	2	SF	178	8.5	600	
Theistareykir	90	2017-2018	45	2	SF	178	8.5	560	738
Flúðir	0.6	2018	0.15	4	B	116		125	5
Total	**755**			**32**				**5,332**	**6,031**

SF: Single flash; DF: Double flash; DS: Dry steam; B: Binary

Figure 4: Geothermal power plants in Iceland.

The Svartsengi co-generation power plant of HS Orka started operation in 1976 with hot water production only until electricity generation started two years later. The plant is located on the Reykjanes peninsula, about 40 km from Reykjavík, and serves about 23,000 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 450 kg/s. Of that about 60% 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 190 MW_{th} for hot water production and 76.4 MW_e for electricity generation in several units (see Figure 4). Of that 8.4 MW_e come from Ormat binary units using low-pressure exhaust steam. A part of the effluent brine from Svartsengi (42 l/s) goes to the Blue Lagoon (see Chapter 5.1), the rest is reinjected into the reservoir.

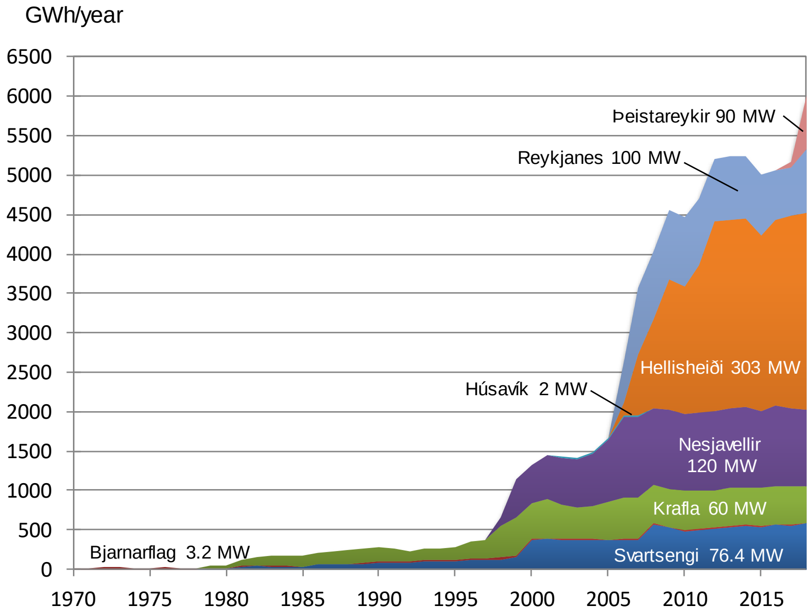


Figure 5: Electricity generation by geothermal energy in Iceland 1970-2018.

HS Orka started operation of a 100 MW_e geothermal power plant at Reykjanes in May 2006 (two 50 MW_e steam turbines with sea cooled condensers). The plant uses 160 kg/s of steam at 18 bar. Work has started on a 30 MW_e expansion of the plant by using brine from the high-pressure separators without increasing the fluid extraction from the geothermal reservoir.

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 water is transported from the wells to a central separator station at 192°C and 12 bar. The primary purpose of the plant was to provide hot water for the Reykjavík area, 27 km away and during the first eight years only the heating plant was in operation, heating fresh groundwater by geothermal steam and hot water in heat exchangers. After the electric plant was commissioned in 1998 the preheating of the freshwater is within the turbine condensers and thereafter by utilizing the water fraction 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 from the power plant, which is at an elevation of 160 m a.s.l., to a large surge tank at an elevation of 400 m a.s.l. from where it flows by gravity to large storage tanks on the outskirt of Reykjavík before distribution. The capacity of the plant is about 300 MW_{th} 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 MW_e steam turbines were put into operation. In 2001, a third turbine was installed and the plant enlarged to a capacity of 90 MW_e, and finally to 120 MW_e in 2005 when the fourth turbine was installed (Figure 4).

Reykjavík Energy started operation of a new 90 MW_e geothermal power plant at Hellisheidi in the southern part of the Hengill area in October 2006. It was expanded by a 33 MW_e low pressure unit (bottoming plant) in 2007 and further by installing two 45 MW_e units in late 2008 and additionally two 45 MW_e units in 2011, increasing the total installed capacity of the plant to 303 MW_e. Hot water production for district heating in Reykjavík started at Hellisheidi in 2010. Due to increased demand for steam, additional four wells drilled in a nearby area in the period 2006-2009 were connected to the plant at the end of 2015. Originally, these wells were planned for a new 90 MW_e power plant that was expected to be built in the area (Hverahlíd), but it was later decided to transport the steam over a distance of 5 km to maintain full generation in the Hellisheidi plant.

Reykjavík Energy, in cooperation with Icelandic and foreign scientists, has developed a process to capture CO_2 and other sour gases from geothermal power plants and permanently store it as rock in the subsurface. 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. This work has been done within the research projects Carbfix and Sulfix. About one-third of the CO_2 released from the Hellisheidi plant is now reinjected and there are plans for increasing the share to two-thirds. Also, a production of CO_2 for industrial uses in the area is being considered.

At Húsavík, in Northeast Iceland, a 2 MW_e geothermal binary-fluid power plant, based on Kalina cycle technology, was put into service in 2000. Due to operational problems the plant has not been in service since January 2008.

Landsvirkjun (The National Power Company) operates the 5 MW power plant in Bjarnarflag and the 60 MW Krafla power plant. It has recently built a 90 MW_e power plant at Theistareykir geothermal field in North Iceland, not far from the Krafla geothermal field (Figure 5). The construction work started in 2015 and the first 45 MW_e unit was commissioned in November 2017 and the second 45 MW_e in April 2018. The field has been under exploration since 1973. The first deep exploration well was drilled in 2002 and a total of 18 wells were drilled up to 2017 for production and reinjection. The main part of the power from the Theistareykir plant goes to a new production plant for silicon metal in the nearby town Húsavík, which has an initial production capacity of 32,000 tonnes per year.

Figure 6: Theistareykir power plant. Photo: Mannvit.

A project developer Varmaorka focuses on harnessing low-temperature geothermal resources for power generation. They have entered a collaboration with the Swedish binary plant supplier to deliver geothermal binary generation units, 150 kW each. The modules are planned to be placed in several locations in Iceland. Their first project consists of four modules, 150 kW each, at Flúdir in southern Iceland, commissioned in June 2018. The binary units use geothermal water at 116°C that is cooled down to 76°C in the power generation process. The effluent water is planned to be used for district heating in the future.

7. DRILLING ACTIVITIES

The development of geothermal drilling activities in Iceland in the period 1970 to 2019 is shown in Figure 7 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. After this period there was a drastic reduction in the geothermal drilling activity in Iceland from a high of 28 high-temperature wells drilled in 2008 to almost no high-temperature drilling activity in the period 2012-2014. Since then about 5 high-temperature wells have been drilled annually in the country.

Work has been ongoing on the IDDP project (Iceland Deep Drilling Project) for about 20 years by a consortium of Icelandic energy companies and international organizations. The aim is to drill 4-5 km deep wells into high-temperature hydrothermal systems in Iceland to reach 400-600°C hot supercritical fluid and find out if it is economically feasible to extract energy and chemicals out of hydrothermal systems at supercritical conditions. The first well was drilled in Krafla in 2008-2009 but the drilling had to be abandoned short of target depth when magma was intersected by the drill bit at 2114 m depth. The well was flow-tested and several research projects carried out. The second well was drilled at Reykjanes where a 2.5 km deep production well was deepened to 4,659 m becoming the deepest geothermal well in Iceland. The drilling of IDDP-2 started in August 2016 and was completed in late January 2017. The well encountered temperatures exceeding 500°C and some permeability at 3-4 km depth. Flow test of the well was initiated in December 2019.

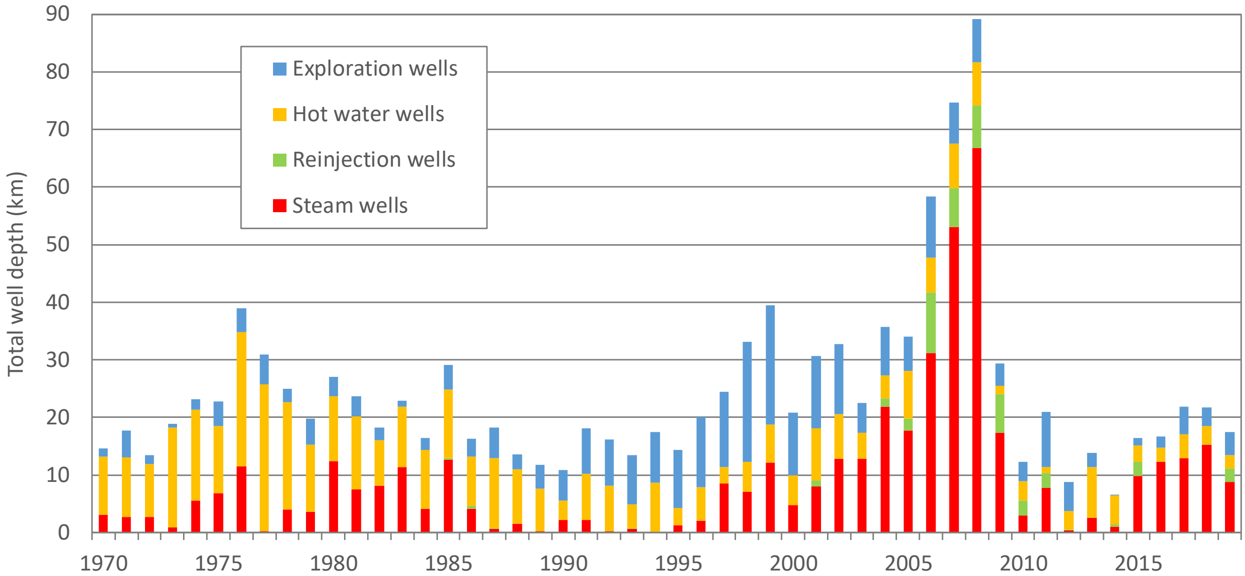


Figure 7: Total depth of geothermal wells drilled annually in Iceland 1970-2019.

8. DISCUSSION

During the last century Iceland has developed the indigenous energy resources, hydropower and geothermal energy, to increase the standard of living and make the country less dependent upon imported fossil fuel. There is a large potential for increased utilization of geothermal energy in Iceland and geothermal electricity generation can be expected to increase in the coming years, but direct uses will most likely only grow at a moderate rate.

The only new development in geothermal power generation that is foreseen in Iceland in the near future it a 30 MW_e expansion of the existing plant at Reykjanes by using brine from the high-pressure separators in binary units. An expansion of the 90 MW power plant at Þeistareykir is likely in the future, but no decision has been made on that. Drilling activities in the coming years will most likely be limited to make-up wells and reinjection wells for the existing power plants as well as the district heating systems.

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TABLE 1. PRESENT AND PLANNED PRODUCTION OF ELECTRICITY

	Geothermal		Fossil Fuels		Hydro		Nuclear		Other Renewables (wind)		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 2019	755	6,010	72	2	1,990	13,813			2.4	4.4	2,819	19,829
Under construction in December 2019					20	140						
Funds committed, but not yet under construction in December 2019	30											
Estimated total projected use by 2025	785	6,420	72	2	2,153	15,013			10	18	3,015	21,453

TABLE 2. UTILIZATION OF GEOTHERMAL ENERGY FOR ELECTRIC POWER GENERATION AS OF 31 DECEMBER 2019

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) Electrical installed capacity in 2019

Electrical capacity actually up and running in 2019

Locality	Power Plant Name	Year Com-missioned	No. of Units	Status[1)]	Type of Unit[2)]	Total Installed Capacity MWe[3)]	Total Running Capacity MWe[4)]	Annual Energy Produced 2019 GWh/yr	Total under Constr. or Planned MWe
Bjarnarflag	Bjarnarflag	1969	1		1F	5		0.2	
Krafla	Krafla	1978/97	2		2F	60		461	
Svartsengi	Svartsengi	1978/99	3		1F	38		587	
Svartsengi	Svartsengi	1989/93	7		B	8.4			
Svartsengi	Svartsengi	2007	1		D	30			
Nesjavellir	Nesjavellir	1998/05	4		1F	120		970	
Hellisheidi	Hellisheidi	2006/11	7		1F	303		2,502	
Reykjanes	Reykjanes	2006	2		1F	100		810	25
Theistareykir	Theistareykir	2017/2018	2		1F	90		678	
Flúdir	Flúdavirkjun	2018	4		B	0.6		0.01	
Total			33			755		6,010	

TABLE 3. UTILIZATION OF GEOTHERMAL ENERGY FOR DIRECT HEAT AS OF 31 DECEMBER 2019 (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]
Veitur (Reykjavík)	DBSIFG	6,494	80	35			1,223	2,922	17,345	0.45
HS Orka	BF	1,132	82	35			223	509	3,158	0.45
HS Veitur	DIBSG	860	82	35			169	387	2,398	0.45
Nordurorka	DBSGIF	729	78	35			131	328	1,861	0.45
Mosfellsbær	DBGSI	312	80	35			59	140	833	0.45
Selfossveitur	DBSI	312	75	35			52	140	741	0.45
Skagafjordur	DFBIS	252	72	35			39	114	554	0.45
RARIK	DBSIG	146	68	35			20	66	286	0.45
Orkubú Vestfjarda	DBI	36	80	35			7	16	96	0.45
Seltjarnarnes	DBS	152	80	35			29	68	405	0.45
Húsavík	DSIBF	147	80	35			28	66	394	0.45
Bláskógabyggd	GDSIB	127	85	35			27	57	377	0.45
Landsvirkjun	B	82	95	35			20	37	291	0.45
Egilsstadir	DBSGI	115	73	35			18	52	260	0.45
Grímsnes, Grafn.	DB	95	80	35			18	43	252	0.45
Flúðir	GDIBS	71	95	35			18	32	252	0.45
Dalvík	DBS	106	64	35			13	48	182	0.45
Eskifjörður	DBS	39	82	35			8	18	109	0.45
Húnaþing vestra	DBIG	44	77	35			8	20	110	0.45
Kjósarveitur	D	25	75	35			4	11	59	0.45
Skútustadahreppur	D	15	95	35			4	7	53	0.45
Landsveit	FDI	9	80	35			2	4	23	0.45
Bergstadir	D	8	80	35			1	4	21	0.45
Öxarfjardarhérad	DB	7	80	35			1	3	19	0.45
Drangsnes	DB	11	60	35			1	5	16	0.45
Brautarholt	DBI	5	70	35			1	2	10	0.45
Orka Náttúrunnar (ON	D	2	80	35			0	1	5	0.45
Autoproducers	SDFIGB	1,298	80	35			244	584	3,468	0.45
TOTAL		12,630					2,367	5,683	33,579	0.45

TABLE 4. GEOTHERMAL (GROUND-SOURCE) HEAT PUMPS AS OF 31 DECEMBER 2019

This table should report thermal energy used (i.e. energy removed from the ground or water) and report separately heat rejected to the ground or water in the 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 (please describe)

3) Report the COP = (output thermal energy/input energy of compressor) for your climate - typically 3 to 4

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. (°C) - outlet temp. (°C)] x 0.1319
or = rated output energy (kJ/hr) x [(COP - 1)/COP] x equivalent full load hours/yr

6) Cooling energy = rated output energy (kJ/hr) x [(EER - 1)/EER] x equivalent full load hours/yr

Note: please report all numbers to three significant figures
Due to room limitation, locality can be by regions within the country.

Locality	Ground or Water Temp. (°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[5] (TJ/yr)	Cooling Energy[6] (TJ/yr)
Different locations	5-10	10	120	W	3-4		13	
Different locations	5-10	150	4	W	3-4		6	
Akureyri	30	1900	2	O	4		0	
TOTAL							19	

TABLE 5. SUMMARY TABLE OF GEOTHERMAL DIRECT HEAT USES AS OF 31 DECEMBER 2019

1) Installed Capacity (thermal power) (MWt) = Max. flow rate (kg/s) x [inlet temp. (°C) - outlet temp. (°C)] 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. (°C) - outlet temp. (°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

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

4) Other than heat pumps

5) Includes drying or dehydration of grains, fruits and vegetables

6) Excludes agricultural drying and dehydration

7) Includes balneology

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]	1,650	24,603	0.47
Air Conditioning (Cooling)			
Greenhouse Heating	57	668	0.37
Fish Farming	110	2,264	0.65
Animal Farming			
Agricultural Drying[5]			
Industrial Process Heat[6]	80	922	0.37
Snow Melting	260	1,889	0.23
Bathing and Swimming[7]	210	3,232	0.49
Other Uses (specify)			
Subtotal	2,367	33,579	0.45
Geothermal Heat Pumps	5.6	19	0.11
TOTAL	2,373	33,598	0.45

TABLE 6. WELLS DRILLED FOR ELECTRICAL, DIRECT AND COMBINED USE OF GEOTHERMAL RESOURCES FROM JANUARY 1, 2015 TO DECEMBER 31, 2019 (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)	5	17			15
Production	>150° C	26				59
	150-100° C					
	<100° C		21			15
Injection	(all)	5	1			5
Total		36	39			94

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 Prograr
(6) Private Industry

Year	Professional Person-Years of Effort					
	(1)	(2)	(3)	(4)	(5)	(6)
2015	70	75	15			90
2016	70	75	18			90
2017	70	80	20			90
2018	70	80	20			90
2019	70	80	20			90
Total						

TABLE 8. TOTAL INVESTMENTS IN GEOTHERMAL IN (2019) 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	985		100
2010-2014	20	40	10	260	25	75
2015-2019	50	175	35	220	15	85