

# Geothermal Country Update for Iceland

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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 61%. Space heating is the most important direct utilization of geothermal energy in Iceland, covering 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<sub>2</sub>) for soft drinks, greenhouses and industry. The total direct use of geothermal energy in 2017 is estimated to have been 9,528 GWh<sub>th</sub> (34,300 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 753 MW<sub>e</sub> and the total generation in 2017 was 5,170 GWh<sub>e</sub>, which is 27% of the electricity produced in the country.

## 1. Introduction

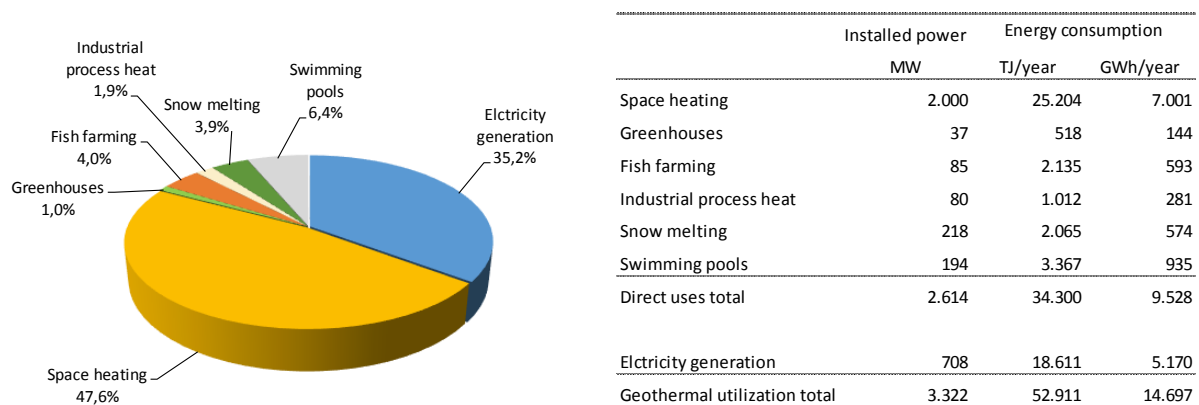
Iceland has a huge geothermal potential based on the location of the country on the Mid-Atlantic Ridge. The country is mountainous and volcanic, with much precipitation, making hydropower resources also abundant. The population of Iceland is about 350,000, of which almost two third live in the Reykjavik capital area. During the course of the 20<sup>th</sup> 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 (61% geothermal, 20% 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 for both electricity generation and direct uses. In the high-temperature ( $>200^{\circ}\text{C}$ ) fields geothermal steam is utilized for electricity generation at eight sites, also the brine for hot water production in so-called co-generation plants at three of the sites. Thus, the energy efficiency is improved considerably. The low-temperature ( $<150^{\circ}\text{C}$ ) 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 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. A master plan assessing the economic feasibility and the environmental impact of proposed power development projects has been adopted by the Icelandic Parliament (Bjornsson et al., 2012).

## 2. Overview of geothermal utilization

Figure 1 gives a breakdown of the utilization of geothermal energy in Iceland for 2017, both for direct uses and for power generation (Orkustofnun A and B, 2018). Direct uses of geothermal energy that year, i.e. for heating, was in total about 34,300 terajoules (TJ), which corresponds to 9,528  $\text{GWh}_{\text{th}}$  of used energy. Calculation of the used energy is based on estimated inlet and outlet water temperature for each category (e.g.  $35^{\circ}\text{C}$  outlet temperature for space heating) and the corresponding annual flow. In addition, electricity production by geothermal amounted to 18,611 terajoules or 5,170  $\text{GWh}_{\text{e}}$  in 2017. The 47.6% share of space heating was by far the greatest geothermal use sector while electricity production accounted for 35.2%.

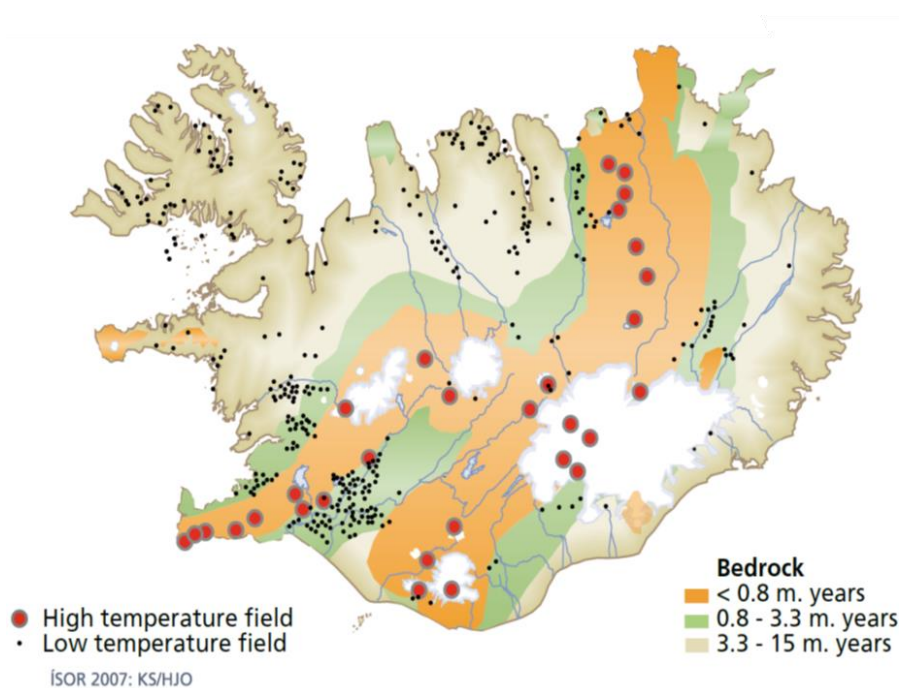


**Figure 1: The sectoral share of geothermal utilization in Iceland 2017. Source of energy consumption: Orkustofnun, OS-2018-T008-01**

## 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<sup>3</sup> 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. A large number of 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 temperatures. At least 25 high-temperature areas exist on land within the volcanic zone with temperatures reaching 200°C within 1000 m depth and several fields are expected to be (a few are known) on the ridges on the ocean floor extended to southwest and north of Iceland. 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

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 District Heating (now Reykjavík Energy) was in 1946. Following the oil price hikes of the 1970s, the government took the initiative in excluding 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%. 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.

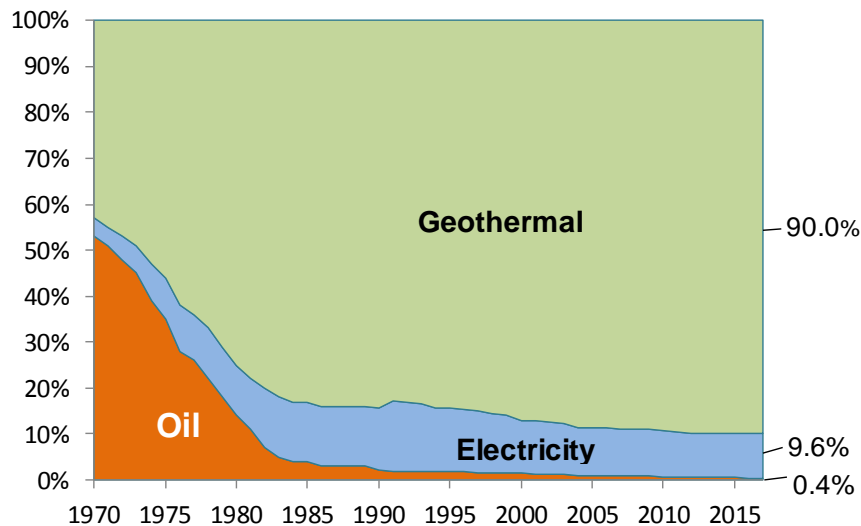


Figure 3: Energy sources used for space heating in Iceland 1970-2017.

#### 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 510 and the turnover in 2017 was about 44,000 million ISK (415 million US\$ based on the average 2017 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 70% of the Icelandic population, the entire population of Reykjavík, plus neighboring communities as well as some additional villages by 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 Hellisheidi cold ground water is heated in co-generation power plants. In the past, Reykjavík Energy has taken over several

district heating systems outside the capital area. 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 1,150 MW<sub>th</sub> and the total hot water production is over 80 million m<sup>3</sup> 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 to electricity legislation in 2008 was divided up into HS Veitur hf. and HS Orka hf. The plant utilizes 240°C geothermal brine from the Svartsengi field to heat fresh water for district heating (190 MW<sub>th</sub>), and to generate electricity (74.4 MW<sub>e</sub>). HS Orka also has a 100 MW<sub>e</sub> 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<sub>th</sub> 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 103 MW<sub>th</sub> and the annual hot water consumption about 9 million m<sup>3</sup>.

### **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 165 recreational swimming centers in the country, 140 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 34,000 m<sup>2</sup>. 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<sup>2</sup> outdoor pools, 1,250 m<sup>2</sup> 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 (1.3 million visitors in 2017), 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. Typically, about 220 m<sup>3</sup> of geothermal water or 40,000 MJ of energy is needed annually for heating one m<sup>2</sup> 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 2017 is estimated to be 3,367 TJ per year (Orkustofnun A, 2018).

The Blue Lagoon mentioned above is a 5,000 m<sup>2</sup> 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 6 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 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 2017, 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<sup>2</sup>, 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 has been installed under most sidewalks and some streets, covering an area of 70,000 m<sup>2</sup>. This system is designed for a maximum heat output of 180 W/m<sup>2</sup> surface area and the annual energy consumption is estimated to be 430 kWh/m<sup>2</sup>. 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 2,065 TJ per year (Orkustofnun A, 2018).

### ***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 Breidafjörður 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<sub>2</sub>) 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 avoided by installing 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. The solubility of calcium carbonate increases

sufficiently at lower temperatures to prevent scaling (inverse solubility). The plant extracts approximately 6 l/s of water from the well and produces some 3,000 tonnes of CO<sub>2</sub> annually, which is a large share 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 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 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<sub>2</sub> 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 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 of CO<sub>2</sub>.

Two salt factories that utilize geothermal energy in their production have been established in Iceland in recent years. The focus is on producing "gourmet" table salt. One of them is Nordursalt, 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 is the Kísildjón diatomite plant at Lake Mývatn, which was among the largest industrial users of geothermal steam in the world. The plant used about 13 kg/s of steam at 180°C (9 bar) and produced about 28,000 tonnes of filter aids for export annually. Kísildjón 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 Hveragerði. Among smaller ongoing activities using geothermal energy are laundry processes and steam baking of bread at several locations and a concrete block plant in steam heated autoclaves. The total geothermal energy used as process heat in industry in Iceland is estimated to be 1,012 TJ per year (Orkustofnun A, 2018).

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 Energy, 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 four different types of food supplements. GeoSilica has plans for expansion and recently new shareholders acquired a 6% stake in the company for about 350,000 USD.

#### ***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 is less than before. CO<sub>2</sub> enrichment in greenhouses is common, primarily by using CO<sub>2</sub> 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<sup>2</sup> 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 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<sup>2</sup> per year in greenhouses with artificial lighting and 5.76 GJ/m<sup>2</sup> per year in greenhouses without artificial lighting (Haraldsson and Ketilsson, 2010). The total geothermal energy used in Icelandic greenhouses is estimated to be 518 TJ per year (Orkustofnun A, 2018).

#### ***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 production was about 21,000 tonnes in 2017. 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). 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. The total geothermal energy used in the fish farming sector in Iceland is now estimated to be 2,135 TJ per year.

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 22,500 m<sup>2</sup> of fish tank area is located close to a 100 MW<sub>e</sub> 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. From there the 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 400 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, but the planned production after reaching the final stage is 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. Table 1 gives an overview of the power plants and Figure 4 shows how the generation has developed during the period 1970-2017. The total installed capacity of geothermal generating plants is now 753 MW<sub>e</sub>. The total production in 2017 was 5,170 GWh<sub>e</sub>, which is 27% of the total electricity production in the country (Orkustofnun B, 2018).

The first geothermal power plant in Iceland is in Bjarnarflag where a 3,2 MW<sub>e</sub> back pressure unit started operation in 1969. The turbine was bought second hand from a sugar refinery, but it was later refurbished. The 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 (Kísildjan diatomite plant), district heating for the community and the Mývatn Nature Bath. The Bjarnarflag power plant has been operated successfully ever since the beginning except for two periods when it was closed, 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. Exploration drilling has been carried out in preparation of further development of the Námafjall field for a new 90 MW<sub>e</sub> 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<sub>e</sub> double flash condensing turbine units were purchased when the construction of 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, 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 generated only 8 MW<sub>e</sub>, but reached 30 MW<sub>e</sub> in 1984. The capacity of the Krafla power plant was expanded in 1997 from 30 to

60 MW<sub>e</sub> by commissioning the second turbine, which reached full capacity in 1999. Further expansion is being considered. Totally, about 40 wells have been drilled in the area. The plant uses 110 kg/s of 6.7 bar saturated high-pressure steam and 36 kg/s of 1.2 bar saturated low-pressure steam.

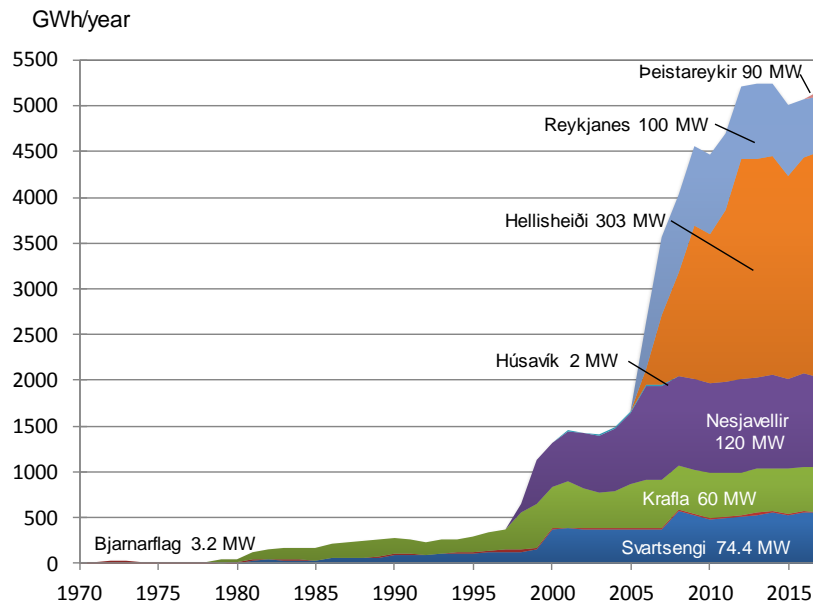
**Table 1 Geothermal power plants in Iceland.**

Plant name	Plant size MW <sub>e</sub>	Year	Unit size MW <sub>e</sub>	No of units	Type	Temp. °C	Press. bar	Flow rate t/h	Estimated production GWh <sub>e</sub> /yr
Krafla	60	1978	30	1	DF	172/122	6.7/1.2	400/130	480
		1997	30	1	DF				
Svartsengi	74.4	1981	6	1	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	3.2	1969	3.2	1	SF	182	9.5	45	26
Nesjavellir	120	1998	30	2	SF	192	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	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
<b>Total</b>	<b>752.6</b>			<b>29</b>				<b>4,418</b>	<b>6,031</b>

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

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<sub>th</sub> for hot water production and 74.4 MW<sub>e</sub> for electricity generation in several units (see Table 1). Of that 8.4 MW<sub>e</sub> 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).



**Figure 4: Electricity generation by geothermal energy in Iceland 1970-2017.**

HS Orka started operation of a 100 MW<sub>e</sub> geothermal power plant at Reykjanes in May 2006 (two 50 MW<sub>e</sub> steam turbines with sea cooled condensers). The plant uses 160 kg/s of steam at 18 bar. An expansion of the plant has been under preparation for some time. The plan is also to produce 30 MW<sub>e</sub> by using brine from the high pressure separators.

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 192°C and 12 bar. The primary purpose of the plant is 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 brine 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 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 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 in the outskirts of Reykjavík before distribution. The capacity of the plant is about 300 MW<sub>th</sub> 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<sub>e</sub> steam turbines were put into operation. In 2001, a third turbine was installed and the plant enlarged to a capacity of 90 MW<sub>e</sub>, and finally to 120 MW<sub>e</sub> in 2005 when the fourth turbine was installed (Table 1).

Reykjavík Energy started operation of a new 90 MW<sub>e</sub> geothermal power plant at Hellisheidi in the southern part of the Hengill area in October 2006. It was expanded by a 33 MW<sub>e</sub> low pressure unit (bottoming plant) in 2007 and further by installing two 45 MW<sub>e</sub> units in late 2008 and additionally two 45 MW<sub>e</sub> units in 2011, increasing the total installed capacity of the plant to 303 MW<sub>e</sub>. 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<sub>e</sub> 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.

At Húsavík, in Northeast Iceland, a 2 MW<sub>e</sub> 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 operation since January 2008.

Landsvirkjun (The National Power Company) operates the 3.2 MW power plant in Bjarnarflag and the 60 MW Krafla power plant. It has recently built a 90 MW<sub>e</sub> 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<sub>e</sub> were commissioned in November 2017 and the second 45 MW<sub>e</sub> 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. 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 33,000 tonnes per year.



**Figure 5: Theistareykir power plant. Photo: Mannvit.**

The Icelandic project developer Varmaorka focuses on harnessing low-temperature geothermal resources. They have recently entered a collaboration with the Swedish binary plant supplier Climeon AB to deliver a large number of geothermal binary generation units, 150 kW each. The modules are planned to be placed in several locations in Iceland. The first delivery consisted of four modules and was delivered to Flúdir in southern Iceland in June 2018. The plant at Flúdir uses geothermal water at 116°C that is cooled down to 76°C in the power generation process and then used further for district heating.

## 5. 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 is expected to increase in the coming years, but direct uses will most likely only grow at a moderate rate.

After the financial crisis in 2008 there was a drastic reduction in the geothermal drilling activity in Iceland from a high of 28 high-temperature wells drilled in 2008 to no high-temperature well drilled in 2014. The drilling activity has now increased again with 4-8 high-temperature geothermal wells drilled annually in the country since 2014. One of them is a part of the IDDP project (Iceland Deep Drilling Project) where a 2.5 km deep production well at Reykjanes was be deepened to 4.6 km 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. It has not yet been production tested.

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