Characteristics And Development Status of Geothermal Resources in Iceland

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Abstract. As Global warming is becoming increasingly severe, decarbonization has become the primary trend in the world. One way to achieve this trend is to use renewable energy resources. Among many kinds of renewable energy, geothermal energy is very neat, and its abundant storage capacity. Also, geothermal resources play a significant role in the energy supply of Iceland. They are utilized both for electricity generation and direct heat application. To this end, this article explains why geothermal energy is abundant in Iceland, and the example of utilization, some advanced technology like drilling technology and power generation technology. In addition, this article introduces the management of geothermal energy like some crucial policies. On this basis, the report concludes Iceland's experience of a successful transition from using traditional fossil fuels to fully utilizing renewable energy. And the report describes the limitation and future development of geothermal energy.

1 Introduction

The main structure of world energy resources is still fossil fuels. The increasing usage of fossil fuels contributes to climate change, air pollution, resource depletion, environmental degradation, import dependency, and hinders renewable energy development, such as global warming, acid rain, and smog. Because of global warming, the earth's temperature has risen by an average of 0.14° Fahrenheit (0.08° Celsius) per decade since 1880 [2]. Also, acid rain leads to environmental damage, soil degradation, corrosion of infrastructure, poor water quality, and harm to people's health. In addition, fossil fuels are non-renewable and sustainable, and drilling for fossil fuels like petroleum is a hazardous process, so it is not wise to focus only on using fossil fuels in the future. Therefore, the World energy resource trend gradually focuses on using renewable and clean energy resources. As shown in Fig. 1, the proportion of renewable energy has been increasing, and the ratio of traditional energy has been decreasing. This fact indicates that the primary energy trend in the world is decarbonization and renewable.

Among many renewable energy sources, geothermal energy has outstanding advantages, such as environmentally friendly, reliable, and highly efficient geothermal systems. Because of these advantages, geothermal energy will become a more popular renewable energy source in the coming decades. Iceland has a long history of geothermal resource utilization and has gained successful experiences in exploiting and managing geothermal resources. Therefore, this paper's research theme is Iceland's geological background. Also, utilization, technology, and IDDP project. Besides, the research will introduce the legal framework and national policy. The direct utilization and geothermal electricity production are increasing, direct use in 2020 is almost ten times that of 1995. However, it is still far smaller than their resources, so It is essential to know about geothermal energy development in developed countries.

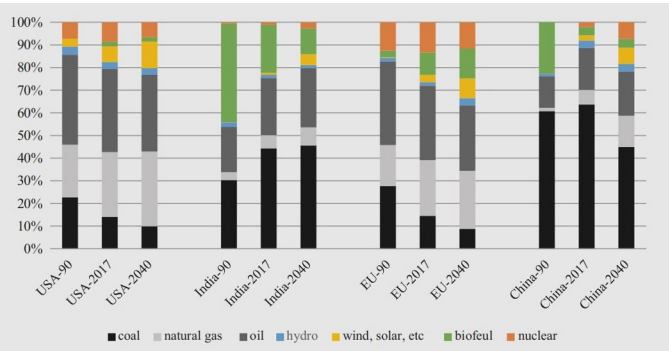

Fig. 1. Energy consumption basket of the USA, India, China, and the European Union in three periods [1,https://doi.org/10.1007/s13762-022-03963-w].

2 Geological background

Iceland is rich in geothermal energy resources, mainly due to its geological structure and geographical location. From the geotectonic position, Iceland is located at the junction of the North American plate and the Eurasian plate.

In the genetic category, Iceland is a volcanic island formed by periodic submarine magmatic activity and submarine volcanic eruption. The upper mantle material and magma erupted from the Mid-Atlantic Ridge Rift zone. In the Mid-Atlantic Ridge Rift zone, the submarine

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volcanoes erupt periodically, and the central ridge keeps rising from the bottom of the sea. Iceland is one of the oceanic volcanic islands that have risen. Iceland's current volcanic and seismic activity is frequent. The volcanic-earthquake zone is spread all over Iceland. It has a wide glacial coverage area, with four ice sheets located in the central and southeastern parts of Iceland, which provide a suitable environment for heat and water exchange. Iceland's high, medium, and low-temperature geothermal fields are scattered all over the island, and hot springs and air holes are scattered all over the country. The unique geological environment makes Iceland one of the wealthiest countries in geothermal resources, and it is widely used in various industries such as power generation, greenhouse, fishery, industry, snow melting, and tourism, which is one of the most essential resources in Iceland.

3 Geothermal utilization

3.1 Direct uses

The direct uses of geothermal heat in Iceland include heating, aquaculture, greenhouses, hot spring pools, drying, and snow melting.

3.1.1 Geothermal heating

In the 1920s and 1930s, Icelanders began to explore the use of geothermal heating due to rising coal prices and the occurrence of freezing weather, etc. In 1953, the parliament passed a law to support geothermal drilling, allowing for financial expenditures of up to 80% of the total investment in drilling and building geothermal wells. The oil crisis in the 1970s spurred the rapid development of geothermal heating in Iceland. Iceland planned to have more than 80% of the country's houses heated by geothermal heat within ten years, starting with establishing a well-developed centralized geothermal heating system in the capital Reykjavik, causing residents of other cities and some villages to relocate to Reykjavik. Now many villages and towns have also established centralized geothermal heating systems. In 2020, 89.6% of space is heated by geothermal energy, which means that Space heating volume by geothermal energy is about 109.261 km^3 [3].

3.1.2 Geothermal greenhouse

Since 1924, Iceland has been trying to build geothermal greenhouses to develop ecological agriculture and sideline industry, which has been successful. Greenhouse products include a variety of vegetables (such as tomatoes, cucumbers, and red peppers) and a variety of flowering plants (such as roses and potted plants) that are in demand in the domestic market. With geothermal greenhouses, Iceland has become Europe’s largest exporter of bananas. The total geothermal energy used in Icelandic greenhouses in 2019 is estimated at 668 TJ [4]. Most greenhouses are located in the country's south and are sealed with glass. In recent years, the increased use of electric lighting has extended the growing period of plants and increased the productivity of greenhouses. The total production of greenhouse cultivation in Iceland has been increasing in the last decade, but the total area of greenhouses has been decreasing.

3.1.3 Geothermal aquaculture

In the mid-1980s, Iceland began to develop geothermal aquaculture, dramatically accelerating the development of Icelandic fisheries by significantly shortening the hatching and growth cycles of fish fry and considerably increasing production through geothermal heating. At present, Iceland has 60 hot water fish hatcheries, with more than 4,000 tons of fish fry raised and nearly 2 million tons of fish caught annually, which is the highest per capita fish catch in the world.

3.1.4 Geothermal hot spring pools

Swimming pool water heating is one of the crucial geothermal energy uses in Iceland. There are about 170 swimming pools in the country, of which 145 are heated by geothermal energy. Most of the public pools are open-air pools that are open all year round, and the pools are mainly used for recreation and swimming training. Iceland relies on its unique geomorphology and numerous spa and health care areas, attracting many foreign tourists annually.

3.1.5 Geothermal drying

Several seaweed manufacturing plants in Iceland use geothermal resources directly for drying. Seaweed manufacturing companies will also use geothermal heat to dry seaweed directly after harvesting. In Iceland, some companies use geothermal energy to produce dried fish products, mainly dried salted fish, cod heads, dried cod, and other products. Dried cod heads are exported up to 15,000 tons per year. Pet food drying is a newly emerged industry with an annual output of about 500 tons [5].

3.1.6 Snow melting on roads

In addition to heating buildings, geothermal heat in Iceland has a particular heating area, heating roadways, and melting snow. This work started in the 1980s. A snow melting system was installed under the sidewalks and streets in the downtown area of Reykjavik, the capital of Iceland, and the energy consumed by the system comes mainly from the return flow of water from the geothermal heating system. The total area of the snow melting system in Reykjavik is approximately 70,000 square meters, and the total snow melting system nationwide is approximately 1,200,000 square meters. The snow-melting runway at Keflavik Airport in Iceland is a model for geothermal snow melting worldwide [4].

3.2 Power generation

Currently, geothermal power plants in Iceland contribute significantly to the country's electricity generation. These power plants tap into underground reservoirs of hot water or steam to produce electricity through turbines connected to generators. The heat is extracted using wells, and the geothermal fluid is used to drive turbines and generate power. It is estimated that geothermal energy accounts for approximately 25% of Iceland's total electricity production. This makes it one of the highest proportions of geothermal energy utilization in any country worldwide. The remainder of Iceland's electricity comes primarily from hydroelectric power, further highlighting the country's commitment to renewable energy sources. The country has many more resources available to construct geothermal power plants, which are limited to the local power load and still need to be fully developed. Fig.2 shows how the generation developed during the period 1970-2018. The total generation is increasing annually. The total installed capacity of geothermal generating plants was 754 MW in 2022 [5].

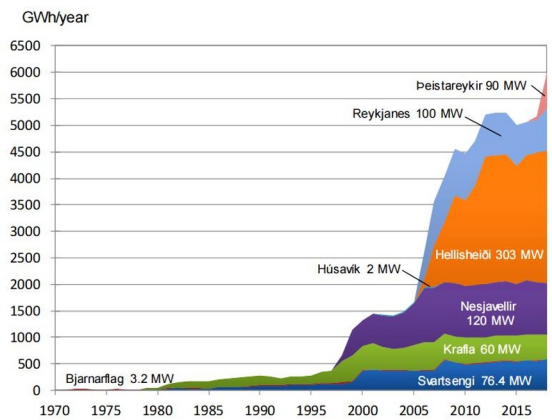

Fig. 2. Electricity generation by geothermal energy in Iceland 1970-2018 [4, https://www.geothermal-energy.org/pdf/IGA standard/WGC/2020/01063.pdf].

4 Technology

4.1 Drilling technology

To meet the demand for geothermal resources, drilling wells should be considered. Drilling of wells is contracted by businessmen companies practiced. Most geothermal wells are relatively shallow in depth. To take full advantage of the abundant natural energy, wells must be drilled much deeper. Therefore, it is essential to use advanced drilling technology.

4.1.1 Combined thermo-mechanical drilling (CTMD)

CTMD is based on employing one of two drilling modes, namely, thermal spallation drilling or flame-assisted rotary drilling (Fig. 3).

Thermal spallation is a process that induces local cracks and fractures. First, a plasma torch or plasma arc system is used to produce a high-temperature plasma jet. This plasma jet can reach temperatures of several thousand degrees Celsius. Then, the plasma jet is directed toward the rock surface, applying intense heat to a localized area—the high temperatures cause the rock to expand and undergo thermal stress. After the rock has been heated, a cooling fluid, such as water or compressed air, is injected into the drilled hole or sprayed onto the rock surface. The rapid cooling causes the outer layer of the rock to contract quickly, inducing high compressive stresses. The combination of the initial heating and rapid cooling induces differential expansion and contraction within the rock. This leads to the formation of microcracks and fractures, causing pieces of the rock to spill off. As the rock spalls off, it is removed from the drilling site through various methods, such as using air or water jets, mechanical tools, or drilling fluid circulation.

Flame-assisted rotary drilling (FARD) is a drilling technique that combines elements of both mechanical drilling and thermal spallation drilling. Rotary Drilling: FARD incorporates a conventional rotary drilling system where a drill bit is attached to the end of a drill string. The drill string rotates, allowing the bit to penetrate the rock formation. First, A high-temperature flame is generated using a flame generator device located near the drill bit. This flame is typically produced by injecting a mixture of fuel (such as natural gas or diesel) and oxidizer (such as compressed air or pure oxygen) into a combustion chamber and igniting it. Then, the flame is directed toward the rock surface being drilled. The intense heat causes thermal stress in the rock, leading to localized expansion. The combination of rotational forces applied by the rotating drill bit and the thermal stress induced by the flame leads to the formation of cracks and fractures in the rock. These fractures facilitate the breaking apart of the rock. As the rock is fractured, the broken pieces are removed from the drilling site using techniques such as mechanical tools, high-pressure jets, or drilling fluid circulation.

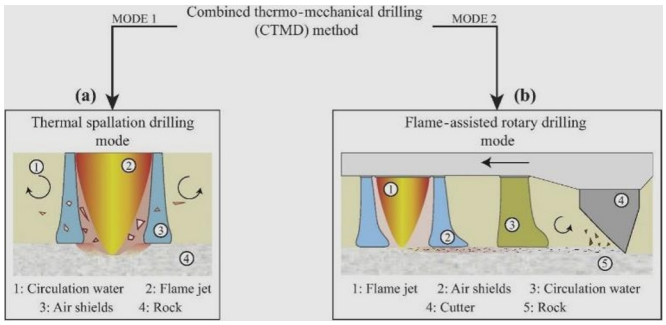

Fig. 3. (a)Thermal spallation and (b) Flame-assisted rotary drilling [8, https://doi.org/10.1016/j.geothermics.2019.101771].

4.1.2 Plasma Pulse Geo Drilling (PPGD)

Drilling rocky sedimentary formations still requires conventional drilling techniques. This is because, in these softer formations, conventional drilling systems can achieve more competitive rates of penetration (ROP). Where plasma tools come into play is when the borehole reaches harder crystalline or basement rocks such as granite, quartzite, and gneiss. Instead of melting or

vaporizing the rock, pulsed plasma drilling techniques use very short, high-energy pulses and high frequencies to suddenly increase the surface temperature of the rock, thereby breaking down its surface to allow thermomechanical rock fracture.

4.2 Drilling technology

Geothermal power generation generally requires geothermal water at a temperature of 150 degrees Celsius. In most countries, geothermal water needs to be dug to a great depth to reach this temperature due to its geographical location. But in some places, it can be a little shallow to get suitable temperatures, like near those volcanic craters - many geothermal power stations are not far from the craters, which is why countries like Iceland have such a high percentage of geothermal energy.

4.2.1 Dry steam power plants

These plants harness the energy of geothermal reservoirs containing high-pressure dry steam. As shown in Fig. 4, these plants use natural steam directly from the geothermal source to generate electricity, making them one of the oldest and most established technologies in the geothermal industry.

A production well is drilled into the geothermal reservoir to access the high-pressure dry steam. The steam flows up the wellbore to the surface under its own pressure. As the steam reaches the surface, it enters a separator. The separator separates the steam from any entrained water or impurities and directs the dry steam toward the turbine. Then the high-pressure dry steam is directed into a turbine, causing the blades to rotate. The turbine is connected to a generator, which converts the mechanical energy from the rotating turbine into electrical energy. After passing through the turbine, the steam exits the turbine and enters a condenser. In the condenser, cold water is circulated, which cools down the steam and converts it back into liquid water. This condensed water is then reinjected back into the geothermal reservoir through an injection well for reheating. Finally, the generated electricity from the generator is sent to a transformer station, where the voltage is increased to facilitate transmission over power lines. The electricity is then distributed to consumers through the power grid.

Dry steam power plants have been successful in areas where there are abundant high-pressure dry steam resources, such as in volcanic regions. They are known for their high-power generation efficiency and low emissions, as they utilize the steam directly without needing additional heat exchange processes.

However, dry steam resources are relatively rare compared to other geothermal resources like hot water or steam fields. They require careful management and monitoring to ensure the long-term sustainability of the geothermal reservoir and the efficient extraction of energy.

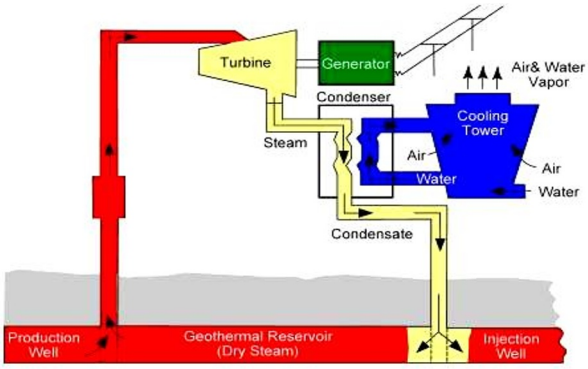

Fig. 4. Dry steam power plants [9,https://www.researchgate.net/profile/Moses-Kabeyi/publication/334988672_Geothermal Electricity_Generation_Challenges_Opportunities_and_Recommendations/links/5d493e6b4585153e594018d2/Geothermal-Electricity-Generation-Challenges-Opportunities-and-Recommendations.pdf].

4.2.2 Flash/double flash steam power plants

These power plants use water with temperatures greater than 360°F (182°C) [10]. As shown in Fig. 5, the process of electricity generation is much more complex than the dry steam power plants.

A production well is drilled into the geothermal reservoir to bring the hot water to the surface. The water is under such high pressure that it remains liquid despite being above its boiling point. As the hot water is brought to the surface, its pressure is rapidly reduced by passing through a separator or a series of nozzles. This sudden pressure drop causes a fraction of the water to "flash" into steam. Then, the flashed steam and the remaining hot water are then separated. The smoke, which contains a higher concentration of energy, is directed toward the turbine. After that, the high-pressure steam drives a turbine, which rotates a generator to produce electricity. Cold water is circulated in the condenser, causing the steam to condense back into liquid water. Reinjecting Fluid: The condensed water, known as brine, is usually reinjected into the geothermal reservoir through an injection well. This helps to sustain the reservoir's pressure and maintain the balance of fluids.

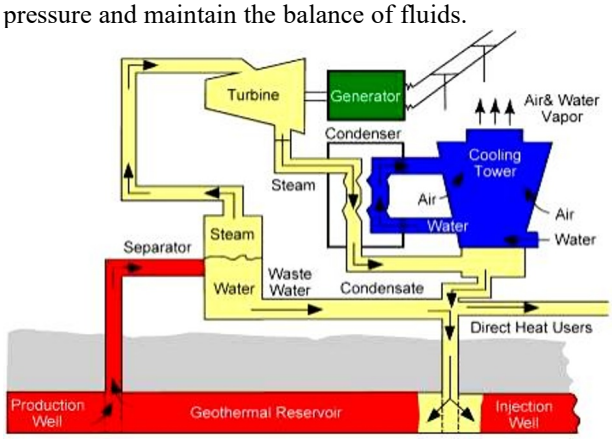

Fig. 5. Flash/double flash steam power plants [9, https://www.researchgate.net/profile/Moses-Kabeyi/publication/334988672_Geothermal_Electricity_Generation_Challenges_Opportunities_and_Recommendations/links/5d493e6b4585153e594018d2/Geothermal-Electricity-Generation-Challenges-Opportunities-and-Recommendations.pdf].

Double flash steam power plants have an additional flash stage compared to flash steam plants, allowing for more efficient utilization of the geothermal fluid's heat energy. This can result in higher power generation capacity and increased overall efficiency.

Both flash steam and double flash steam power plants are widely used in geothermal power generation, leveraging the natural heat resources available in geothermal reservoirs to produce reliable and renewable electricity.

4.2.3 Binary cycle power plants

As shown in Fig. 6, it adopts two cycles, namely the working fluid cycle and the geothermal water cycle. The following is the working principle of the system. Firstly, the hot water underground is extracted through wells or boreholes. Geothermal water contains high-temperature thermal energy deep in the Earth's crust. These geothermal waters are usually rich in minerals and thermal energy, with temperatures typically between 107 ℃ and 182 ℃ [10]. Then, the geothermal water enters a heat exchanger to exchange heat with the heat transfer medium in the working medium cycle (such as organic Rankine cycle medium). The heat energy of geothermal water is transferred to the heat transfer medium, causing it to evaporate.

After that, Steam is fed into the steam turbine, pushing it to rotate. The rotating turbine is connected to the generator, converting mechanical energy into electrical energy. This is the committed step of transforming Geothermal energy into electric energy.
After driving the turbine, the steam will cool down and become condensed water. This condensed water is sent back to the heat exchanger through a cooling cycle for heat exchange with geothermal water. During this process, the condensed water will release heat to the geothermal water, thereby becoming hot water again.

The entire system is a closed-loop cycle, where the geothermal water cycle and the working fluid cycle are interconnected and interact with each other. Geothermal water transfers heat energy to the working fluid through a heat exchanger, causing it to evaporate and drive the turbine to rotate. After the steam passes through the generator to generate electrical energy, it cools and returns to the heat exchanger for further heat exchange with geothermal water. This recycling uses underground geothermal energy and converts it into sustainable power output.

Binary cycle geothermal power system has advantages such as efficiency, environmental protection, and sustainability, making it widely used in areas with abundant geothermal resources and becoming an essential clean energy power generation technology.

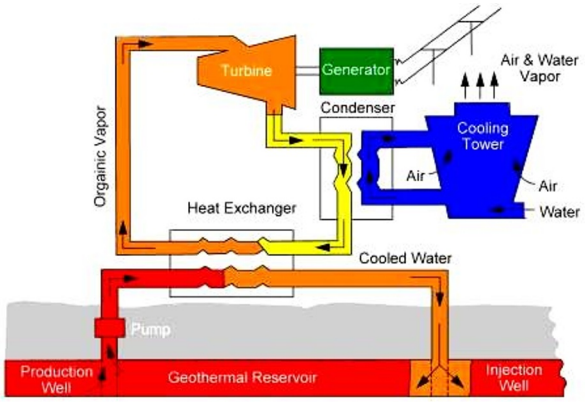

Fig. 6. Binary cycle power plants/organic rankine cycle system [9, https://www.researchgate.net/profile/Moses-Kabeyi/publication/334988672_Geothermal_Electricity_Generation_Challenges_Opportunities_and_Recommendations/links/5d493e6b4585153e594018d2/Geothermal-Electricity-Generation-Challenges-Opportunities-and-Recommendations.pdf].

4.3 Geothermal exploration

Geothermal exploration involves the systematic process of identifying and assessing potential geothermal resources. Several methods are used to explore and characterize geothermal reservoirs. Here are some common techniques:

Geological Mapping: Geologists study surface features, rock types, and geological structures to identify areas with potential geothermal resources.

Geochemical Surveys: Measurements of soil gases, hot springs, or surface water are taken to detect anomalies such as high concentrations of geothermal indicators (e.g., gases like helium, methane, or carbon dioxide).

Seismic Exploration: Seismic waves are generated, and their reflections and refractions are measured to determine subsurface rock layers, faults, and potential fluid reservoirs.

Gravity and Magnetic Surveys: These surveys detect variations in gravitational and magnetic fields caused by subsurface structures or density contrasts, helping to locate possible geothermal reservoirs.

Electrical Resistivity Surveys: Electrical currents are injected into the ground, and measurements of the resulting voltage gradients are taken to assess subsurface resistivity variations.

5 Geothermal management

The state manages the exploration, development, and utilization of geothermal energy, and the management bodies include the National Energy Agency, the National Geological Survey, and the Energy Corporation. The National Energy Authority provides advice to the government on energy and other related issues, advises associations and companies, and is responsible for the development of geothermal resource exploration and development policies.

The National Geological Survey (ISOR) is a new advisory and research department that was carved out of the National Energy Agency in 2003 based on new legal

regulations and is an independent yet government-owned research and service agency. The Energy Corporation is responsible for the exploration, development, production, and operation of the country's hydro and geothermal resources.

As one of the leading countries in the development and utilization of geothermal resources, Iceland has enacted a series of laws to promote the sustainable development of geothermal resources, including the Law on Research and Use of Underground Resources, the Nature Conservation Act, the Environmental Impact Assessment Act, and the Energy Act, to ensure that all aspects of geothermal resource exploration, development, and utilization are rational and orderly.

The most important of Iceland's geothermal energy use is the Act on the Investigation and Use of Ground Energy No. 57 of 1998 and the Electricity Act No. 65 of 2003. Based on these two laws, although the ownership of the resources is vested in the ownership of the land, the power to utilize and research the ground resources comes from the government's permission.

The Act passed in 2008 only allows states and municipalities to sell land or resources capable of generating up to 7 MW of electricity to private owners. Resources may be leased for personal development, but the right to explore and exploit the subsurface is subject to the Surface Resources Exploration and Use Act, which gives the government control over both public and private land resource exploration and surveying rights.

Under the Electricity Act, the establishment and operation of an electric utility requires a license granted by the Industrial Energy Tourism Department. However, no such permit is required to construct power companies with less than 1 MW. Important project works need to be evaluated by the Environmental Impact Assessment Act. The Natural Resources Protection Act also provides protection and monitoring measures, which are used to regulate the development of geological energy.

The impact, effectiveness, and benefits of these legislation and measures include:

(1) Promote the sustainable development and utilization of geothermal resources;

(2) Ensure the rationality and orderliness of geothermal resource exploration, development, and utilization;

(3) Provide a licensing system to regulate the utilization of geothermal resources;

(4) Emphasize the importance of environmental impact assessment to ensure the environmental sustainability of geothermal projects;

(5) Provide regulatory and protective measures to ensure Geothermal energy development meets regulatory and environmental requirements.

These legislation and measures generally provide an institutional framework and environmental protection for developing Geothermal energy in Iceland and promote sustainable utilization.

6 Conclusion

Since 1907, Iceland has utilized geothermal energy to generate electricity, bathing, snow melting, space heating, and so on. Also, in so many years of utilizing geothermal energy, they started using advanced technology, such as thermal spallation reduce the cost of drilling. In addition, Iceland now has flawless policies to manage the geo-energy. Benefiting from these advancements, Iceland begins to conduct more deep well projects. Electricity production by geo-energy is more common than before. But the construction and maintenance costs of geothermal power generation facilities are still high, requiring a significant investment of funds and human resources. The geographical environment limits development. As Iceland is located in a volcanic zone, geothermal energy is mainly distributed in specific areas, while other places lack rich resources. This means that the supply of geothermal energy needs to be balanced, and the transmission and distribution need to be effectively planned. However, despite these challenges, geothermal energy remains a valuable and reliable source of electricity and heat in Iceland. In addition, Iceland is exploring the integration of geothermal energy with other renewable sources like hydroelectric power and wind energy. This integrated approach helps balance fluctuations in electricity production, ensuring a stable and reliable energy supply. It also enables Iceland to optimize the use of different renewable resources based on their availability and complementarity.

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