CHAPTER 11

Geothermal Power Generation

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1 Introduction

The word *geothermal* comes from the Greek *gê* and *thermòs*, which literally means *Heat of the Earth*.

Geothermal energy derives from thermal energy that is contained within the Earth. The main sources of this energy are the radiogenic heat produced by the radioactive decay of isotopes (atoms of a given element, in this case potassium, thorium and uranium, with the same number of protons but different numbers of neutrons) in the mantle and crust, and the primordial heat left over from the formation of the Earth. This heat is constantly transferred from the interior of the Earth to its surface: due to this heat flow, the rock temperature increases by about 30 °C for each km of depth (geothermal gradient). Rainwater circulating underground through porous, fractured, permeable rocks is heated up. The hot water (or steam), rising through faults and fractures, can reach the surface and form hot springs, fumaroles and geysers but most of it, instead, remains underground, trapped in fractures and porous layers of rock between impermeable surfaces. Drilling wells connect the geothermal resource with the surface for using the thermal energy contained in the fluid.

The total estimated thermal energy of the Earth is immense but only a fraction can be recovered and utilised by humankind.

Geothermal energy from natural pools and hot springs was known since ancient times. More than 10,000 years ago, Native Americans used geothermal energy for cooking, bathing and warming. The beneficial effects of baths

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heated by hot springs and thermal waters were considered sacred gifts by Egyptians, Israelites, Hindus. Also Greeks and Romans used the water for bathing, cooking and curative purposes and one of the best-preserved evidence is the Roman city of Pompeii during the first century CE, where the water supply and the heating system were constantly updated with the most advanced techniques of that time. Such uses of geothermal energy were initially limited to sites where hot water and steam were accessible.

The world's pioneer district heating system was installed at Chaudes-Aigues (France) at the beginning of the fourteenth century, but only in the late nineteenth century, it was commercially introduced in several cities of USA and industry began to realize the economic potential of geothermal resources. Today the world's largest geothermal district heating system is in Reykjavik (Iceland), which has utilized natural hot water to heat its buildings and houses since 1930. Early industrial applications included the extraction of boric acid from geothermal fluids in Larderello (Italy) during the early nineteenth century. The first attempt at geothermal electric power generation took place in Larderello, with the successful development of an experimental plant in 1904. The first geothermal well was drilled in Japan in 1919, and at the Geysers in northern California in 1921. Geothermal power plants were then commissioned in New Zealand in 1958, in Mexico in 1959, in the USA in 1960, and later in many other countries.

2 Geothermal Energy Technology and Utilization

Geothermal energy can be found around the globe and is not conditioned by external conditions (whereas e.g. solar and wind energy present higher variability and intermittence) but upon the depth to the resource and economic convenience to produce it. Growing awareness and interest in renewable resources has raised the need to homogenize the reporting requirements for geothermal resources so that they can be applied worldwide. As no internationally agreed standards, guidelines or codes exist, the ambiguity inherent in the definition of geothermal assessments leads to increased resource uncertainty, more investment risk and less confidence in development Beyond the fact that the classification of a geothermal resource is strongly dependent on different approaches (i.e. by temperature, use, type and status, accessibility, electric power generation, stored heat, specific energy, recoverable volume, recoverable heat, recoverable power, net profit) (Falcone et al. 2013), it can be used to generated clean electricity, for heating and cooling or for industrial purposes. However, for electricity generation, medium- to high-temperature resources, which are usually close to volcanically active regions, are needed. A simplified scheme based on reservoir temperature, fluid type (water or steam), applications and technology is shown in Fig. 11.1.

Geothermal energy utilization is commonly divided into two categories: electric energy generation and direct uses. Deep geothermal technologies generally take advantage of a much deeper (commonly more than 2 km depth),

RESERVOIR TEMPERATURE	FLUID TYPE	APPLICATION	TECHNOLOGY
HIGH -T >150°C	water, vapour	electricity generation direct heat use	▪ DRY STEAM TURBINE ▪ SINGLE/DOUBLE/TRIPLE FLASH ❖ HEAT EXCHANGER
MEDIUM-T 90-150°C	water	electricity generation direct heat use	▪ BINARY CYCLE ❖ HEAT EXCHANGER ❖ GEOTHERMAL HEAT PUMP
LOW-T <90°C	water	direct heat use	❖ HEAT EXCHANGER ❖ GEOTHERMAL HEAT PUMP ❖ DIRECT HEAT USE

Fig. 11.1 Simplified scheme of geothermal resources, application and technology

higher temperature geothermal resource to generate electricity, while ground source heat pumps and direct use geothermal technologies utilize shallower, lower temperature geothermal resource for heating, cooling and industrial applications.

2.1 Dry Steam Power Plants

These plants draw from underground resources of steam. The conversion device is a steam turbine designed to directly use the low-pressure, high-volume fluid produced in the steam field. The steam is piped directly from underground wells to the power plant, where it is directed into a turbine/generator unit. Dry steam plants commonly use condensing turbines. The condensate is re-injected (closed cycle) or evaporated in wet cooling towers. This type of geothermal power plant uses steam of 150 °C or higher. Direct dry steam plants range in size from 8 MW to 140 MW (S&P Global Platts 2016).

2.2 Flash Steam Power Plants

These conversion facilities are the most common type of geothermal electricity plants in operation today. They are similar to dry steam plants; however, the steam is obtained from a separation process called flashing. They use geothermal reservoirs of very hot water that flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and directed to the turbines. The fluid fraction exiting the separators, as well as the steam condensate (except for condensate evaporated in a wet cooling system), is usually re-injected. The temperature of the fluid drops if the pressure is lowered, so flash power plants work best with well temperatures greater than 180 °C. Flash plants vary in size depending on whether they are single-(0.2–80 MW), double—(2–110 MW) or triple-flash (60–150 MW) plants (S&P Global Platts 2016).

2.3 Binary Cycle Power Plants

These plants operate on water at lower temperatures. The primary resource fluid is used, via heat exchangers, to heat a secondary working fluid, usually an organic compound with a low boiling point (i.e. ammonia/water mixtures used in Kalina cycles or hydrocarbons in Organic Rankine Cycles—ORC), in a closed loop. Typically, binary plants are used for resource temperature between 100 °C and 170 °C. Although it is possible to work with temperatures lower than 100 °C. Binary plants range in size from less than 1 MW to 50 MW (S&P Global Platts 2016).

2.4 Combined-Cycle or Hybrid Plants

Some geothermal plants use a combined cycle, which adds a traditional Rankine cycle to produce electricity from what otherwise would become waste heat from a binary cycle (ORMAT 2017). The typical size of combined-cycle plants ranges from a few MW to 10 MWe. Hybrid geothermal power plants use the same basics as a stand-alone geothermal power plant but combine a different heat source into the process; for example, heat from a concentrating solar power (CSP) plant. This heat is added to the geothermal brine, increasing the temperature and power output.

Geothermal electricity generation relies mainly on technologies that exploit conventional geothermal resources, such as: dry steam plants, flash plants, binary plants, and combined-cycle or hybrid plants. However, as high-quality conventional resources become harder to access, deeper resources may become accessible in the future through the development of Enhanced Geothermal System (EGS).

2.5 Enhanced Geothermal System (EGS)

A large part of the geothermal potential is heat stored at depths greater than commonly drilled.

The principle of the EGS is to create artificial fractures to connect production and injection wells by hydraulic or chemical stimulation. Stimulation is accomplished by injecting water (natural water flow is absent) and a small amount of chemicals at high pressure to create or reopen fractures in the deep rock. The EGS uses binary plants to produce power from the hot brine, which needs then to be totally re-injected in order to keep the pressure and production stable. During EGS reservoir creation and stimulation, rocks may slip along pre-existing fractures and produce micro-seismic events, which is one of the major controversial issues for the development of these systems.

2.6 Heat Pump and Direct Use Systems

A ground source heat pump utilizes the naturally occurring difference between the subsurface ground temperature (average temperature at depth of 20–100 m is 14 °C depending on the site) and the subsurface ambient air temperature. Geothermal hot water can be used for many applications that require heat. In these systems, a well is drilled into a geothermal reservoir to provide a steady stream of hot water. The water is brought up through the well (horizontally or vertically drilled), and a mechanical system (piping, heat exchanger and controls) delivers the heat directly for its intended use. A disposal system then either injects the cooled water underground or disposes of it on the surface. The heat pump can also operate in reverse, moving heat from the ambient air in a building into the ground, in effect cooling the building. A supplementary advantage of this system is that hot water can also be supplied to the building using the same loop. During the heat exchange, the excess heat from the building is transferred to its hot water system before reaching the ground loop. No additional energy is required to heat the water and no gases are released as everything is in a closed loop.

Beyond the heat pump systems for heating and cooling buildings and district heating, direct use systems have a wide range of applications such as greenhouse operations, heating the sidewalks and roads to melt snow, hot water supply, aquaculture and other industrial uses like laundries, drying, biological processes, waste management, resorts and spas in tourism industry. With some applications, researchers are exploring ways to effectively use the geothermal fluid for generating electricity as well.

3 Geothermal Power Generation Worldwide and Market Overview

The renewable power capacity data shown in the tables and figures below represent the maximum net generating capacity of power plants and other conversion facilities that use renewable energy sources to produce electricity. For most countries and technologies, the data reflect the capacity installed and connected at a given year. The capacity data are presented in megawatts (MW) and the generation data are presented in gigawatt-hours (GWh).

Geothermal installed capacity worldwide has continued to grow in the last decade (Fig. 11.2). In 2020, global geothermal installed capacity has increased up to 14,013 MW, representing approximately 0.5% of renewable power capacity worldwide. Tables 11.1 and 11.2 and Figs. 11.3 and 11.4 show data of the total installed geothermal capacity respectively per region and per country. The Asian regions share 32.4% of the total geothermal installed capacity due to the remarkable contribution of Indonesia (2131 MW) and the Philippines (1928 MW) followed by Japan (481 MW). North America shares 24.9% of the total with the highest contribution per country given by the USA (2587 MW). Europe shares 11.8% of the total and the major contribution is given by Italy

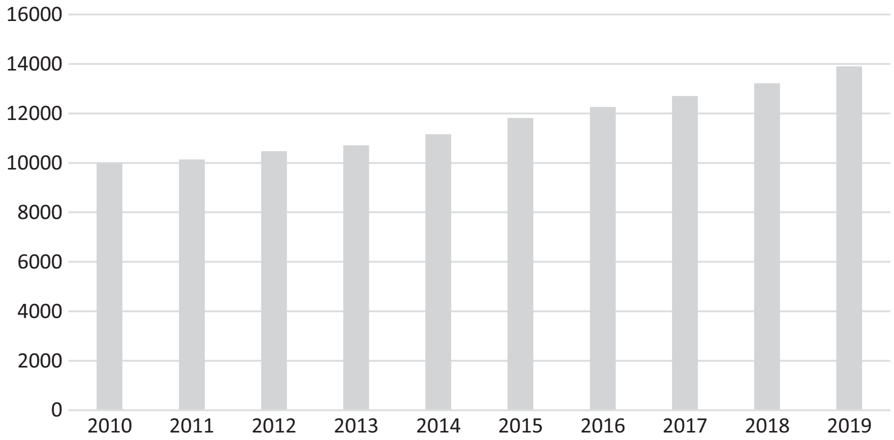

Fig. 11.2 Total Geothermal Installed Capacity (MW). (Source: IRENA_Renewable_Energy_Statistics_2021)

Table 11.1 Geothermal installed capacity by region

Region	*Geothermal Installed Capacity (MW)*	*Share of Total*
Asia	4540	32.4%
N America	3492	24.9%
Europe	1652	11.8%
Eurasia	1695	12.1%
Oceania	1040	7.4%
Africa	831	5.9%
C America + Carib	723	5.2%
S America	40	0.3%
Total	14013	100.0%

Data Source: IRENA_Renewable_Energy_Statistics_2021. The data refer to 2020 obtained from a variety of sources, including: the IRENA questionnaire; official statistics; industry association reports; and other reports and news articles

(797 MW) and Iceland (756 MW). Eurasia (Russian Federation and Turkey) shares 12.1%, almost all in Turkey (1613 MW), with only a minor estimated contribution by the Russian Federation (81 MW). In Oceania, a major contribution is given by New Zealand (984 MW). The African countries share 5.9% of the total, basically concentrated in Kenya (824 MW) and Ethiopia (7 MW). Central America and the Caribbean are mainly represented by Costa Rica (262 MW), El Salvador (204 MW) and Nicaragua (153 MW). The geothermal installed capacity in South America is completely concentrated in Chile (40 MW).

Table 11.2 Geothermal Installed Capacity by country in 2020

Country	*Geothermal Installed Capacity (in MW)*	*Share of Total*
United States	2587	18.5%
Indonesia	2131	15.2%
Philippines	1928	13.8%
Turkey	1613	11.5%
New Zealand	984	7.0%
Mexico	906	6.5%
[a]Kenya	824	5.9%
Italy	797	5.7%
Iceland	756	5.4%
Japan	481	3.4%
Other	1006	7.2%
Total	14,013	100.0%

Data Source: IRENA_Renewable_Energy_Statistics_2021. Data obtained from a variety of sources, including: the IRENA questionnaire; official statistics; industry association reports; and other reports and news articles

[a] Data estimated by IRENA from a variety of different data sources

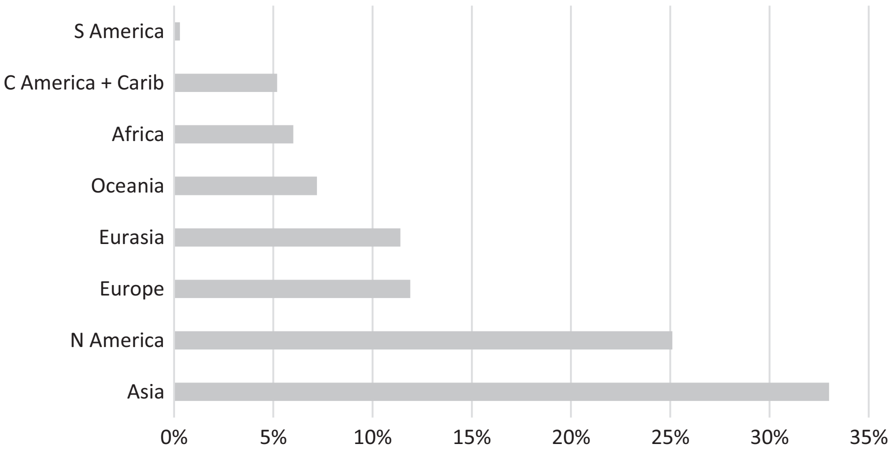

Fig. 11.3 Share of Total Geothermal Installed Capacity by region in 2020. (Source: IRENA_Renewable_Energy_Statistics_ 2021)

Coherently also the electricity generation from geothermal has grown from 69,856 GWh in 2011 to 92,047 GWh in 2019. The top ten countries are listed below in Table 11.3 and shown in Fig. 11.5.

At the end of 2020, there were 139 geothermal power plants with 3.5 GWe of geothermal electricity capacity across Europe. In 2020, Turkey has become the most active geothermal power market in the world with 8 new plants which added 165 MWe of geothermal electricity installed capacity. Moreover, a profitable development is driven by the confirmation from the Turkish government on the extension of the feed in tariff program applicable to plants entering in

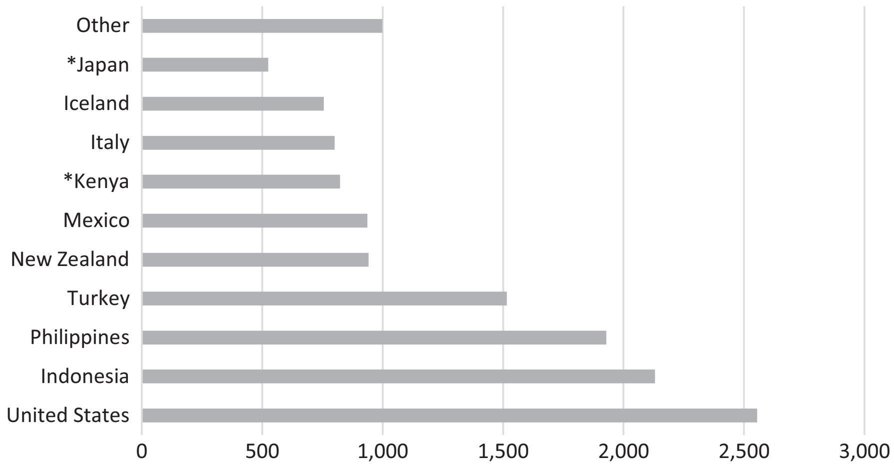

Fig. 11.4 Installed Geothermal Capacity by country in 2020 (MW). (Source: IRENA_Renewable_Energy_Statistics_ 2021)

Table 11.3 Geothermal electricity production by country in 2019

Country	*Electricity Production (GWh)*	*Share of Total*
United States	18,364	20.0%
Indonesia	14,100	15.3%
Philippines	10,691	11.6%
Turkey	8952	9.7%
New Zealand	8041	8.7%
Mexico	5330	5.8%
[a]Kenya	5384	5.8%
Italy	6075	6.6%
Iceland	6018	6.55%
Japan	2830	3.1%
Other	6262	6.8%
Total	92,047	100.0%

Data Source: IRENA_Renewable_Energy_Statistics_2021. Data obtained from a variety of sources, including: the IRENA questionnaire; official statistics; industry association reports; and other reports and news articles
[a] Data estimated by IRENA from a variety of different data sources

operation by 2025 (EGEC 2020). The European geothermal electricity market remains highly dominated by Italy and Iceland. The geothermal power potential is large and could cover, or exceed, the actual electricity demand in many countries. The EU Member States' National Energy and Climate Plans (NECPs) indicate as their target to reach the electricity production of 8 TWhe by 2030.

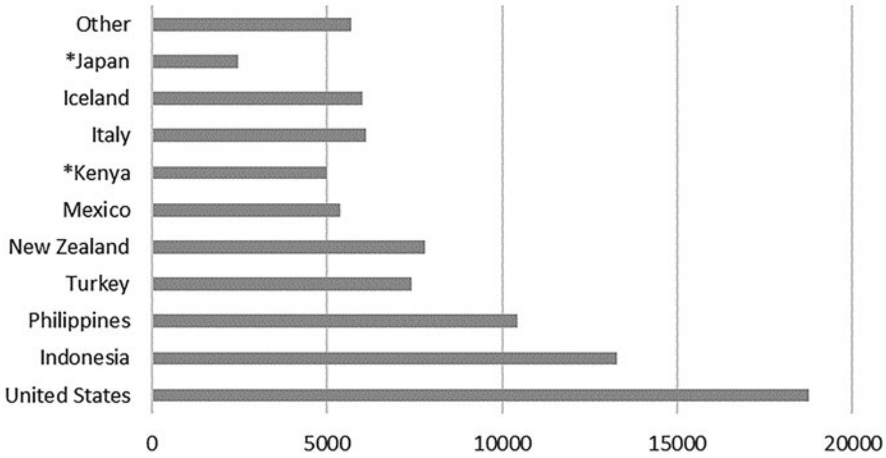

Fig. 11.5 Geothermal Electricity Production by country in 2019 (GWh) (Source: IRENA_Renewable_Energy_Statistics_2021)

Europe is a principal global market for geothermal district heating and cooling for buildings, industry and other services. In 2019, there were 5.5 GWht of installed geothermal district heating and cooling capacity in 25 European countries, corresponding to 327 systems. In 2020 a total of 350 geothermal district heating and cooling systems in operation plus 232 under development ready to be operational by 2025 (EGEC 2020). The status of geothermal district heating and cooling in Europe reflects a strong interest for this renewable resource and the possibility to implement it almost everywhere in Europe. The Netherlands continues to be the driving European market for deep geothermal heating and cooling.

The European geothermal heat pump market reached the milestone of 2 million units installed, as it is becoming a major heating and cooling solution in some regional or national markets because of its high efficiency and decreased costs due to the distribution of bigger systems in large edifices. Mature market for geothermal heat pumps in Europe include Germany, France and Switzerland. In colder climate countries, geothermal heat pumps are closer to market maturity and Sweden is the only country qualified as a mature market.

4 Geothermal Energy Costs and the Financing of Geothermal Power Plants

The overall cost of a geothermal project is extremely site-sensitive in the broadest sense, depending not only upon the geological setting but also, to a large extent, on market and policy from national to local scale. There are however, economic factors common to all projects such as provision of fuel (resource type), conversion technology, revenue generation and financing. The investment cost is basically divided into the cost of surface infrastructures and operations and the cost of subsurface activity. The surface costs include the cost of surface exploration and resource assessment and the cost of conversion technology (design and construction of the conversion facility and related surface equipment, such as electrical generation plant with required transformers and transmission lines, roads, buildings), while the cost of subsurface investment is that of drilling (exploration drilling, drilling of production and injection wells). While surface costs can be predicted with a certain degree of accuracy, higher uncertainty is represented by the drilling cost. The drilling cost for a low-temperature geothermal development typically is 10–20% of the total cost, and that for a high-temperature field is usually 20–50% of the total cost. Although drilling costs have a strong influence on the overall cost, the uncertainty driving the geothermal development cannot be exclusively attributed to them.

Typical costs for geothermal power plants range from 2000 USD/kW to 6000 USD/kW (depending on the site, if installing additional capacity at existing brown field or new green field). The data for recent projects shows that global weighted-average total installed costs were USD 4468/kW in 2020, slightly lower than in 2019, but broadly in line with values seen over the last four years.

The LCOE from a geothermal power plant is generally calculated by using the installed costs, operations and maintenance (O&M) costs, economic lifetime, and weighted average cost of capital. The global levelized cost of electricity (LCOE) of geothermal power of commissioned plants in 2020 was USD 0,071/kWh, having slightly declined from previous years (IRENA 2021, Renewable Power Generation Costs in 2020). O&M costs are high for geothermal projects, because of the need to work over production wells on a periodic basis to maintain fluid flow and hence production.

Capacity factors for geothermal plants, are the highest with respect to all other renewables, typically expected in the range of 70–90%, but lifetime capacity factors, considering a 25-year economic life, will depend heavily on well performance and ongoing investment to maintain production wells or drill new ones as the reservoir responds to the extraction and reinjection of fluids.

Costs for geothermal technologies are expected to continue to drop through 2050 (Sigfusson and Uihlein 2015). The economics of geothermal power plants may be improved by exploiting by-products such as silica, carbon dioxide and other chemicals.

Geothermal power plant development is capital-intensive due to exploration and drilling costs, for which it can be difficult to obtain bank loans. Since geothermal exploration is considered high risk, developers generally need to obtain some type of public financing. This risk is derived from the fact that capital is required before confirmation of the presence of the resource and therefore before project profitability can be determined. Policy makers can surely contribute to decrease the risk and the capital cost for private developers by deploying economic and financial instruments for example, by cost-sharing for drilling and by the activation of public-private risk insurance schemes; by data sharing with developers (including seismic events/fractures and deep drilling data owned by national or local governments).

5 Outlook for Geothermal Energy

The transition from current fossil-fuel energy system towards a sustainable one-based requires renewable energy technology. The potential of geothermal energy is huge and can be used globally. Given the somewhat unique nature of geothermal resources, geothermal power generation is very different to other renewable power generation technologies. Geothermal is a mature, commercially proven technology and with advances in technology and processes, it can become increasingly competitive as expected by 2050. Moreover, advantages of geothermal energy are not only the generation of electricity in different plant configurations but also the direct application of heat in industry, the heating and cooling. It is well positioned to play an important role in mitigating global climate change, increasing national energy security, and making the economy more competitive.

There are significant risks involved with initial exploration and drilling, but favourable regulatory environments (including tax incentives and land permitting and licensing legal framework) can do much to facilitate further developments in the sector. Besides, from being a clean and renewable energy source, geothermal power is also suitable for base load electricity generation and thus has the potential to become the backbone of local grid systems.

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