



Geothermal energy for sustainable development

A.Coskun Avci¹, O. Kaygusuz², K.Kaygusuz^{3,*}

¹Duzce, Department of Mechanical Engineering, Duzce, Turkey.

²Graduate School of Natural and Applied Sciences, Giresun University, Giresun, Turkey.

³Karadeniz Technical University, Department of Chemistry, Trabzon, Turkey.

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Abstract

That heat energy is geothermal energy. It is remnant heat derived from the formation of the planet 4.5 billion years ago, as well as heat from the radioactive decay of naturally occurring radioactive isotopes. That heat is sufficient to power plate tectonics, which is the slow movement of the continents and the ocean floor that make up earth's crust, and the upper mantle. It provides the energy to drive mountain building processes that occur when continents and oceans collide. It is also sufficient to melt rocks, generate volcanoes, heat water to form hot springs, and keep basements of buildings at a constant temperature. It is a perpetual, renewable, and inexhaustible energy resource. An estimated 0.7 GW of new geothermal power generating capacity came online, with Turkey, Indonesia and Kenya leading new installations. Direct use of geothermal energy for thermal applications grew most rapidly in space heating, with China, Turkey, Iceland and Japan representing 75% of direct geothermal use. As in previous years, the geothermal industry was inhibited by challenges of high project costs and lack of adequate funding. Research into new and innovative technologies and processes helped fuel optimism for the future. This study shows that there is some good global technical geothermal potential for heating and electricity generation with less environmental pollution.

Keywords: Renewable energy; geothermal power; geothermal heat pump; carbon free energy.

1. Introduction

Energy is a principal motor of economic growth, prosperity and economic development, a prerequisite for meeting basic human needs, while at the same time a source of environmental stress. Energy in itself is a vital component of sustainable development [1]. Different energy types have different types of impacts during their development. Along all energy chains, from the extraction of the resource to the provision of energy services, pollutants are produced, emitted or disposed of, often with serious health and environmental impacts [2]. During an energy project's lifecycle, emissions and wastes may be also associated with the manufacture or construction of energy systems [3].

Fossil fuels are largely responsible for urban air pollution, regional acidification and climate change. The use of nuclear power has created a number of concerns, such as the storage or disposal of high-level radioactive waste and the proliferation of nuclear weapons. Biomass use in some developing countries contributes to desertification and loss of biodiversity, as well as energy crop cultivation having significant impacts on food prices worldwide

[4]. Other renewable energy sources such as hydro- and wind power have significant implications for land-use as well as significant ecosystem and visual impact [1-4].

Geothermal energy has not until recently become a significant source of electricity and heat, with of course exceptions in countries such as the USA, Indonesia, Iceland and Italy [3]. In 2008, geothermal energy represented around 0.1% of the global primary energy supply, but estimates predict that it could fulfill around 3% of global electricity demand, as well as 5% of global heating demand by 2050 [4]. Geothermal energy is usually considered a renewable energy source, but its development and use can however have significant multi-dimensional sustainability implications [5]. Given the certainty that geothermal energy usage is set to increase substantially, it is important to ensure that geothermal resources are developed in a sustainable manner, in particular for electricity generation projects. As well as this, the international community has called for the development of indicators to measure progress towards sustainable development

[1]. Until now no framework however exists that enables formal assessment of the sustainability of geothermal energy development and use [1-4].

The objectives of this study are to discussing the literature on sustainability impacts of geothermal power development for electricity generation and thereby identify the most important issues of concern whilst assessing the sustainability of geothermal

energy projects. Review the available sustainability assessment frameworks and thereby determine thebest structure for an assessment framework for geothermal energy projects. Demonstrate the need for assessing sustainability in the geothermal energy sector and to provide the scientific basis for the creation of a formal sustainability assessment framework.

2. Geothermal energy for sustainable heating and electricity

2.1. Global energy demand

Global primary oil demand grew by a little more and to reach 87.4 million barrels per day in 2011 [1]. The trajectory that oil use over the coming decades differs considerably, reflecting the different assumptions about government policies to curb rising demand and emissions. According to the Scenarios, oil use increases in absolute terms to 2040, driven mainly by population and economic growth in the emerging economies, in response to strong policy action to curb fossil-energy use. The share of oil in total World energy demand falls and it reaches 27% in 2040 while 32% in 2011 [1-4].

The first of these fundamental trends is that the

world’s energy needs are set to rise. With the assumed expansion of the global economy of almost 140% and an increase of 1.7 billion in the world’s population, more energy will be needed to satisfy growing demand for energy services, even though new policies and programs are put in place to encourage energy savings [1]. World primary energy demand increases by 35% between 2018 and 2040 in the Energy Scenario as shown in Table 1 and Figure 1 [1]. This represents a sharp slowdown in the energy demand growth experienced over the past two decades, testament to the anticipated effect that already implemented and planned policies would have on energy markets [1-3]

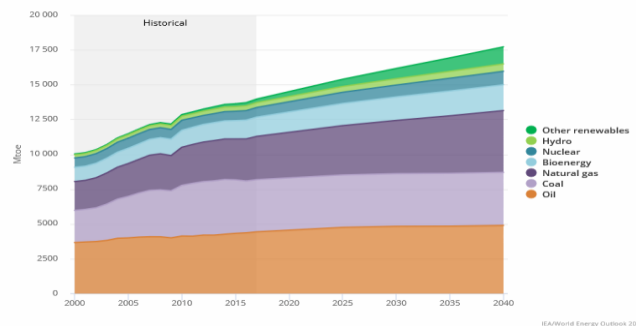


Figure 1. Global energy demand (Mtoe) [1].

Table 2 shows the global renewable energy capacities in 2018 [2]. As shown in Table 1 and 2, the share of renewables in world primary energy demand was reached from 13% in 1990 to 15% in

2018. This increase is underpinned by incentives to overcome market barriers, falling technology costs, rising prices and in some cases carbon pricing [2,3].

Table 1. World primary energy demand by fuel (Mtoe)

Fuel	1990	2000	2010	2018
Coal	2 231	2 317	3 576	3 821
Oil	3 232	3 665	4 086	4 501
Gas	1 668	2 083	2 746	3 273
Nuclear	526	675	624	709
Hydropower	184	225	298	362
Biomass & Bioenergy	905	1 012	1 296	1 357
Other renewables	36	60	124	294
Total World	8 782	10 037	12 750	14 314

Table 2. Global renewable energy capacities in 2019

Renewable energy	Capacity
INVESTMENT	
New annual investment (billion USD)	301.7
POWER	
Renewable power capacity with hydropower (GW)	2 588
Renewable power capacity without hydropower (GW)	1 437
Hydropower capacity (GW)	1 150
Wind power capacity (GW)	651
Solar PV capacity (GW)	627
Bio-power capacity (GW)	139
Geothermal power capacity (GW)	13.9
Concentrating solar power (CSP) capacity (GW)	6.2
HEAT	
Modern bio-heat demand (EJ)	14.1
Solar hot water demand (EJ)	1.4
Geothermal direct-use heat demand (PJ)	421
TRANSPORT	
Etanol annual production (billion litres)	116
Biodiesel annual production (billion litres)	54

Most of the growth occurs in the power sector (2378 GW), where their share in total generation grows from 20% to 31%, a near tripling in actual generation. Hydro accounts 1018 GW capacity for

power generation and its share is 64%. The second contribution is given by wind energy (319 GW). The amount of transport fuels is around 153 billion liters per year in 2018 [2, 3].

2.2. Geothermal energy for sustainable development

Geothermal energy is heat energy from the depths of the earth. It originates from the earth's molten interior and from the decay of radioactive materials in underground rocks. The heat is brought near the surface by crustal plate movements, by deep circulation of groundwater and by intrusion of

molten magma, originating from a great depth, into the earth's crust (see Fig. 2). In some places the heat rises to the surface in natural streams of steam or hot water, which have been used since prehistoric times for bathing and cooking [4-7].

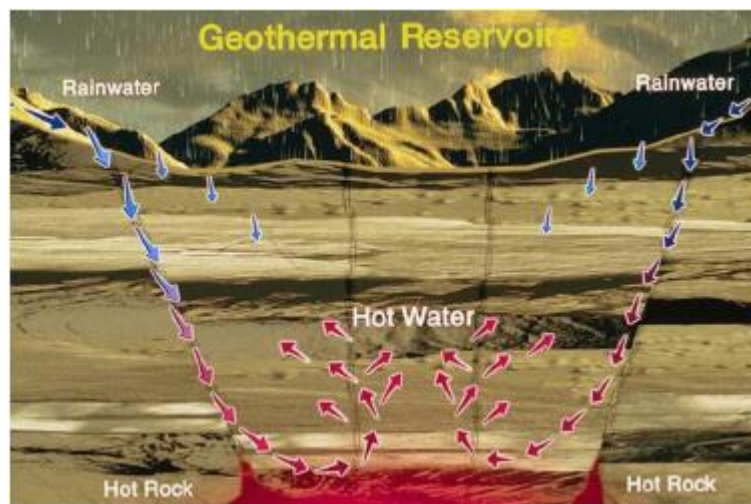


Figure 2. A representative geothermal reservoir.

Zones of high heatflow maybe located close to the surface where convective circulation plays a significant role. Deep circulation of groundwater along fracture zones brings heat to shallower levels, collecting the heatflow from a broad area and

concentrating it into shallow reservoirs. By drilling wells, this heat can be tapped to supply pools, greenhouses and power plants. The quantity of this heat energy is enormous; it has been estimated that over the course of 1 year, the equivalent of more than

100 million GWh of heat energy is conducted from the earth's interior to the surface [8]. Yet geothermal energy tends to be relatively diffuse, which makes it difficult to tap. If it were not for the fact that the

earth itself concentrates geothermal heat in certain regions—typically regions associated with the boundaries of tectonic plates (see Fig. 3) then geothermal energy would be essentially useless.

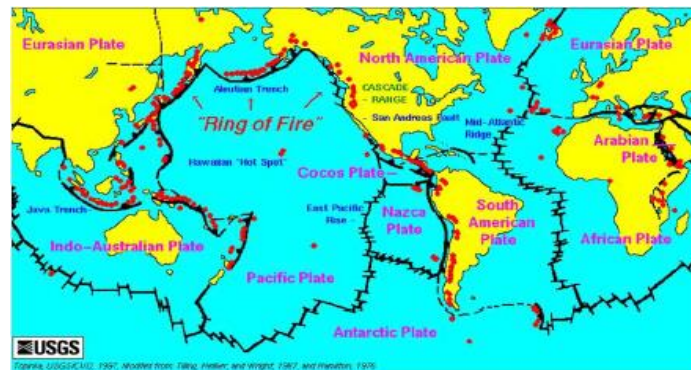


Figure 3. World map showing lithospheric plate boundaries.

Geothermal resources are renewable within the limits of equilibrium between offtake of reservoir water and natural or artificial recharge. Within such an equilibrium the energy source is renewable for a long period of time. At other sites the resource lifetime, if not recharged, may be limited to several decades. In

any case, if it is not technically renewable, the global geothermal potential represents a practically inexhaustible energy resource. The issue is not the finite size of the resource, but the availability of technologies able to tap the resource economically [9-14].

2.3. Nature of the geothermal energy resource

On average, the temperature of the earth increases by about 3 °C for every 100 m in depth. This means that at a depth of 2 km, the temperature of the earth is about 70 °C, increasing to 100 °C at a depth of 3 km, and so on. However, in some places, tectonic activity allows hot or molten rock to approach the earth's surface, thus creating pockets of higher temperature resources at easily accessible depths [5-8].

One of these belts rings the entire Pacific Ocean, including Kamchatka, Japan, the Philippines, Indonesia, the western part of South America running through Argentina, Peru, Ecuador, Central America, and western North America. An extension also penetrates across Asia into the Mediterranean area. Hot crustal material also occurs at mid-ocean ridges (e.g., Iceland and the Azores) and interior continental rifts (e.g., Kenya and Ethiopia) [2].

The extraction and practical utilisation of this heat requires a carrier which will transfer the heat towards the heat-extraction system. This carrier is provided by geothermal fluids forming hot aquifers inside permeable formations. These aquifers or reservoirs are the hydrothermal fields. Hydrothermal sources are distributed widely but unevenly across the earth. High-enthalpy geothermal fields occur within well-defined belts of geologic activity, often manifested as earthquakes, recent volcanism, hot springs, geysers and fumaroles. The geothermal belts are associated with the margins of the earth's major tectonic or crustal plates and are located mainly in regions of recent volcanic activity or where a thinning of the earth's crust has taken place [1-5].

Low-enthalpy resources are more abundant and more widely distributed than high-enthalpy resources. They are located in many of the world's deep sedimentary basins, e.g. along the Gulf Coast of the United States, western Canada, in western Siberia, and in areas of central and southern Europe, as well as at the fringes of high-enthalpy resources. There are four types of geothermal resources: hydrothermal, geopressured, enhanced geothermal systems (formerly Hot Dry Rock, HDR), and magma. Although they have different physical characteristics, all forms of the resource are potentially suitable for electric power generation if sufficient heat can be obtained for economical operation [2-5].

2.4. Hydrothermal resources

These are the only commercially used resources at the present time. They contain hot water and/or steam trapped in fractured or porous rock at shallow

to moderate depths (from approximately 100–4 500 m). Hydrothermal resources are categorised as vapour-dominated (steam) or liquid-dominated (hot

water) according to the predominant fluid phase. Temperatures of hydrothermal reserves used for electricity generation range from 90 °C to over 350 °C, but roughly two thirds are estimated to be in the moderate temperature range (150°–200 °C). The highest quality reserves contain steam with little or no entrained fluids, but only two sizeable, high-quality dry steam reserves have been located to date, at Larderello in Italy and The Geysers field in the United States.

Recoverable resources available for power generation far exceed the developments to date. Many countries are believed to have potential in

2.5. Geopressed resources

Geopressed geothermal resources are hot water aquifers containing dissolved methane trapped under high pressure in sedimentary formations at a depth of approximately 3–6 km. Temperatures range from 90° to 200 °C, although the reservoirs explored to date seldom exceed 150 °C. The extent of geopressed reserves is not yet well known world-wide, and the only major resource area identified to date is in the

2.6. Enhanced geothermal systems

These resources are accessible geologic formations that are abnormally hot but contain little or no water. The EGS potential is 200 GW in the USA and 60 GW in Europe. The basic concept in HDR technology is to form a manmade geothermal reservoir by drilling deep wells (400–5 000 m) into

2.7. Ecological and Environmental Impact

Geothermal energy use has a net environmental impact. Geothermal power plants have fewer and more easily controlled emissions than any similar-sized fossil fuel power plants (see Fig. 4). Direct heat uses are even cleaner and are practically non-polluting when compared to conventional heating. There are other environmental advantages to

excess of 10 000 MWe which would fulfil a considerable portion of their electricity requirements for many years. Important low-enthalpy hydrothermal resources are not necessarily associated with young volcanic activity. They are found in sedimentary rocks of high permeability which are isolated from relatively cooler near-surface groundwater by impermeable strata. The water in sedimentary basins is heated by regional conductive heat flow. These basins are commonly hundreds of kilometres in diameter at temperatures of 20°–100 °C. They are exploited in direct thermal uses or with heat pump technology [1-6].

northern Gulf of Mexico region where large reserves are believed to cover an area of 160 000 km². This resource is potentially very promising because three types of energy can be extracted from the wells: thermal energy from the heated fluids, hydraulic energy from the high pressures involved, and chemical energy from burning the dissolved methane gas [6].

high-temperature, low-permeability rock and then forming a large heat-exchange system by hydraulic or explosive fracturing. Injection and production wells are joined to form a circulating loop through the man-made reservoir, and water is then circulated through the fracture system [6].

geothermal energy, such as the fact that power plants using geothermal energy require far less land area than other energy resources (see Table 3). Another advantage, which differentiates geothermal energy from other renewables is its continuous availability 24 hours a day, all year round [6].

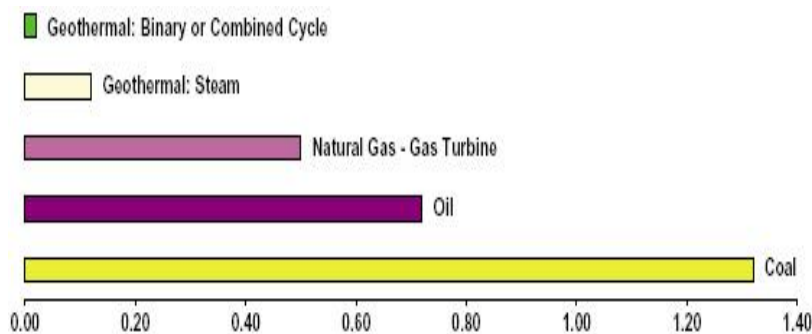


Figure 4. Relative emissions (kgCO₂/kWh) for different energy resources.

Table 3. Energy technology and occupied land area for 30 year time period

Energy technology	Land occupies(m ² /GWh/yr)
Coal with mining	3 642
Solar thermal	3 561
Photovoltaics	3 237
Wind turbines and roads	1 335
Geothermal	404

2.8. Mainstream Technologies

Geothermal energy has been used for centuries for bathing, therapeutic utilisations and water heating. Only in the 20th century has geothermal energy been harnessed on a large scale for other purposes, such as

space heating, industry and electricity generation. The range of potential methods for utilising any geothermal resource depends mostly on the temperature of the resource [1-8].

2.9. Direct Heat Use

Lower-temperature geothermal resources occur in many world regions. They can provide useful energy for space and water heating, district heating, greenhouse heating, warming of fish ponds in aquaculture, crop drying (see Fig. 5). Geothermal fluids are generally pumped through a heat exchanger to heat air or a liquid in direct use,

although the resources may be used directly if the salt and solid contents are low. In comparison with geothermal electricity production, direct use has several advantages, such as higher energy efficiency (50–70%), generally the development time is shorter and less capital investment is involved.

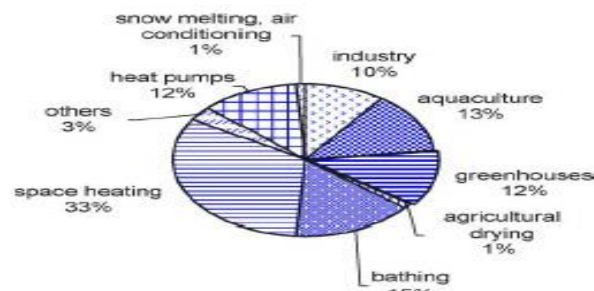


Figure 5. Direct-heat uses.

Geothermal heat pump (GHP) technology can use geothermal sources of 20 °C or less. GHP can move heat in either direction; in winter heat is removed from the earth and delivered to the home or

building—heating mode, while in summer heat is removed from the home or building and delivered for storage to the earth—air conditioning mode [8-14].

3. Geothermal power generation technologies

There are several types of energy-conversion processes for generating electricity from hydrothermal resources. These include dry steam and

flash steam systems, which are traditional processes; binary cycle and total flow systems, which are newer processes with some significant advantages [6-8].

3.1. Dry steam plants

Conventional steam-cycle plants are used to produce energy from vapour-dominated reservoirs. As is shown in Figure 6, steam is extracted from the wells, cleaned to remove entrained solids and piped directly to a steam turbine. This is a well-developed, commercially available technology, with typical unit

sizes in the 35–120 MWe capacity range. Recently, in some places, a new trend of installing modular standard generating units of 20 MWe has been adopted. In Italy, smaller units in the 15–20 MWe range have been introduced.



Figure 6. Dry steam power plant.

3.2. Flash steam plants

More complex cycles are used to produce energy from liquid-dominated reservoirs which are sufficiently hot (typically above 160 °C) to flash a large proportion of the liquid to steam. As shown in Figure 7, single-flash systems evaporate hot geothermal fluids to steam by reducing the pressure of the incoming liquid and direct it through a turbine. In dual-flash systems, steam is flashed from the remaining hot fluid of the first stage, separated and

fed into a dual-inlet turbine or into two separate turbines. In both cases, the condensate may be used for cooling while the brine is re-injected into the reservoir. This technology is economically competitive at many locations and is being developed using turbogenerators with capacities of 10–55 MWe. A modular approach, using standardised units of 20 MWe, is being implemented in the Philippines and Mexico.

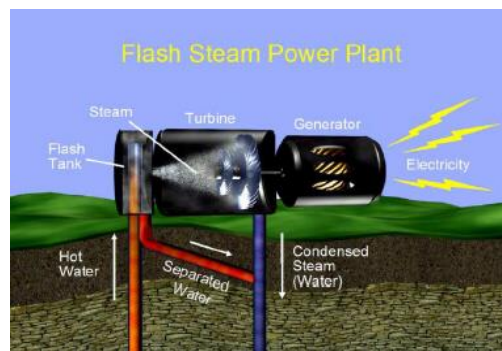


Figure 7. Flash steam power plant.

3.3. Binary-cycle plants

Operating experience over the years has confirmed the advantages of binary geothermal plants, not only for low-enthalpy water-dominated resources but also for high-enthalpy resources with high aggressive brine or brine with high non-condensable content. The systems deliver sustainable zero-pollution energy and avoid a long-term depletion of the resource (which is 100% reinjected) [6].

- *Low-Enthalpy Resources (100°–160 °C)*. For low-enthalpy resources, binary plants based on the use of organic Rankine cycles (ORC) are utilised to convert the resource heat to electrical power (see Figure 8). The hot brine or geothermal steam is used as the heat source for a secondary (organic) fluid, which is the working fluid of the Rankine cycle. In the early 1980s, in order to increase the power output from a given brine resource by increasing the thermal cycle efficiency, a

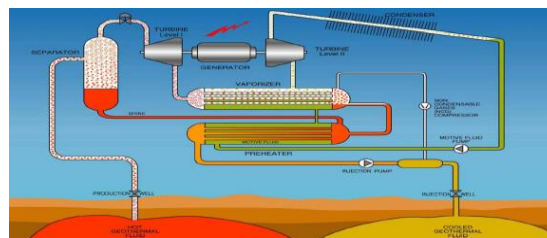
supercritical cycle using isobutane was developed, as well as a cascade concept. The supercritical cycle may be slightly more efficient than the cascading cycle, but the cascading system has the advantage of lower operating pressures and lower parasitic loads in the cycle pumps. For example, at a power plant in Southern California, a three-level arrangement was employed and resulted in increased efficiency or power output gain of about 10% over that achievable with a simple ORC. In all of the above arrangements, a modular approach was employed so that high plant availability factors of 98% and above were achievable.

- *Moderate-Enthalpy Resources (160° – 190 °C)*. For moderate-enthalpy, two-phase resources with steam quality between 10 and 30%, binary plants are also efficient and

costeffective. Furthermore, when the geothermal fluid has a high non-condensable gas (NCG) content, even higher efficiency can be obtained than with condensing steam turbines. This binary two-phase configuration is used in the São Miguel power plant in the Azores Islands (Figure 9). Separated steam containing NCG is introduced in the vaporiser heat exchanger to vaporise the organic fluid. The geothermal condensate at the vaporiser exit is then mixed with the hot separated brine to provide the preheating medium of the organic fluid. Since the onset of silica precipitation is related to its concentration in the brine, dilution of the brine with the condensate effectively lowers the precipitation temperature at which silica crystallises. This lower temperature added 3.5 MW of heat to the cycle representing 20% of the total heat input. This additional heat is utilised at the same thermal efficiency as the remaining heat, owing to the nature of the combined steam-brine cycle. Since the cycle efficiency is about 17%, this low-temperature heat produces about 600 additional kW. The second way to improve the utilisation of the

resource is the use of a regenerative cycle by the addition of a recuperator heat exchanger between the organic turbine and the air-cooled condenser, since the organic vapour tends to superheat when the vapour is expanded through the turbine. In this case the recuperator reduces the amount of heat that needs to be added to the cycle from the external source, thereby reducing the brine flow rate required. This results in a reduction of about 7% in the total heat input required to produce the design level of power output.

- *Geothermal Combined Cycle Plants.* To best utilise a steam-dominated resource, a Geothermal Combined Cycle is used where the steam first flows through a back-pressure steam turbine and then is condensed in the organic turbine vaporiser. The condensate and the brine are used to preheat the organic fluid as in the two-phase binary configuration above. This concept was first used in 1989 in repowering a back-pressure steam plant in Iceland, then with a 30 MW plant in Hawaii in 1992, followed by a 125 MW plant in the Philippines and a 60 MW plant in New Zealand.



• Figure 8. Air-cooled binary plant (Source: Ormat).



• Figure 9. Two-phase binary geothermal power plant.

4. Recent developments

4.1. Current uses and commercial markets

Geothermal resources are utilised for energy applications through two primary pathways, either through the generation of electricity or through various “direct use” thermal applications, such as space heating and industrial heat input. In 2019, geothermal electricity output was approximately 95

TWh while direct useful thermal output was around 117 TWh. Some geothermal plants produce both electricity and heat for various thermal applications, but this is contingent on thermal demand being relatively near the resource. An estimated 0.7 GW of new geothermal power generating capacity came

online in 2019, bringing the global total to around 13.9 GW. As in 2018, Turkey and Indonesia remained in the lead for new installations, followed closely by Kenya. Together, these three countries

represented three-quarters of new installations globally. Other countries that added new geothermal power facilities in 2019 were Costa Rica, Japan, Mexico, the US and Germany (See Figure 10) [2].

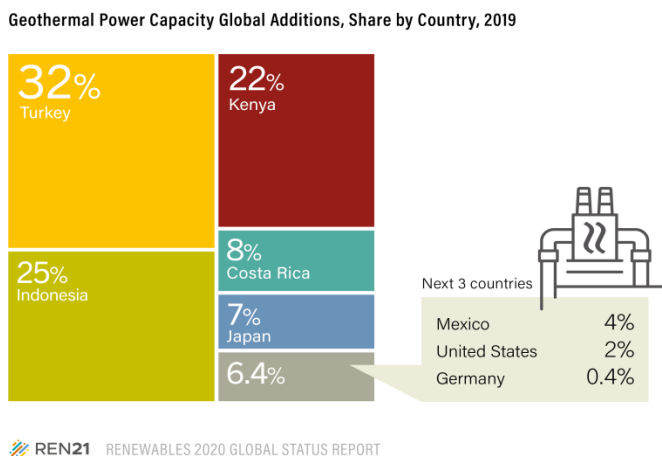


Figure 10. Global geothermal power capacity addition.

The top 10 countries with the largest stock of geothermal power capacity at the end of 2019 were the United States, Indonesia, the Philippines, Turkey, New Zealand, Mexico, Kenya, Italy, Iceland and Japan. (See Figure 11) In some instances, effective generating capacity may be lower than indicated values, due to gradual degradation of the steam-generating capability of geothermal fields or to insufficient drilling of make-up wells to replenish

steam flow over time. For example, the effective net generation capacity in the United States was 2.5 GW at the end of 2019, whereas the gross nameplate generator capacity was 3.7 GW. Turkey and Indonesia have been, by far, the most active geothermal markets in the world in recent years. Since 2016, each country has added more than 0.8 GW of capacity, with no other market coming close in that time frame [2].

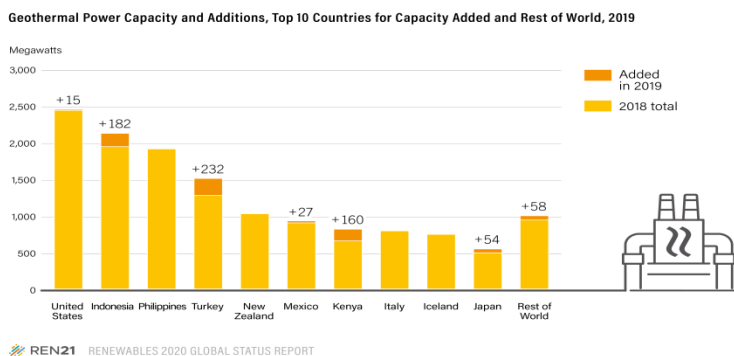


Figure 11. Global geothermal capacity in 2019.

Following capacity expansion of 219 MW in 2018, Turkey brought online a net additional capacity of 232 MW in 2019.8 Among the units entering operation was the 32 MW Unit 6 at the Pamukören complex. A 30 MW unit also was added to Maspo Energy’s existing 10 MW facility, and the company was continuing feasibility studies for a third unit. In 2019, Turkey ranked fourth globally for total geothermal power capacity, with 1.5 GW. The bulk of Turkey’s geothermal capacity has been built over the last decade in response to a technology-specific feed-in tariff (FIT) in place since 2011. In 2019, the

country’s geothermal industry leadership awaited new subsidy schemes to replace the expiring FIT, suggesting that uncertainty about renewal of the FIT may have been holding back financing and investments in new projects. At an average project cost of USD 4 million per megawatt, the current growth of 200-250 MW per year represents USD 1 billion in annual investment going forward. In early 2020, with its subsidy scheme under review, the Turkish government indicated that its support for renewables would continue [6-12].

Turkey's geothermal sector also faced mounting community concern about the potential adverse impacts of air emissions (mainly hydrogen sulphide) and groundwater contamination (heavy metals) from existing geothermal power plants on public health, wildlife and agricultural output (primarily olives and figs). Most of the country's geothermal plants are located in the agricultural regions of western Anatolia, bordering the Aegean Sea. Also of concern, carbon dioxide emissions from Turkey's geothermal operations, which range from 1.0 to 1.3 kilograms of CO₂ per kWh at the time of plant commissioning, are nearly 10 times above the global average. Recent observations suggest that CO₂ emission rates at the country's geothermal fields decline over time, although outcomes vary by facility [6].

Indonesia added 182 MW of geothermal capacity in 2019, following the 140 MW added in 2018, for a year-end operating total of 2.1 GW. 20 Construction was completed on three units: the 42.3 MW Sorik Marapi Unit 1 in North Sumatra, and the 55 MW Lumut Balai and the 85 MW first stage of the Muara Laboh facility, both in South Sumatra. The Sorik Marapi is expected to expand to five generating units and a total of 240 MW by 2023, with the second unit to be ready by the end of 2020. The Indonesian government's target for 23% renewables in the energy mix by 2025 assumes that geothermal power capacity will reach 7 GW. In an effort to mitigate geothermal project risk and to stimulate investment to achieve its target, the government pursued exploratory drilling in three separate locations during 2019.

Elsewhere in Asia, most geothermal power capacity is located in Japan and the Philippines. Japan's geothermal capacity has expanded very little in recent years despite plentiful resources, which made 2019 relatively eventful. The 7.5 MW Matsuo Hachimantai geothermal power plant was completed in Iwate Prefecture in the north-eastern part of Honshu. As is common for geothermal projects, the development timeline was lengthy: initial research for the single-flash plant began in 2011, exploration started in 2015, and resource development began in 2017. At the time of completion, Hachimantai was the largest geothermal plant to be built in Japan in more than 20 years. By mid-2019, the double-flash 46 MW Waisabizawa plant began operation in neighbouring Akita Prefecture. Although Japan has some 550 MW of installed generating capacity, the country's actual effective (running) capacity may be around 330 MW. The average capacity factor of geothermal power plants in the country has been

declining since the 1970s.

At the end of 2019, the Philippines continued to rank third for total installed capacity, at 1.9 GW, although no new capacity came online during the year. The country has large untapped potential for geothermal energy, but the leading local developer does not foresee much new development. Reasons include a lack of financial incentives, a challenging permitting process and a lack of investors willing to absorb the development risk that is endemic to the industry [1-3].

Kenya closely followed Turkey and Indonesia for new installations (160 MW), and ended the year with 0.8 GW of total capacity. The country is Africa's most active market for geothermal power and the only one on the continent to add capacity in 2019. Also of note in Kenya was the African Development Bank's issuance of a partial risk guarantee in support of the long-delayed Menengai geothermal project. With the requisite drilling already complete, the guarantee was expected to hasten construction of the initial three 35 MW units [2].

Costa Rica ranked fourth globally for newly installed capacity. The 55 MW Las Pailas II geothermal plant was completed, finalising the complex that also includes the 35 MW Las Pailas I, which came online in 2011. The Las Pailas II production field encompasses 21 wells with an average depth of 2,200 metres. The country's capacity reached 262 MW by year's end, second only to Mexico in Latin America. Mexico also added new operating capacity, inaugurating a 27 MW unit in the state of Michoacán at the Los Azufres power plant, and bringing the plant's total to 10 generating units and 252 MW of capacity [2].

Also in Latin America, construction began on Chile's 33 MW expansion of the Cerro Pabellón geothermal power plant. Combined with two high-enthalpy binary-cycle units already in place, the plant is expected to reach a total capacity of 81 MW when completed. In 2019, the country's net geothermal capacity expanded by only 14.8 MW, bringing total net operating capacity to 2.5 GW. Geothermal power in the United States generated 16 TWh in 2019, virtually unchanged from 2018, representing less than 0.4% of US net electricity generation [9-16].

Only a few countries in Europe have geothermal power plants, and most of the region's operating capacity is in Italy and Iceland, although neither country added capacity in 2019. Croatia officially

unveiled its first geothermal power plant, the 16.5 MW Velika Ciglana, late in the year, having completed the construction in 2018. New capacity was brought online in Germany as well. Following the start of operations for district heating in late 2018, the town of Holzkirchen initiated power generation from its 3.2 MW geothermal combined heat and power plant [1, 2, 3, 6, 8].

Around the world, the capacity for geothermal direct use increased by an estimated 2.2 GW in 2019, or nearly 8%, to an estimated 30 GWth. Geothermal energy use for thermal applications grew an estimated 10 TWh during the year to an estimated 117 TWh (421 PJ).

The largest category of direct use was bathing and swimming, comprising around 44% of total use in 2019 and growing about 9% annually. Second was

4.2. Heat pump applications

During the last decade a number of countries have encouraged individual house owners to install ground-source heat pumps to heat their homes in the winter and (as needed) to cool them in summer. Financial incentive schemes have been set up, commonly funded by the governments and electric utilities, as the GHP reduce the need for peak power

4.3. Research and development

Several demonstration projects are under development in the framework of Enhanced Geothermal Systems, with the participation of the USA, the European Union, Germany, France,

4.4. The future

The growth rate of the geothermal energy market is not limited by a lack of resources. During the early oil crises, intensive investigations led to the discovery of many geothermal reservoirs for electricity generation, some of which are in operation, while about 11 000 MWe of proven resources are not yet tapped. In the near future, the growth rate will most probably be 3–4% annually, as has been the case during the past few years [3, 6, 14-26].

The report prepared by the Geothermal Energy Association shows that geothermal resources using today's technology have the immediate potential to support between 35 450 and 72 390 MW of electrical generation capacity. Using enhanced technology, currently under development, the geothermal resource could support between 65 580 and 138 130 MW of electrical generation capacity. Assuming a

space heating (around 39% of direct use), the fastest growing category with around 13% annual growth. The remaining 17% of direct use was allocated to greenhouse heating (8.5%), industrial applications (3.9%), aquaculture (3.2%), agricultural drying (0.8%), snow melting (0.6%) and other uses (0.5%).

The top countries for geothermal direct use in 2019 were China, Turkey, Iceland and Japan, which together represented roughly 75% of the global total. China is both the largest user of geothermal heat (47% of the total) and the fastest growing market, having grown more than 20% annually on average over the last five years. That period of growth coincides with the government's first geothermal industry plan, issued in 2017, for rapid expansion of geothermal energy use, especially for heat applications [4-6].

and thus replace new electric generating capacity. The US Government Heat Pump Consortium estimates that there were 750 000 GHP units installed in the USA (in 2002), which reduced electricity demand by some 1 900 MW. In 2002 the European Union countries installed more than 50 000 GHP units [1-3].

Switzerland, Italy, Japan and Australia. HDR projects are under development at Fenton Hill (USA), Soultz-sous-Forêts (France) and Hunter Valley (Australia) [6].

90% availability factor, which is well within the range experienced by modern geothermal power plants, this electric capacity could produce over a trillion kWh of electricity annually [6-10].

Worldwide the report indicates that geothermal power could serve the electricity needs of 865 million people, or about 17% of the world's population. It identifies 39 countries which could be 100% geothermal powered, mostly in Africa, Central and South America and the Pacific. However, if the environmental impacts of energy use are internalised, then the real value of geothermal technology, including its superior environmental characteristics and local resource features, will be taken into account and the geothermal market will become more profitable. As a result, there will be enhanced geothermal exploration and R&D. The growth rate should then reach 6–7% and more. This outlook

should encourage the development of other geothermal resources. The EGS and geopressed

technologies may reach maturity around 2020 [22-26].

5. Conclusions

Geothermal energy is a renewable energy source that has been utilised economically in many parts of the world for decades. A great potential for an extensive increase in worldwide geothermal utilisation has been proven. This is a reliable energy source which serves both direct use applications and electricity generation. Geothermal energy is independent of weather conditions and has an inherent storage capability which makes it especially suitable for supplying base load power in an economical way, and can thus serve as a partner with energy sources which are only available intermittently. The renewable energy sources can contribute significantly to the mitigation of climate change and more so by working as partners rather than with each other.

Presently, the geothermal utilisation sector growing most rapidly is heat pump applications. This development is expected to continue in the future making heat pumps the major direct utilisation sector. The main reason for this is that geothermal heat pumps can be installed economically all over the world. One of the strongest arguments for putting more emphasis on the development of geothermal resources worldwide is the limited environmental impact compared to most other energy sources.

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The geothermal exploitation techniques are being rapidly developed and the understanding of the reservoirs has improved considerably over the past years. Combined heat and power plants are gaining increased popularity, improving the overall efficiency of the geothermal utilisation. Also, low-temperature power generation with binary plants has opened up the possibilities of producing electricity in countries which do not have high-temperature fields. Enhanced Geothermal Systems (EGS) technologies, where heat is extracted from deeper parts of the reservoir than conventional systems, are under development. If EGS can be proven economical at commercial scales, the development potential of geothermal energy will be limitless in many countries of the world.

A project for drilling down to 5 km into a reservoir with supercritical hydrous fluids at 450-600°C is under preparation (IDDP). If this project succeeds, the power obtained from conventional geothermal fields can be increased by an order of magnitude. This would mean that much more energy could be obtained from presently producing high-temperature geothermal fields from a smaller number of wells.

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