Geothermal Energy

REVIEW

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Evolution of worldwide geothermal power 2020–2023

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Abstract

Only 32 countries in the world have geothermal power plants in operation, with a combined capacity of 16,318 MW installed in 198 geothermal fields with 673 individual power units. Almost 37% of those units are of flash type with a combined capacity of 8598 MW (52.7% of total), followed by binary ORC type units with 25.1% of the installed capacity. The select list of geothermal power countries continues to be headed by the US, followed by Indonesia, the Philippines and Türkiye, and generated 96,552 GWh of electricity, at an average annual capacity factor of 67.5%, which represented 0.34% of the worldwide electric generation. Electricity from geothermal origin represented more than 10% of the total generated in at least seven countries, headed by Kenya, Iceland, and El Salvador. Practically, all geothermal fields in operation are harnessing resources from hydrothermal, conventional reservoirs, through an estimate of 3700 production wells at an annual average production of almost 3 MWh per well. Things could be similar in the next few years if the current trend continues, but all can change due to the world urgency to maintain global warming below the 1.5 °C threshold in the following years.

Keywords: Geothermal power, Installed capacity, Electric generation, Capacity factor, Geothermal fields, Power plant types

Introduction

The first World Geothermal Congress (WGC), properly named so, was held in Florence, Italy, in May 1995 convened by the then recently founded International Geothermal Association (IGA), and hosted by the Italian electric utility ENEL. There, Huttrer started the tradition of preparing a rapporteur's general report to summarize the worldwide status of geothermal power, based mainly on the national update reports presented in the same event, but also in personal research and other sources. This first report also included a brief description of countries with no power plants in that moment, but with geothermal exploration studies and development plans (Huttrer 1995). The author had had a similar task in the 1990 annual meeting of the former Geothermal Resources Council (GRC, currently Geothermal Rising), where several national geothermal reports were presented, and he also continued with this task in the following WGC of 2000 held in Beppu-Moriaka, Japan. The world geothermal reports of the following WGCs, convened in Antalya, Turkey (2005), Bali, Indonesia (2010), and Melbourne, Australia–Auckland, New Zealand (2015), were professionally prepared by Bertani, whose unexpected and regrettable passing away in 2018 led to the Technical Committee of the WGC2020+1, held in Reykjavik, Iceland, in 2021, to ask Huttrer to make the job one more time.

Now, trying to go on the track left by these two pioneers who made remarkable works, following is the geothermal worldwide report presented in the WGC 2023, which covers the information and developments of the last 3 years, but also includes info available up to beginning of 2024. It also intends to be a modest homage to Huttrer and Bertani.

Since the mentioned 1990 GRC annual meeting, and more formally since the first WGC in 1995, a set of tables were prepared to uniformize the data and information regarding the status of geothermal fields, wells, power plants, generation, direct uses, technical personnel and estimated investments in geothermal exploration and development. The set evolved over time, and by WGC2020+1 it was composed of eight tables in an Excel template that the technical committee of the respective congresses used to send to the invited authors of the country update reports for them to fill out. Authors invited are well-informed on geothermal development in their respective countries, in some cases appointed by national geothermal associations. Those tables included the present and planned production of electricity, utilization of geothermal energy for power generation, amount and combined depth of geothermal wells, allocation and type of professional personnel devoted to geothermal activities, and public and private investments subclassified into research exploration and drilling-development operation.

In 2022, the IGA Education and Information Committee, chaired by Adele Manzella, adopted a new set of only four, but much more complete tables, two for geothermal indirect use (electricity generation) and two for direct uses (heating and cooling). The goal behind these new tables is not only to use them for the country update reports to the WGCs, but mainly to build "a framework for geothermal data standards and methods to improve data collection (…) to support the process of collecting, storing, and sharing coherent geothermal datasets" (Manzella and Krieger 2022). The database was being prepared by Gregor Rumberg, the IGA's Events & Operations Lead when writing this report, and is planned to be updated at least annually by a group of correspondents (IGA Ambassadors) worldwide. The set of new tables was sent to the invited authors of the country reports for the WGC2023.

The country update reports received in the WGC2023 with the new tables filled provided more detailed information than in the past congresses. However, there were fewer reports than in previous WGCs, and then it was necessary to recur to other sources and info for several countries, including some of the top power producers, which, on the other hand, also used to happen when Huttrer and Bertani prepared their respective world reports.

Current geothermal power and electricity generation

As of December 2022, the most likely geothermal installed capacity in the world amounted to 16,318 MW, distributed in 32 countries and approximately 198 geothermal fields in operation. It represented a tiny fraction (0.16%) of the worldwide electric installed capacity on the same date, which was 10,216,390 MW (OWD 2023). Geothermal electric generation in those fields and countries during 2021 amounted to 96,552

Table 1 Evolution of geothermal power worldwide in the last 43 years

Years	Capacity (MW)	Capacity Factor (%)	Generation (GWh)			Share of (%)	
			Geothermal	Clean energy	Total	Clean energy	Total
1980	2110	70.87	13,100	2,438,000	5,633,000	0.54	0.23
1985	4764	69.32	28,930	3,547,900	9,831,380	0.82	0.29
1990	5834	69.33	35,430	4,351,600	11,853,110	0.81	0.30
1995	6832	63.55	38,035	5,022,400	13,382,480	0.76	0.28
2000	7972	70.54	49,261	5,485,400	14,971,790	0.90	0.33
2005	8933	71.19	55,709	6,044,100	17,763,940	0.92	0.31
2010	10,897	70.45	67,246	6,958,800	20,938,060	0.97	0.32
2015	12,284	68.35	73,550	8,142,800	23,660,330	0.90	0.31
2020	15,414	66.35	89,587	10,186,500	26,276,910	0.88	0.34
2023	16,318	67.54	96,552	11,143,100	28,254,250	0.87	0.34

Prepared with data taken or updated from Bertani (2015) and Huttrer (2020), from the country update reports and from OWD (2023). Data for geothermal electric generation in 1980 and 1985 are estimated. *Most geothermal data for 2023 correspond to 2021, but worldwide clean energy and total generation are for 2022*

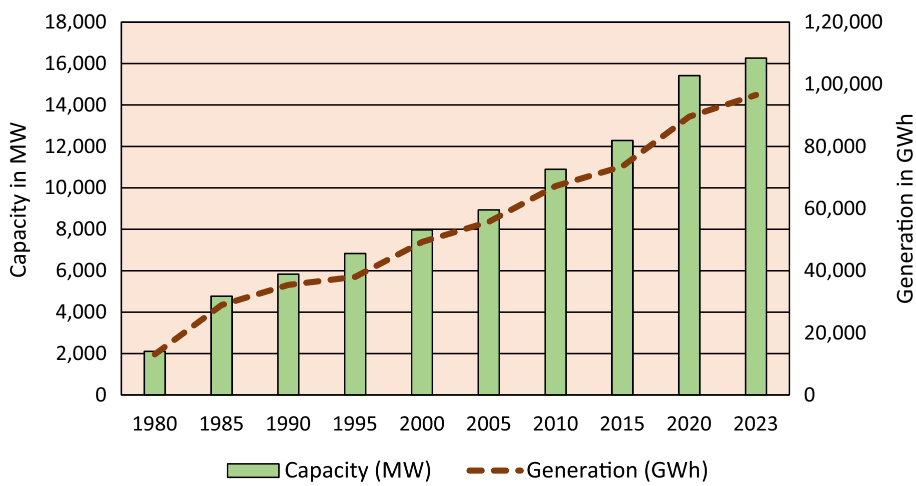

Fig. 1 World geothermal capacity and electric generation between 1980 and 2023. Electric generation in 1980 and 1985 are estimated

GWh, representing 0.34% of the world electric generation, and 0.87% of the clean energy generated in the world (Table 1). Clean energy is defined as electricity generated by low-carbon sources, which basically include all renewables plus nuclear.

Table 1 reports the evolution of the geothermal capacity and electric generation in the last 43 years, from 1980 to 2023. Geothermal installed capacity data for 1980–2010 were taken from Bertani (2015), as well as electricity generation data for 1995–2010; data for 2015–2020 were taken and adjusted from Huttrer (2020), and data for clean energy and global electricity generation came from Low-Carbon Power (2023). It is worth noting that geothermal data actually correspond to 1 or 2 years ***before*** the indicated year, since the country update reports present 1–2 years of delayed data.

Figure 1 shows the graph for geothermal installed capacity and generation during those 43 years, presented in the second and fourth columns of Table 1. As seen in the graphic, the geothermal installed capacity shows almost eightfold growth (7.7 times),

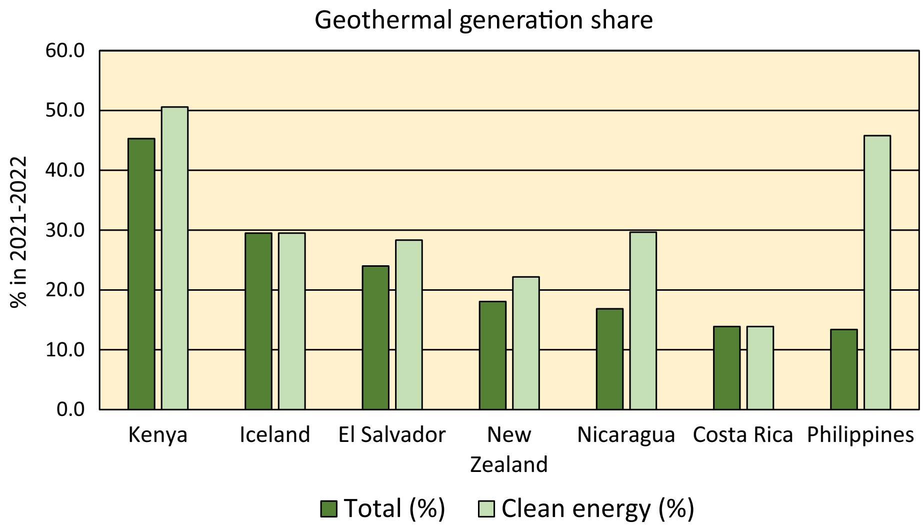

Fig. 2 Contribution of geothermal electric generation to the total electric generation in selected countries and to the total generated by clean energy sources

passing from 2110 to 16,318 MW during those years, while the annual geothermal generation has a similar growth (7.4 times), from the estimated 13,100 GWh in 1980 to 96,552 GWh in 2023 (actually, in 2021). Both parameters show a steady but constant tendency.

According to the data in Table 1, the mentioned annual growth in geothermal generation (7.4 times) is higher than the growth of total worldwide generation in the same period (5.6 times, from 5633 to 28,254 TWh), as well as the growth of low-carbon electric generation (4.6 times, from 2438 to 11,143 TWh). This means, of course, that the geothermal industry has grown a slightly more than the electric industry in general, and the clean-energy industry in particular, which seems to be counterintuitive. However, it also explains why the share of geothermal energy in both, total and clean generation, has been increasing during those decades, from 0.23 and 0.54% up to 0.34 and 0.87%, respectively (Table 1). Certainly, it is a minuscule global increase, but it is fundamental in countries where geothermal energy contributes a significant part of the electricity portfolio.

There are several countries where geothermal energy is currently a major game player in their electricity mix. As of 2021–2022, there were seven countries, three of them in Central America, where geothermal electric generation contributed a minimum of 10% of their total electric generation: Kenya, with 45%, Iceland with almost a third, El Salvador with almost a fourth, and New Zealand, Nicaragua, Costa Rica, and the Philippines between 10 and 20% (Fig. 2).

Figure 2 also includes the geothermal contribution to generation from clean energies (or low-carbon sources), which is higher than the share of the total, except in the cases of Iceland and Costa Rica, countries whose electric generation totally came from clean sources in 2021–2022. Thus, in Nicaragua, geothermal energy provided approximately 16.8% of the total generation in the country, but almost 30% of the clean generation, while in the Philippines, the contrast is more remarkable: 10.8% of

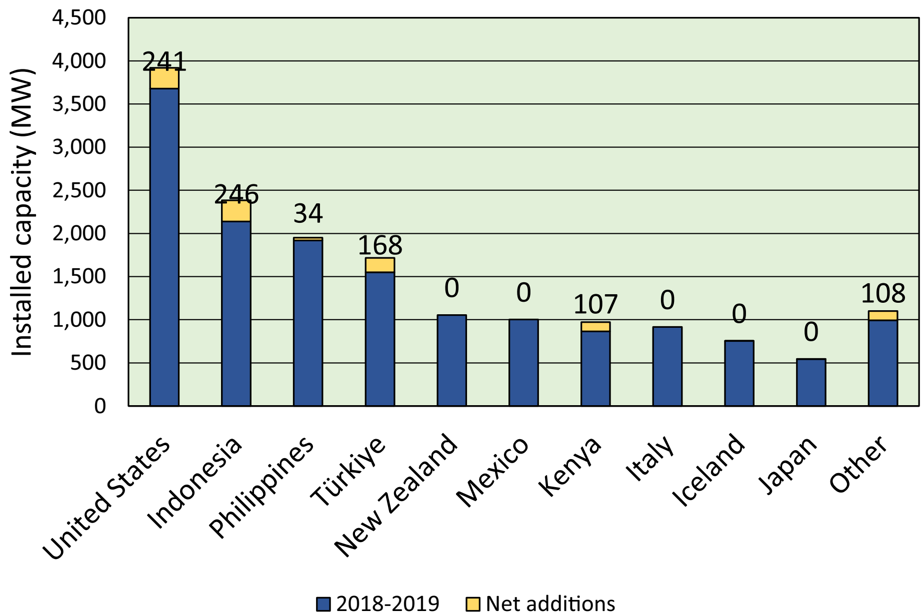

Fig. 3 Top ten countries with the highest geothermal installed capacity in 2020–2021, and net additions in MW over the last 3 years

national electricity generation was of geothermal origin, and 45.2% of the national generation from low-carbon sources. Therefore, while all geothermal power plants could be shut-down with no perceptible impact in the world, it would be catastrophic at least in those seven countries, as well as in certain regions of some countries such as the State of Nevada in the US (almost 10% of electric generation in 2022), the isolated electric system of Baja California in Mexico (almost 20% of the electricity demand), and specific regions in other countries.

According to Table 1, in the last 3 years since WGC2020+1, the world geothermal installed capacity increased by 905 MW (i.e., 5.8%), or less than 2% annually, from 15,414 MW in 2018–2019 to 16,318 MW in 2020–2021. To have a better picture, the world increase in these last years is equivalent to more than half of the current geothermal installed capacity in Türkiye. This global increase is composed of net capacity additions in the US (241 MW), Indonesia (246 MW), Türkiye (168 MW), Kenya (107 MW), Costa Rica (46 MW), Philippines (34 MW), Chile (33 MW), China (16 MW), Nicaragua (10 MW), Canada (6 MW) and Taiwan (6 MW), based on data presented in this report. The top ten countries by installed capacity in 2021, and their net additions are presented in Fig. 3.

As shown in Table 1, global geothermal generation presents a higher increase (7.8%) than the installed capacity, having grown 6965 GWh, from 89,587 GWh in 2018–2019 to 96,552 GWh in 2020–2021, and nearing the milestone of 100 TWh—which was probably reached in 2022 with an estimated 101 TWh of geothermal generation, as reported by REN21 (2023). In any case, the 3-year increase in electricity generation is significant, being lower but comparable, to the annual generation of New Zealand (7820 GWh in 2021).

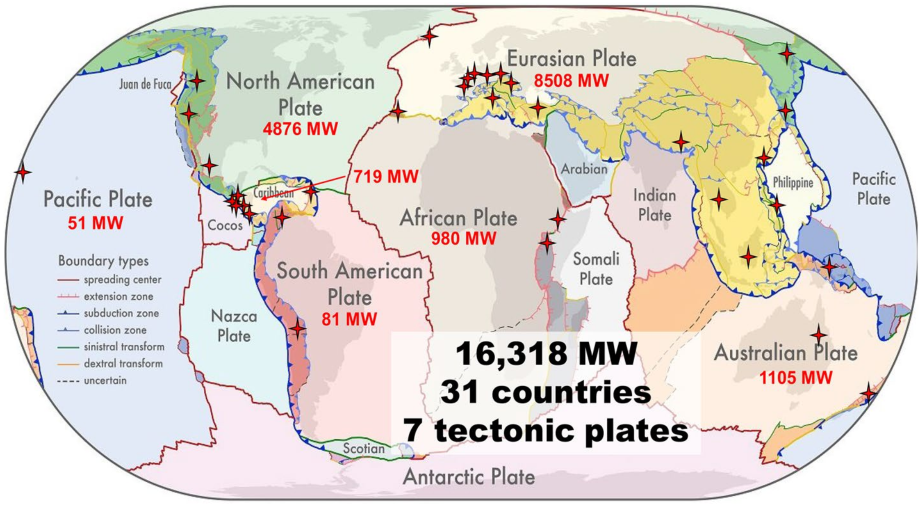

Fig. 4 Distribution of countries with geothermal power development in the world, with installed capacity as of 2021–2022 (Background figure taken from Hasterok et al. 2022)

Finally, the global average capacity factor (Table 1, third column) for geothermal power plants in 2021–2022 is 67.5%. It is only a general, not much significative estimation, since it combines data for 2021 in most cases and for 2022 in some other cases, and it was applied to a mix of relatively new and other very old plants, still in operation. The capacity factor is a concept to be calculated for every power unit to assess its performance during a defined period. The US Energy Information Administration (EIA 2023) defines the capacity factor in its Glossary as "The ratio of the electrical energy produced by a generating unit for the period of time considered to the electrical energy that could have been produced at continuous full power operation during the same period" (which is usually a calendar year). However, it can offer an idea about the global performance of geothermal plants in the world during more than 40 years, which is approximately 69% with a minimum of 63.6% in 1995 and maximum of 71.2% in 2005 (Table 1).

To summarize this section, the geothermal power operating industry at the beginning of 2023 is scattered in 32 countries distributed into six of the major tectonic plates, and one of the minor plates (the Caribbean Plate) (Fig. 4). The Eurasian Plate has more than a half of the total installed capacity, since it comprises countries with long geothermal development, such as Indonesia, the Philippines, Türkiye, and Italy, followed by the plates of North America, Oceania, and Africa, the Caribbean subplate, and the South America and Pacific plates. As expected, most of the large geothermal fields in operation are located on or near the inter-plate borders, where subduction, collision, spreading, extension and/or slipping processes occur, together with volcanism and seismicity, with isolated hotspots in the center of the plates.

Country geothermal status

Table 2 shows the list of countries with geothermal power plants in operation reported in the last WGC2020+1 and their current status in 2021–2022 as informed by the authors of the WGC2023 country update reports and/or investigated in different sources, as reported in the following descriptions for each country.

Table 2 Changes in geothermal installed capacity and generation in the last 3 years

Country	2018–2019		2021–2022		Net changes in:	
	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)	Capacity (MW)	Generation (GWh)
Australia	0.3	1.7	0.3	0	0	− 1.7
Austria	1.2	2.2	1.3	0.5	0	− 1.7
Belgium	0.8	2.0	0	0	− 0.8	− 2.0
Canada	0	0	6.3	0	6.3	0
Chile	48.0	400.0	81.0	600.0	33.0	200.0
China	29.1	174.6	45.1	131.2	16.0	− 43.4
Colombia	0	0	0.1	0	0.1	0
Costa Rica	207.0	969.0	252.5	1599.0	45.5	630.0
Croatia	16.5	76.0	16.5	74.7	0	− 1.4
El Salvador	204.4	1442.0	204.4	1575.0	0	133.0
Ethiopia	7.3	0	7.3	0	0	0
France	17.0	136.0	17.2	127.0	0.2	− 9.0
Germany	46.1	165.6	47.0	207.7	1.0	42.1
Guatemala	52.0	237.0	46.5	310.0	− 5.5	73.0
Honduras	35.0	270.0	35.0	297.0	0	27.0
Hungary	3.0	15.6	3.0	18.1	0.0	2.5
Iceland	755.0	6010.0	755.3	5788.4	0.3	− 221.6
Indonesia	2138.5	15,315.0	2384.4	16,588.2	245.9	1273.2
Italy	915.5	6015.0	915.8	5917.0	0.3	− 98.0
Japan	545.2	2409.0	545.7	2660.8	0.6	251.8
Kenya	865.4	5240.0	972.5	5590.0	107.1	350.0
Mexico	1005.8	5375.0	1001.9	4511.5	− 3.9	− 863.5
New Zealand	1054.8	7564.0	1054.8	7820.0	0.0	256.0
Nicaragua	155.0	492.0	165.2	780.0	10.4	288.0
Papua–New guinea	50.0	118.3	50.0	118.3	0	0
Philippines	1918.0	9893.0	1951.8	11,670.0	33.8	1777.0
Portugal	33.0	216.0	31.8	158.9	− 1.2	− 57.1
Romania	0.05	0	0.1	0.8	0.05	0.8
Russia	81.9	440.7	81.9	440.7	0	0
Taiwan	0.3	2.6	6.6	25.0	6.3	22.4
Thailand	0.3	1.6	0.3	0.2	0	− 1.4
Türkiye	1549.0	8168.0	1717.3	10,840.0	168.3	2672.0
United States	3678.2	18,435.0	3919.4	18,702.2	241.2	267.2
Total	15,413.5	89,586.9	16,318.4	96,552.1	904.9	6965.2

In some cases, reductions in capacity or generation are due to adjustments in the measures. Data for 2018–2019 are taken from Huttrer (2020), with eventual adjustments

The following is a description of the status in every country, presented in alphabetical order.

Australia

Perhaps, the most remarkable fact on the Australian geothermal power sector in the last 3 years is the commissioning in 2020 of the first geothermal power project in the last decade in Winston, Queensland. The project is composed of two small binary ORC units of 0.155 MW each, fed by a couple of 890 m depth wells. The power units, built by the company gTET, were out of operation in 2022 but are expected to generate again during 2023. This, and the recent interest to "produce 'green' hydrogen for domestic consumption and export", and the intent of "large industries to decarbonize their energy sources" have reignited the interest in geothermal power, according to Beardsmore et al. (2023). They also noted that a company (Strike Energy Ltd) "has applied for Western Australia's first new geothermal exploration license in a decade in late 2021" and that "Other companies have applied for large exploration areas in South Australia, Northern Territory, Queensland and South Australia" (Beardsmore et al. 2023).

The bad news, on the other hand, is the lack of financial support or incentives in recent years from the Australian federal, state and local governments for investment in geothermal power generation. The current governmental incentives and support are focused only on intermittent wind and solar projects and "on the production of hydrogen as a storage/carrier medium", which dismisses "the fact that nonintermittent geothermal power could be used to produce hydrogen on a sustainable basis without the need for backup energy sources or storage" (Beardsmore et al. 2023).

Solar and wind energy, in contrast, have experienced a high increment in the last years: between 2015 and 2022 wind energy experienced an annual average growth of 14%, and small-scale solar energy of 22%, while large-scale solar generation passed from 0 to 5% of total electricity generation between 2016 and 2022 (Australian Government 2024).

In general, it seems to be a better perspective for the geothermal power sector in Australia than in the past years. Beardsmore et al. (2023) foresee soon re-commissioning the only geothermal power plant, after modifications from its original plan, as well as a restarting of serious geothermal exploration in large areas granted for exploration, after a 10-year hiatus. Unfortunately, they do not see any major change in governmental policies to stimulate the geothermal development.

Austria

Data from Austria was taken from the country update report presented in the 2022 European Geothermal Congress by Goldbrunner and Goetz (2022), who report data for 2020, but the geothermal power installed capacity is the same in 2022 (1.25 MW in two small binary ORC units of 1.0 and 0.25 MW), as well as the electricity generation (Low-Carbon Power 2023), although the plant was not operating in 2021. The 1 MW plant in Altheim uses water at 106 °C from a nearby well, which is used first to supply the hot water demand of the village (approximately 6000 inhabitants) and then is conducted to a thermal exchanger to produce electric energy, mainly in summer, when hot-water demand is lower. The working fluid is organic but not flammable, like other organic fluids used in ORC geothermal plants (Gaia 2002). The 0.25 MW power plant of Bad Balmau was the first geothermal project developed in Austria by the private sector, commissioned in 2001. It is a combined heat and power (CHP) plant that utilizes brine at 110 °C, available from a 3000 m deep production well. Exiting the power unit at a temperature of 85 °C, the brine is then fed into the district heating system, providing heat for the Rogner Bad Blumau Hotel & Spa. The geothermal brine is returned from the district heating system and injected into a 3000 m depth reinjection well (Legmann 2003).

Perspectives on geothermal development in Austria are practically focused on direct uses, with no high expectations for power, and thus only 5 MW of geothermal power plants are expected by 2028 (Goldbrunner and Goetz 2022). However, in early 2024 the Federal Government announced a new funding program of US$ 10.8 million to support deep geothermal projects, which would help to geothermal power development (Offshore Network 2024).

Belgium

Information from Belgium was taken from the country report presented in the 2022 European Geothermal Congress by Dupont et al. (2022). Huttrer (2020) reported a binary ORC power plant in Mol-Donk, northern Belgium, with 0.8 MW and electricity generation of 2 GWh, fed by two wells producing fluids at 130–142 °C that were primarily used for district heating. That is why Belgium is included in Table 2. However, the 2022 report informs textually that "There are no geothermal power plants in Belgium", with no reference to the Mol-Dank plant whatsoever. Therefore, probably the power plant was stopped and dismantled, but currently there are not power plants in the country, nor perspectives in the near future.

Canada

A small geothermal power plant of binary ORC type and approximately 6 MW in capacity started to operate in January 2023 in Greater Swan Hills, Alberta. It is deemed the first stage of the South Swan Hills Geothermal Project, and is part of a pioneering 21-MW power project operating with co-produced hydrocarbon fluids from an enhanced oil recovery (EOR) operation (Patel 2023).

Swan Hills is one of the largest oil and gas reservoirs in Alberta that has produced light oil since the sixties. The oil and gas reservoir has been slowly depleted and replaced with water, as part of a secondary oil recovery technique known as 'waterflooding' that basically consist of injecting water pressure into the reservoir through the wells, to conduct the remaining hydrocarbons to surface. The water heats up and is then re-produced with the hydrocarbon. The oil and gas company Razor Energy, owner of the project and based in Calgary, installed a 15-MW natural gas turbine that, together with the binary ORC turbine, inject 21 MW to the electric grid, in this co-produced geothermal and natural gas hybrid power project using preexisting infrastructure (Patel 2023).

There are 84 production wells in the Western Canadian Sedimentary Basin, where the project is located, which have the potential to deliver up to 19 billion tons daily of water at 90–100 °C. At least 14 of those wells are sited in the field at depths of 2500 m. Thus, the potential for co-produced geothermal energy is very high, and the current South Swan Hills project could be applied anywhere oil and gas is produced, as suggested by Razor Energy. For now, the company is designing a second co-produced geothermal power project (Patel 2023).

Chile

Located in the South American plate, Chile was the second in the region with a geothermal plant in operation. Its neighbor, Argentina, installed a binary ORC power plant of 0.67 MW in capacity in 1988, in Copahue, Neuquén Province, near the border with Chile, which was stopped in 1996 (Gutiérrez-Negrín, 2022). Power plants in operation in Chile are in the geothermal field of Cerro Pabellón, located in the

Fig. 5 View of the first power plant of Cerro Pabellón, Chile (Credit: ThinkGeoEnergy, 2018; https://creativecommons.org/licenses/by-nc/2.0/deed.en#)

Atacama Desert at 4500 m above sea level (masl), near the border with Bolivia. It is operated by Geotérmica del Norte, a joint venture between Enel Green Power (85%) and the Chilean national oil company ENAP (15%) (Morata et al. 2023). There are currently three power units of binary ORC type and manufactured by Ormat, two of them of 24 MW in capacity, and the more recent of 33 MW, for a total of 81 MW. The first units started to operate in 2017 (see Fig. 5), and the latter was commissioned in 2021; thus, as shown in Table 2, Chile presents a net increment of 33 MW in the last 3 years, equivalent to 69%, in the geothermal installed capacity. Geothermal generation increased approximately 200 GWh, or 50%.

Cerro Pabellón is a field of hydrothermal, liquid dominant and high enthalpy type, and there were ~11 production wells operating in 2022, the deepest of which is 2500 m, according to the IGA reporting-tables filled by Morata et al. (2023). Considering the gross generation of 600 GWh (Table 2), the average production was 6.3 MWh per production well. Another important parameter is the annual capacity factor, which results in 84.6%.

The main geothermal power parameters in Chile for 2021–2022 are as follows:

- Geothermal fields in operation:	1
- Production wells:	13
- Capacity (MW)	81
- Generation (GWh)	600
- Capacity factor (%)	84.6
- Average production per well (MWh):	6.3

The geothermal–electric potential in the country is the largest in the region, due to its geologic context characterized by the continuous subduction of the Nazca and Antarctic plates beneath the South American plate (see Fig. 4), with active volcanism and seismicity along the subduction zone. The Chilean–Andean volcanic zone can be divided into three areas: Northern, Central-South and Austral, where many high-temperature hot spring areas and other superficial manifestations have been identified. Thus, the active magmatism and the high secondary permeability controlled by faults in several areas of the Chilean–Andean Cordillera, form a favorable set for the existence of large convective geothermal play type provinces (Morata et al. 2023).

Although there is no precise and modern estimation of the geothermal potential in Chile, it ranges from 16,000 MW estimated in 1986–1988 to 2086 MW estimated by the Mesa de Geotermia for 2050 and presented by the Chilean Ministry Energy in 2018, which is considered "the most realistic quantification about the geothermal potential, reservoir estimation and cost for geothermal development in Chile" (Morata et al. 2023). Additionally, between 16,000 and 40,000 MW can be considered inferred geothermal resources, although this academic estimation "is currently in progress by CEGA (Centro de Entrenamiento Geotérmico de los Andes)" (Morata et al. 2023).

The electricity market in Chile is controlled by a few private companies, and the state controls the regulatory entity. The total installed capacity in 2022 was 33,318 MW, generating 80,439 GWh (Morata et al. 2023), of which 33,439 GWh was produced by clean sources. Geothermal generation in 2022 represented only 0.75% of the total and 1.8% of clean or low-carbon generation.

In conclusion, the geothermal–electric potential in Chile is very high, but to harness it "a change in the Chilean energy policy is required. Several modifications are necessary, along with extensive community work with indigenous groups", which is "completely addressable in the next few years, but a real interest from the state is mandatory" (Morata et al. 2023).

China

This section does not include Taiwan, which is described separately. The main use of geothermal energy in China is not for power generation but for direct applications (heat and cooling) (Guo et al. 2023). High-temperature hydrothermal resources able to be used for electricity generation are in the Qinghai–Tibetan Plateau (Pang et al. 2023) in southern Tibet, western Yunnan, western Sichuan and Taiwan, where more than 200 high-temperature geothermal systems have been reported (Wang et al. 2023).

An installed capacity of 34.89 MW was reported in the country and worldwide reports in the last WGC2020+1 (Huttrer 2020; Tian et al. 2020), but in Table 2 of the country report (Tian et al. 2020) the installed capacity as of December 2019 was 29.07 MW, not counting several retired small power units, although the more recent plant in Yangyi was mentioned. Therefore, the installed capacity in 2018–2019 is reported as 29.1 MW (Table 2), with a generation of 174.6 GWh in 2018, representing an average capacity factor of 68.4. Since five production geothermal wells were reported (Tian et al. 2020), the average well production at that time was almost 4 MWh.

Thus, for the current report, the only new power plant is the 16 MW binary ORC power plant installed in Yangyi, which started to operate at the end of 2018 (Guo

Table 3 Number, type, capacity, and generation of geothermal power units in China in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	4	26.0	7.0	0	0
Binary ORC	2	18.5	9.3	131.2	65.6
Other	2	0.7	0.4	0	0
Total	8	45.1	5.6	131.2	16.4

et al. 2023). The plant is located in Damxung County, in the regional capital of Lhasa. More recently, it was reported that the Yangyi power plant has been exploring the possibility of an expansion project, expecting to provide more heat direct applications including space heating, vegetable greenhouses, and medical and healthcare, with an estimated investment of 480 million yuan (~ US$70 million) (China Daily 2023).

The total installed geothermal power capacity in 2021 in China is 45.1 MW, with an annual generation of 131.2 GWh (Table 3). That represents a minuscule percentage of the total electric capacity and generation in the country, equivalent to 0.002% and 0.003%, respectively.

Thus, the main geothermal power parameters in China for 2021–2022 are as follows:

- Geothermal fields in operation:	4
- Production wells:	8
- Capacity (MW)	45.1
- Generation (GWh)	131.2
- Capacity factor (%)	33.7
- Average production per well (MWh):	1.9

The search for and use of geothermal resources in China can be traced back to King You of Zhou (781–771 BC), who was the last ruler of the Western Zhou Dynasty. Later, during the Grand-Ming Dynasty (1368–1644) *The Travels of Xu Xiake* was published, defined as "a geographical masterpiece", giving more detailed documentation of hot springs outcropping at Jiuqitai in Yunnan. Modern searching for geothermal resources in the country appeared in the first decades of the twentieth century, when the first document on geothermal manifestations listing 140 hot springs was published in 1908 by Tian Beihu, and a decade afterwards (1919) Su Shen published another list of hot springs identified in various provinces, including 74 related to volcanoes, in the book poetically titled *China's Volcanic Veins*. A few years later, Zhang Hongzhao of the Central Geological Survey published in 1926 a paper titled *The Distribution of Hot Springs in China and the Relationship with Geological Formation*, presented at the Third Pan-Pacific Academic Conference and listing 500 hot springs, grouped into three categories according to their temperature: high (constant boiling), low (warm but not boiling), and unknown. After the founding of the People's Republic of China, in October 1949, geothermal exploration and searching were conducted in a more systemic way since 1956, by the Ministry of Geology, the Institute of Hydrogeology and Engineering Geology, the Institute of Geomechanics, the Institute of Geology of the Chinese Academy of Sciences, the Institute of Hydrogeology and Engineering Geology, and more recently the CGS (all references taken from Wu et al. 2023).

As pointed out by Wu et al. (2023), it seems that China has started a new journey to become "a modern socialist country in all aspects," which includes its net-zero carbon goals by 2050. Within that context, geothermal energy can play a relevant role passing "from local alternatives to mainstream energy." To do that, they suggest four main tasks, applicable not only to conventional, hydrothermal geothermal resources but also for EGS and other unconventional ones: (1) Strengthen the survey of nationwide geothermal resources; (2) Establish and improve a national system of geothermal exploration, observation, and monitoring; (3) Prepare maps of geothermal zones and provide intelligent services; and (4) Speed up technological innovation. It seems to be good advice.

China is hungry for natural resources, including minerals and oil, both of which are abundant at depth. Thus, on May 30, 2023, China broke ground in its first borehole to drill 10 km beneath the Earth's crust. The borehole is located in the Taklamakan Desert, part of the resource-rich Xinjiang Uyghur Autonomous Region located in northwestern China, and it is expected to be completed in 457 days. Aside from the potential to uncover natural resources, deep drilling could also provide China with a better understanding of seismic activity and natural disaster risks (Quartz 2023).

Deep-drilling exploration is one of the strategic areas in China. In 2021, president Xi Jinping delivered a speech to the country's scientific community outlining four areas in which to focus their efforts: deep Earth, deep sea, deep blue (meaning information technology), and deep space. In January 2023, China's minister of natural resources, Wang Guanghua, highlighted the importance of sourcing raw materials and energy domestically to wean off foreign dependence (Quartz 2023). Geothermal energy must be part of that.

Colombia

In 2021, a geothermal pilot power plant of 0.1 MW in capacity started to operate in the country in the sedimentary basin of Llanos Orientales. It is a binary ORC unit installed in an oil well in the field of Las Maracas, and the project was developed by Parex Resources Inc., which is a joint project with the Universidad Nacional de Colombia-Medellín, the national government through the Ministry of Mines and Energy, and an international oil and gas exploration company. The power unit was designed, built, and commissioned by the Spanish-based manufacturer Rank and is capable of generating approximately 860 MWh annually, but there were no data for 2022. The project takes advantage of high temperature gradients, permeable rocks, and fresh water which could be brought to the surface without drilling costs, as a byproduct of oil extraction (Casallas-Veloza and Matiz-León, 2023).

Geothermal exploration with power targets started in the sixties in the Nevado del Ruiz geothermal system, where a deep exploration well was drilled in 1997, and includes the southern part of the country with a joint exploration agreement with Ecuador for the Tufiño–Chiles–Cerro Negro binational system. The volcanic–tectonic framework of Colombia, which is part of the Pacific Ring of Fire and is affected by the interactions between the Caribbean, Nazca and South American plates (Fig. 2), includes ocean ridges, oceanic trenches, subduction zones, accretionary prisms, deformation belts,

Table 4 Number, type, capacity, and generation of geothermal power units in Costa Rica in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	4	195.0	48.8	1258.0	314.5
Binary ORC	2	52.5	26.3	312.0	156.0
Backpressure	1	5.0	0.5	29.0	29.0
Total	8	252.5	5.6	1599.0	200.0

transform faults, and other structural elements, as referred to by Casallas-Veloza and Matiz-León (2023). Given that context, the high geothermal power potential estimated for the country in the more recent assessment, which is 1170 ± 32 MW under the optimistic scenario, with 138.6 ± 1.8 EJ of stored heat, is not surprising. The assessment was based on 324 hot springs, grouped into 165 clusters and 21 geothermal interest areas, the most important of which are San Diego (142 MW), Santa Rosa volcano (137 MW), Cerro Machín volcano (130 MW), Caldera del Paletará (117 MW), Nereidas-Botero Londoño (101 MW), Nevado de Tolima volcano (83 MW) and Azufral volcano (82 MW) (Casallas-Veloza and Matiz-León, 2023).

In general, it seems to be a good perspective in the following years in Colombia, due to the recent implementation of the regulatory framework for geothermal resources in the country, particularly of the hydrothermal, conventional type, which is deemed a trigger and accelerator for geothermal development both for public and private participants. However, there are also good prospects for conductive geothermal resources, with two more pilots, similar to the Las Maracas plant, in Campo La Rumba, and the Chichimene project (Casallas-Veloza and Matiz-León, 2023).

Costa Rica

This Central American country currently has the highest geothermal power capacity in the region, and the second highest in Latin America, with 252.5 MW in seven units installed in two geothermal fields: Dr Alfredo Mainieri Protti, formerly Miravalles, and Las Pailas, and geothermal electric generation of 1599 GWh. This means net increases of 45.5 MW and 630 GWh since WGC2020+1 (Table 2).

There are currently three flash condensing power units in operation in the field Dr Alfredo Mainieri: two of 55 MW commissioned in 1994 and 1998 and manufactured by Toshiba and Ansaldo, respectively, and one of 30 MW commissioned in 2000 and built by Mitsubishi. One backpressure unit of 5 MW built by Mitsubishi and one binary ORC unit of 10 MW, provided by Ormat in 2003, complete the installed capacity of 155 MW in that field. In the other field, Las Pailas, there is one binary ORC plant of 42.5 MW manufactured by Ormat in 2011, and a 55 MW flash plant, built by Mitsubishi in 2019, which is the more recent addition (Table 4). There are two more power units planned to be installed in 2027 and 2030 in another geothermal field, called Borinquen, where 17 production wells are being drilled for the first unit (Borinquen I) (Sánchez-Rivera and Solís-Salguero 2023).

Both fields present hydrothermal-type geothermal reservoirs, biphasic and liquid dominated, but the Dr. Alfredo Mainieri Protti reservoir is low-enthalpy, while Las Pailas is high-enthalpy, according to the classification of the ICE (Instituto Costarricense de

Electricidad), which is the operator of the field and power plants. There are 19 production wells in operation in the latter, with a maximum depth of 2500 m, and 45 in the first, with a maximum depth of 2300 m (Sánchez-Rivera and Solís-Salguero 2023). The main features of the power units are presented in Table 4.

The main geothermal power parameters in Costa Rica for 2021–2022 are as follows:

- Geothermal fields in operation:	2
- Production wells:	64
- Capacity (MW)	252.5
- Generation (GWh)	1599.0
- Capacity factor (%)	72.3
- Average production per well (MWh):	2.9

As of December 2022, geothermal plants represented 7.0% of the total installed capacity in Costa Rica, providing 13% of the national production of electricity (see also Fig. 2). All geothermal fields and power units are managed and operated by the public utility ICE (Instituto Costarricense de Electricidad).

The third geothermal field still in development is Borinquen, located near Las Pailas, on the west flank of the Rincon de la Vieja volcano, and is projected to generate 110 MW. Intensive development started by 2018. The geothermal aquifer is chemically neutral, with a sodium–chloride composition, high salinity content, and temperatures of 240–273 °C. Thirteen wells have been drilled, six of which are producers and five are injectors (Sánchez-Rivera and Solís-Salguero 2023).

In addition to those geothermal fields, there are several more where exploration surveys have been made by ICE, including geophysical studies such as magnetotelluric soundings and implementation of thermal images captured by drones. Among those promising areas are Turrialba, Vara Blanca, Tenorio, Arenal-Pocosol, Platanar, and the north sector of Rincón de la Vieja. The Costa Rica geothermal potential update study report by ICE in 2022, shows a possible distribution of high- and moderate-temperature resources for electric generation, indicating a potential of approximately 1000 MW for Costa Rica, based on the available information and subsequent interpretations (Sánchez-Rivera and Solís-Salguero 2023).

Croatia

Geothermal energy in Croatia is mainly used for heating and cooling, or direct uses, and there is only one geothermal power plant in operation. It is the Velika 1 plant, a binary ORC power plant of 16.5 MW in capacity, manufactured by Turboden and commissioned in 2018, which is operated by the company Geoen in the Velika Ciglena site, near the town of Bjelovar, in the central part of the country. The plant is fed by a couple of deep geothermal wells, drilled at a maximum depth of 4570 m; the wells produce from a hydrothermal biphasic aquifer with dominant liquid and low temperature. Only 10 MW out of the 16.5 MW total capacity of the plant is sold to the electric grid, as established in the contract with the electricity transmission operator (Živković et al. 2023).

This plant was reported in the WGC2020+1 (Huttrer 2020), and there was no new geothermal plant in recent years. According to the official IGA tables, the plant generated 74.65 GWh in 2021, and probably 60.3 GWh in 2022. Table 2 includes the first value, which is reported in the tables filled by Živković et al. (2023).

Since the northern part of the country lies in the southwestern part of the Pannonian Basin, the geothermal potential in Croatia is related to the geological evolution and features of this important basin, whose formation started in the Early Miocene. Convergent movements of the African plate toward the Euro-Asian plate (see Fig. 4, produced subduction of the continental crust and thermal perturbations in the crust, forming a back-arc-type basin, characterized since the first phases of its development by thinning of the crust and isostatic subsidence. Thus, the thickness of the continental crust in the Croatian part of the Pannonian basin area is 25–30 km, and consequently, in this part the geothermal gradient is higher than Europe's average (Živković et al. 2023).

Therefrom, the portion of the Pannonian Basin included in the Croatian territory has a high geothermal potential, but only in the last 5 years has it been harnessed for electricity generation. The commissioning of the first, and still unique, geothermal power plant in 2018, triggered interest in geothermal exploration. In addition, new funding opportunities coming from the recovery and resilience plan and the EEA Grant's Energy and Climate Change Program, have motivated the Croatian Hydrocarbons Agency, local communities, and private investors to explore both known and new geothermal potential. Consequently, 14 exploration and 7 exploitation licenses for deep drilling commitments, indicate promising new developments in the following years, either for direct heat consumption or for electricity generation (Živković et al. 2023).

El Salvador

The first geothermal power unit installed in Central America was a flash condensing plant in the Salvadorean geothermal field of Ahuachapán with 30 MW in capacity, commissioned in 1975. Another plant of the same capacity started operations the next year, and in 1981 a third unit of 35 MW was commissioned, to reach 95 MW, which is still the total capacity in that field. The other geothermal field in operation in El Salvador is Berlín, which started to be explored in the 1960s, but its first geothermal power units were commissioned in 1992 after the long interruption due to the civil war between the FMLN (Frente Farabundo Martí de Liberación Nacional) and the government (1980–1992). They were a couple of backpressure units of 5 MW each, that were eventually replaced by more efficient flash units, and so currently there are three of 28-MW each and another of 44 MW, as well as a binary ORC power plant of 9.4 MW, totaling 109.4 MW in this field (Gutiérrez-Negrín, 2022). All those plants were reported by Bertani (2015) and Huttrer (2020), so there were no new geothermal plants in El Salvador in the last decade.

Electricity generation in 2022 in both fields is ~ 1575 GWh, according to Low-Carbon Power (2023), and therefore there was an increase of 133 GWh compared to the generation reported 3 years before (Table 2), equivalent to 9.2%. Geothermal generation in 2022 was 24% of the total electric generation in the country, and 28% of the clean generation (see also Fig. 2). The main features of the power units are presented in Table 5.

Both geothermal fields and all the power plants are managed and operated by LaGeo, which is a company owned by the government of El Salvador. According to LaGeo, the Ahuachapán geothermal field has an extension of ~ 2.5 km^2, and 50 geothermal wells

Table 5 Number, type, capacity, and generation of geothermal power units in El Salvador in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	6	195.2	32.5	1503.0	250.5
Binary ORC	1	9.2	9.2	72.0	72.0
Total	7	204.4	29.1	1575.0	225.0

have been drilled: 19 production, 8 injection, 2 monitoring and 21 observation wells, with depths between 650 and 2750 m. The Berlín geothermal field extends over an area of 8 km^2, and the company reports 37 wells: 14 production, 20 injection, 2 monitoring and 1 well in observation, with depths from 500 to 3455 m (LaGeo 2023).

The main geothermal power parameters in El Salvador for 2021–2022 are as follows:

- Geothermal fields in operation:	2
- Production wells:	33
- Capacity (MW)	204.4
- Generation (GWh)	1575.0
- Capacity factor (%)	88.0
- Average production per well (MWh):	5.5

The total geothermal potential in El Salvador from hydrothermal, conventional resources has been estimated to be between 500 and 600 MW, with several identified zones of interest, such as Chinameca, San Vicente and Coatepeque.

Ethiopia

Ethiopia is traversed by the northern portion of the African Rift Valley from northeast to southwest, which forms the depression known as the Ethiopian Rift System (ERS), which is divided into two tectonic parts, known as the Main Ethiopian Rift (MER), composed mainly of silicic volcanoes, and the Afar Depression, related mainly to NW–SE structural systems and some eruptive centers. The continental crust below the ERS has been thinning, and there is an upper mantle intrusion beneath that thinned crust, that produces a regional temperature gradient anomaly. In addition, recent volcanic activity with residual magmatic chambers in the subsurface, also produces areas of high heat flow anomalies and good geothermal potential (Fedaku et al. 2023).

The first geothermal exploration activities started at the end of the sixties, with regional geological reconnaissance studies over the whole MER that resulted in geothermal manifestations at 120 localities, approximately 20 of which were deemed as to have high-temperature geothermal potential, even for electricity generation. In the late seventies, geological, geochemical and geophysical surveys were carried out at the south-central part of the MER, and at the Tendaho prospect in the Afar Depression in northern Ethiopia. A more detailed exploration of several sites in central and southern Afar was also carried out in 1986.

Further exploration works, including drilling of eight exploration wells, were developed in late 1980s in the Aluto Langano geothermal field, located at southern MER. Four of those wells were productive, two of them producing high-temperature fluids and the other two produced fluids of lower temperature. Thus, it was decided to use the high-temperature wells to fed a flash power unit of 4 (or 4.6) MW, and the low-temperature fluids to fed a binary ORC plant, with isopentane as the working fluid, of 3.6 (or 3.9) MW, which were commissioned in 1998. Both units were operating intermittently and were finally stopped circa 2010, although a wellhead unit of 5 MW is planned to be installed in the field (Fekadu et al. 2023).

Therefore, the current installed capacity in Ethiopia is 7.6 MW with one flash and one binary power unit, which are currently out of operation. This is the same capacity reported by Huttrer (2020), although a geothermal generation of 58 GWh was reported.

The geothermal power potential of Ethiopia was estimated at 4200 to 10,800 MW in ~ 22 prospects, after the Geothermal Master Plan completed in 2015. Modern scientific surface investigations, including, geology, geochemistry, and geophysics (MT/TEM, gravity, and micro-seismicity) have been carried out at Aluto Langano, with the aim of restarting and expanding the field, whose potential is now estimated at 70 MW. Five directional production wells were drilled in 2021–2022 in the area, four of which produce enough steam for 21.5 MW. Besides Aluto Langano, private companies are developing the fields of Corbetti 1 (50 MW) and 2 (100 MW), and Tulu Moye 1 (50 MW) and 2 (100 MW), which are expected to be commissioned between 2024 and 2026 (Fedaku et al. 2023).

France

Data from France comes from the paper presented in the European Geothermal Congress 2022 by Schmidlé-Bloch et al. (2022) and some additional sources such as Low-Carbon Power (2023). The status of geothermal electricity generation remains practically equal to that reported 3 years ago, since no more installations were commissioned in continental France, but the revamping of the Soultz-sous-Forêts plant was completed. The Bouillante plant on Guadeloupe Island has the same installed capacity of 15.7 MW, although it is still expected to install a new power plant of 10 MW in the following years.

The Bouillante plant is composed of two condensing units, one of 2-flash and 4.7 MW in capacity commissioned in 1986, and another of single flash and 11 MW in capacity commissioned in 2004 (see Fig. 6). Both were operated by the French geological survey (BRGM) but were sold to Ormat in 2016, and it is estimated that generated ~ 115 GWh in 2020, enough to supply 10% of the electric demand on the island. There is another project known as Bouillante 2 that expects to drill two new wells at 1000–1600 m depth to install an additional plant of 10 MW (Schmidlé-Bloch et al. 2022).

The plant in the Soultz site, near Strasbourg, was commissioned in 2016. It is a binary ORC unit of 1.7 MW in capacity that is fed by geothermal fluids at ≥ 150 °C, produced by one production well (GPK-2) at 4.5–5 km depth. Fluids are highly saline (TDS approximately 100 g/l), so the heat is exploited via heat exchangers. The brine is discharged at 150 °C on the surface and then reinjected into the crystalline reservoir at 60–70 °C through two reinjection wells (GPK-3 and 4), which are also drilled at a depth of 5 km and encased up to 4.5 km (Schmidlé-Bloch et al. 2022).

Geothermal development around Strasbourg has been reported in standby since the seismic crisis of October 2020, when several seismic events were felt and clearly related to tests carried out at the plant. Therefore, the operator stopped all activities in December 2020, and three expert groups were formed with the aim of identifying best practices

Fig. 6 View of the Boulliante 2 geothermal power plant at Guadeloupe Island (Credit: 2023 © Guadeloupe Energie. Taken from: https://www.guadeloupe-energie.gp/en/renewable-energy/geothermal-energy/the-geothermal-energy-sector-in-guadeloupe/)

Table 6 Number, type, capacity, and generation of geothermal power units in France in 2020

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	2	15.7	7.9	115.0	57.5
Binary ORC	1	1.7	1.7	12.0	12.0
Total	3	17.4	5.8	127.0	225.0

for EGS projects. Two geothermal sites near Strasbourg, with well doublets between 3500 and 5000 m, are currently in stand-by (Schmidlé-Bloch et al. 2022).

One novelty in recent years seems to be geothermal exploration focused on systems of deep crustal faults, where deep geothermal fluids are expected to be circulating along the fault planes, particularly in the Massif-Central, which is a highland composed of mountains and plateaus located in the central-south part of France, at a peak altitude of 1890 m. Several exploration licenses were granted to a consortium of Storengy and TLS Geothermics, and the first drilling operation license was granted in 2022 for the drilling of two doublets at ~3500 m depth (Schmidlé-Bloch et al. 2022).

Another interesting development in France is lithium exploitation. A lithium cluster is working to gather French companies to work on lithium extraction, refining and utilization, since lithium is present in geothermal brines of the Rhine Graben (Schmidlé-Bloch et al. 2022).

The main features of the power units are presented in Table 6.

The main geothermal power parameters in France for 2021–2022 are as follows:

- Geothermal fields in operation:	2

- Production wells:	5
- Capacity (MW)	17.4
- Generation (GWh)	127.0
- Capacity factor (%)	84.3
- Average production per well (MWh):	2.9

Germany

In Germany, some hydrothermal reservoirs with temperatures and permeabilities suitable for power generation are already used in the Upper Rhine Graben, as an active and deep fault system, and in the Alpine Molasse Basin, which is an orogenic foreland basin (Weber et al. 2023). However, in general, the German territory lacks natural steam reservoirs that could be used to directly drive turbines, predominating conduction heat systems. According to Weber et al. (2023), this explains why geothermal electricity generation in Germany is based on binary cycle systems, including both ORC and Kalina cycle power plants, which makes it possible to use geothermal fluids even at temperatures of 100 °C.

At the end of 2021, 11 geothermal plants with an installed capacity of 47.0 MW were in operation in the country, which generated 207.7 GWh in that year. Three years ago, the installed capacity reported was almost the same (46.05 MW), but the annual generation now presents an increment of 42 GWh, equivalent to 25% (Table 2). Ten of the 11 power plants are type ORC with capacities from 3 to 5.5 MW, and the only Kalina cycle type plant has 0.5 MW. All the plants are fed by wells with depths varying from 2452 m up to 5078 m, and 9 of them are used for combined heat and power (CHP) production.

Since the last WGC2020+1, only two new geothermal power plants have been commissioned in Germany, one with a capacity of 4.9 MW in Garching, and the other with a capacity of 4.4 MW in Kirchweidach, both located in the South German Molasse Basin. The latter is a CHP project fed by a geothermal brine at 155 °C, which is the highest in all projects in that basin so far. The two-staged ORC plant utilizes an advanced four-staged turbine with two injection points at different pressure levels. Thus, the power generation of the two-staged ORC system is realized within the same turbine, resulting in a high efficiency (Weber et al. 2023).

Garching is also a CHP project, whose remarkable feature is its condensation system that uses cold water from a nearby industrial channel for a water-cooled condenser. With respect to most of the existing ORC power plants, which use air-cooled condensers, the plant in Garching has higher ORC efficiencies during summer due to the lower condensation temperatures compared with air-cooled condenser systems. Moreover, the water-cooled system reduces the investment costs and auxiliary power demand, producing lower noise emissions (Weber et al. 2023).

Incidentally, it is worth noting that some power plants reported in WGC2020+1 seem to have been decommissioned in the last 3 years, since the current installed capacity (Table 2) increased by just 1 MW while it should have been ~9 MW higher; alternatively, the total was overcalculated.

A new binary ORC plant of ~4 MW is under construction in the same locality of Kirchweidach, at a project that has provided heat for several years. Other currently planned geothermal projects in the South German Molasse Basin present a certain trend

Table 7 Number, type, capacity, and generation of geothermal power units in Germany

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Binary ORC	10	46.5	4.7	207.7	20.8
Binary Kalina	1	0.5	1.7	0	0
Total	11	47.0	4.3	207.7	20.8

toward larger projects of four wells, instead of the usual doublets. This is the case for three planned projects in Tengling, Palling and Traunstein that would have an installed capacity of 10 to 15 MW each (Weber et al. 2023).

Another novel development is the geothermal project in Geretsried, Bavaria, where it is planned to use one existing well to develop a deep closed-loop concept known as the Eavor Loop by a Canadian company. In Geretsried, four such systems could be developed with a capacity of approximately 9 MW (Weber et al. 2023). Should the project be successful, it could trigger an extensive utilization of the high geothermal potential in the region.

Incidentally, a lithium project like that mentioned in France (Schmidlé-Bloch et al. 2022), could be interesting in Germany to be developed in the German portion of the Rhine Graben.

The main features of the power units are presented in Table 7.

The main geothermal power parameters in Germany for 2021–2022 are as follows:

- Geothermal fields in operation:	11
- Production wells:	25
- Capacity (MW)	47.0
- Generation (GWh)	207.7
- Capacity factor (%)	50.5
- Average production per well (MWh):	1.0

Guatemala

The status of geothermal plants in Guatemala is the same as that reported 3 years ago, with 46.5 MW of installed capacity, although the capacity in 2018–2019 was incorrectly reported at 52 MW (Table 2). There are two geothermal fields under exploitation in this Central American country, Amatitlán and Zunil. Commercial operation in Amatitlán started in 1998, when the Instituto Nacional de Electrification (INDE) installed a back-pressure unit of 5 MW in capacity, to test the reservoir in actual conditions and generate electricity commercially. This power plant was replaced later by another similar, sold by the Mexican CFE, which in turn was replaced in 2007 by a new binary ORC unit of 22 MW gross (20 MW net) in capacity, manufactured by Ormat under a BOT (Build Operate, Transfer) financial scheme; in fact, Ormat is still operating the plant through its filial company Ortitlán, since the BOT contract will finish in 2027. In Zunil, there are seven modular units of binary ORC of 3.5 MW each, for a total of 31.5 MW gross, which were successively commissioned starting in 1999. Ormat also built this plant under a similar BOT contract covering up to 2034 and continues operating the field.

Table 8 Number, type, capacity, and generation of geothermal power units in Guatemala in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Binary ORC	2	46.5	23.3	310.0	155.0

Geothermal generation in the country was reported to be 310 GWh in 2021 (Low-Carbon Power 2023), which represents an increase of 73 GWh, or 31%, over the generation reported in the WGC2020+1 (Table 2).

The main features of the power units are presented in Table 8.

The main geothermal power parameters in Guatemala for 2021–2022 are as follows:

- Geothermal fields in operation:	2
- Production wells:	7
- Capacity (MW)	46.5
- Generation (GWh)	310
- Capacity factor (%)	76.1
- Average production per well (MWh):	5.1

Guatemala is located at the confluence of three tectonic plates (North America, Caribbean and Cocos, see Fig. 4). Its territory hosts 37 volcanoes, three of which are active (Volcán de Fuego, Santiaguito and Pacaya), as well as a couple of active and complex parallel faults (Polochic and Motagua). Thus, the geothermal power potential in the country has been estimated to be 950–1000 MW and some additional areas of interest are known in the country, including El Ceibillo, Tecuamburro, Moyuta, and San Marcos (Gutiérrez-Negrín, 2022). For several years, INDE has been planning to expand the Zunil geothermal field toward the sector called Zunil 2, a few kilometers east of the current field. Both areas are located inside the volcanic caldera of Quetzaltenango and seem to be two distinct reservoirs divided by a large fault. At least three exploration slim-holes were drilled, confirming that the geothermal reservoir had a temperature of 300 °C and a preliminary potential of 50 MW. Up to 1990, the Guatemalan government supported geothermal exploration in the country, but then the government decided to privatize some of its organizations and allow private companies to develop geothermal resources, and that support was missed (Moya-Rojas 2016).

Honduras

Honduras is another Central American country, neighboring Guatemala, with only one geothermal field in operation, named Platanares, which is the most recent field in the region. There is one binary ORC power unit operating in the field, manufactured by Ormat with a 35 MW net in capacity and commissioned in 2017. Ormat also operates the field and the plant through its subsidiary Geoplatanares, and by 2021, the electricity generated was 297 GWh (Low-Carbon Power 2023), or approximately 10% more than reported in the WGC2020+1.

Geothermal exploration studies started in the country in the late seventies, and then the United Nations Developing Program (UNDP) financed more systematic surveys that led to the identification of several geothermal areas of interest, including Platanares, with 48 MW in potential, San Ignacio (20 MW), Azacualpa (22 MW), Sambo

Creek (15 MW) and Pavana (11 MW). In 2014, the private company GeoPower signed an agreement with Ormat to install a first unit of 18 MW through a BOT contract, and the first deep wells were drilled in 2015. GeoPower decided to withdraw due to the poor results initially achieved, but eventually Ormat completed the drilling and commissioned the power unit (Moya-Rojas 2016).

There are no new geothermal projects planned in Honduras, but in 2022 the Energy Ministry announced that an international bid to develop 40 MW was going to be launched in 2023, which had not occurred before the writing of this report.

The main geothermal power parameters in Honduras for 2021 are as follows:

- Geothermal fields in operation:	1
- Production wells:	5
- Capacity (MW)	35
- Generation (GWh)	297
- Capacity factor (%)	96.9
- Average production per well (MWh):	6.8

Hungary

No changes occurred in Hungary regarding geothermal power, since the installed capacity reported in WGC2020+1 is the same as that reported now. It is a binary ORC unit of 3 MW gross in capacity (2.3 MW net), operating in Tura, north-central Hungary, since 2018. The plant is fed by one well at 1500–1800 m depth that was originally drilled for hydrocarbon purposes. The well produces 2200 L per minute of water at 108 °C, which is reinjected at 8 bars of pressure into the same reservoir (Toth and Nádor 2023), after exiting the heat interchanger in the power plant. Geothermal electric generation in 2021 was 18.13 GWh (Low-Carbon Power 2023), which is an increase of 16% over the 15.6 GWh produced in 2019 (Table 2).

According to Toth and Nádor (2023), the Hungarian territory is in the Pannonian basin, which shows positive geothermal anomaly with heat-flow from 50 to 130 mW/m^2 and a geothermal gradient of approximately 45 °C/km. Two main types of geothermal reservoirs have been identified. Type 1 is a multilayered porous sediment (Upper Miocene–Pliocene 'Pannonian' basin fill sequence) of low heat conductivity, composed of alternate deposits of clay and sand. The main hot aquifers (60–90 °C) within this thick basin-fill sequence are located at 700–1800 m depth in the middle of the basin, and are composed of sandy units 100–300 m thick that are former delta-front facies. Type 2 reservoirs are related to the uppermost karst zones of the deeply buried Paleozoic–Mesozoic basement carbonates, as well as to the fractured and weathered zones of crystalline rocks, characterized by high secondary porosity. At $\geq$ 2000 m depth, temperatures can exceed 100–120 °C, and provide favorable conditions for developing medium-enthalpy geothermal systems and CHP plants. In addition, EGS projects could be developed in deeply buried granitoid rocks with high in situ temperatures ($\geq$ 200 °C), extensional regimes, and low levels of natural seismicity.

A call to support drilling of geothermal wells for heating reducing geological risks of the first reinjection wells (at 1000–2500 m depth) was launched in 2023. The total budget is approximately US$18 million (Toth and Nádor 2023).

No new geothermal power projects are planned, but some 20 MW are expected by 2028. However, "for the Hungarian geothermal industry to progress, it needs a well-considered energy policy together with a framework of supportive legal and financial conditions" (Toth and Nádor 2023).

Iceland

Iceland is a geothermal country per excellence giving that 65% of its primary energy supply and 30% of its electric demand (Fig. 2) are provided by geothermal energy (Rágnarsson et al. 2023). Just one small binary ORC plant of 0.3 MW has been commissioned in the country since WGC2020+1, and so the installed capacity is 755.3 MW, although the oldest power plant in Iceland, originally commissioned in 1969 in Bjarnarflag, was replaced by a new backpressure unit in 2019. The electricity generation in 2022 was lower, with a total of 5788.4 (Ragnarsson et al. 2023) (Table 2).

This island state has a huge geothermal potential, due to its location on a hot spot on the Mid-Atlantic Ridge, the boundary between the North American and Eurasian plates (see Fig. 4), which are moving apart at a rate of ~ 2 cm/year and that is why the geological and tectonic processes in the country are quicker than in other parts, and more easily observed. Between 20 and 30 volcanic eruptions occur every century on average, and approximately 4.5 km^3 of magma equivalent is erupted every century on average. The Mid-Atlantic Ridge outcrops along 400 km on the island, making it possible to observe on land a variety of tectonic and volcanic processes that only occur at the bottom of the sea in the rest of the oceanic ridge (Ragnarsson et al. 2023).

There are numerous active volcanoes and hot springs in the country, as well as frequent earthquakes. The main volcanic zone, composed of more than 200 volcanoes, crosses the island from NE to SW; at least 30 of those volcanoes have erupted since the country was settled approximately 1150 years ago. As expected, there are numerous geothermal systems related to the volcanoes, whose fluids vary in composition from freshwater to saline and from warm to supercritical in temperature. At least 25 high-temperature areas have been identified within the volcanic zones with ≥ 200 °C at ≤ 1000 m depths, and some high-temperature fields are known (and more are expected) in ocean ridges southwest and north of Iceland. Moreover, there are ~ 250 separate low-temperature areas (≤ 150 °C at ≤ 1000 m depth) in the country, mostly located in the flanks of active volcanic zones, and over 600 hot spring areas with temperatures ≥ 20 °C have been located (Ragnarsson et al. 2023).

Considering the mentioned tectonic and geological characteristics of Iceland, it is no surprise that the country started to use its vast geothermal resources for power generation in the late sixties, when the first power plant was commissioned at Bjarnarflag in 1969, as mentioned above. It was a single-flash, backpressure unit of 3.2 MW in capacity, followed in 1978 by the smaller Unit 1 of 1 MW in Svarstengi and by the larger Unit 1 in Krafla with 30 MW, both still in operation. Currently, there are 35 individual geothermal power units in Iceland, distributed into eight geothermal fields, and fed by approximately 200 production wells that produce 5332 m^3/hour of steam. Most of the power plants are of the single or double-flash type, with inlet temperatures varying from 122 to 210 °C and admission pressures from 1.25 to 18 barg. The binary ORC plants are located at Svarstengi, Flúdir, and Reykholt, and work

Table 9 Number, type, capacity, and generation of geothermal power units in Iceland in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	19	709.0	35.8	5470.7	287.9
Dry Steam	1	30.0	30.0	234.0	234.0
Binary ORC	13	9.3	1.7	47.4	3.6
Backpressure	2	7.0	3.5	36.3	18.5
Total	35	755.3	23.6	5788.4	165.3

at lower temperatures and pressures, and there is one plant using dry steam in the Svarstengi field. There are also two backpressure units.

The main features of the power units are presented in Table 9.

The main geothermal power parameters in Iceland for 2021–2022 are as follows:

- Geothermal fields in operation:	8
- Production wells:	200 (estimated out of 1008 wells in operation)
- Capacity (MW)	755.3
- Generation (GWh)	5788
- Capacity factor (%)	87.5
- Average production per well (MWh):	3.4

The Icelandic government has a permanent policy to increase the use of renewable resources, not only for power generation and heating but also for the transport sector. The conservationist consensus has been influenced by increased environmental awareness, which has triggered opposition against hydropower and some geothermal projects. The ownership of energy resources in Iceland is based on land ownership, but the exploration and utilization of geothermal resources are subject to licensing, and are regulated under the general umbrella of a parliamentary master plan to assess the economic feasibility and environmental impact of power projects. The third phase of the master plan was passed in June 2022, and of course it includes new geothermal projects. Currently, the only new geothermal project that is active in the geothermal sector in Iceland is the 30-MW expansion of the Reykjanes power plant that started operations in the spring of 2023, but new developments for electricity generation are expected. The expansion of Reykjanes uses flash steam from the high-pressure separator brine of the original plant without increasing the fluid extraction from the geothermal reservoir (Ragnarsson et al. 2023).

A very interesting project in progress was launched by Landsvirkjun in 2022, to capture and reinject carbon dioxide from its Theistareykir geothermal plant, and to reduce CO_2 emissions from its Krafla field. The project, called Koldís, includes capturing CO_2 and H_2S, dissolving these gases in water and reinjecting them into their natural source, with the participation of the company Carbfix, the holder of the CO_2 sequestration patent of the same name and subsidiary of Reykjavik Energy. The project is in line with the governmental Climate Action Plan, which aims to reduce emissions from geothermal plants in Iceland by 47% by 2030, compared to emissions in 2005 (TGE 2022a).

Indonesia

This archipelagic country, located in the southern portion of the large Eurasian Plate, is the second with most geothermal plants in operation in the world, only behind the US (see Fig. 3). It was also the host of the WGC2010, held in Bali.

Three years ago, Indonesia had an installed capacity of 2138 MW and now it is 2384, so it was an increase of ~ 245.9 MW or 11.5%. The new geothermal plants are installed in Sumatra and Flores (Nusa Tenggara) islands, and include Sorik Marapi (143 MW), Rantau Dedap (98.4 MW), and Sokoria (8 MW) (Darma et al. 2023). Geothermal–electric generation also grew, in this case 8.3% (Table 2).

Approximately 48 individual power plants are operating in the 18 geothermal fields, scattered on four islands: Java, Sumatra, Sulawesi, and Flores-Nusa Tenggara. Those fields are the following: Kamojang, Darajat, Patuha, Wayang Windu, Karaha and Salak in West Java; Dieng in Central Java; Sibayak, Sarulla, and Sorik Marapi in North Sumatra; Lumut Balai and Rantau Dedap in South Sumatra; Muara Laboh in West Sumatra; Ulubelu in Lampung and Lahendong in North Sulawesi; Ulumbu, Mataloko and Sokoria in Flores–Nusa Tenggara (Darma et al. 2023).

Most of the fields are harnessing geothermal resources of hydrothermal, liquid-dominated, and high-temperature reservoirs, except for the fields of Kamojang and Darajat, in West Java, which exploit vapor-dominated reservoirs. Consequently, most of the power plants in operation (33 of 48) are of the condensing, flash type, only eight are dry steam plants installed in the mentioned fields of Kamojang (235 MW) and Darajat (270 MW), and seven are of binary ORC type with 520 MW, including 190 MW in Sorik Marapi of the screw expander technology.

The largest individual field by its installed capacity is Gunnung Salak in West Java, with 376.8 MW in six single-flash power plants. The field is operated by the company JOCC Star Energy Geothermal Salak, Ltd., and generated 2855 GWh in 2021 at an annual capacity factor of 86.5%. Next is the field Sarulla, in North Sumatra, with 330 MW in three power plants of binary ORC type, operated by the company JOCC Sarulla Operations Ltd., which generated 2032.6 GWh in 2021 with an annual capacity factor of 70.3%. The following largest fields are the two dry steam fields, Darajat, and Kamonjang, also in West Java. The first one has 270 MW in three power plants of 121 MW, 94 MW and 55 MW, is operated by JOCC Star Energy Geothermal Darajat II, Ltd., and produced 2106 GWh in 2021, at a capacity factor of 89%. The installed capacity in Kamonjang is 235 MW, with two units of 55 MW and three other units with capacities of 30, 35 and 60 MW; the field is managed and operated by PT Pertamina Geothermal Energy, and generated 1679.4 GWh, with 81.6% as the annual capacity factor (data taken from Susmanto et al. 2023).

The next largest fields are Wayang Windu in West Java, with 227 MW, and Ulubelu in North Sulawesi, with 220 MW. The first one has two power units of 110 and 117 MW, is operated by JOCC Star Energy Geothermal Wayang Windu, and generated 1884.1 GWh in 2021, at a capacity factor of 94.7%. The Ulubelu field has four units of 55 MW each, is operated by PT Pertamina Geothermal Energy, and generated 1553.2 GWh in 2021, at a capacity factor of 80.6%. The other fields have installed capacities lower than 200 MW, with the smallest being Sokoria in Flores–Nusa Tenggara (8 MW gross) and Sibayak in North Sumatra (11.3 MW) (data taken from Susmanto et al. 2023).

Table 10 Number, type and capacity (as of 2023), and generation of geothermal power units (as of 2021) in Indonesia

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	33	1359.4	41.2	9945.8	301.4
Dry Steam	8	505.0	63.1	3785.5	473.1
Binary ORC	7	520.0	74.3	2856.9	408.1
Total	48	2384.4	51.2	16,588.2	345.6

It is estimated that approximately 520 geothermal production wells were operating in all 18 fields during 2021–2022, which produced an annual total of 123.59 million m^3 of steam at an annual average rate of 14,108 m^3/h. The annual average production of steam was 27.1 m^3/h per production well (Susmanto et al. 2023).

The main features of the power units are presented in Table 10.

The main geothermal power parameters for Indonesia in 2021–2023 are as follows:

- Geothermal fields in operation:	18
- Production wells:	520
- Capacity (MW)	2384
- Generation (GWh)	16,588
- Capacity factor (%)	79.4
- Average production per well (MWh):	3.63

The volcanic–tectonic frame of Indonesia results in a huge geothermal potential, estimated at 23,357 MW, the largest in the world, which is located between the eastern end of the Mediterranean Volcanic Belt and the western side of the Circum-Pacific ring. It is composed of 5849 MW of so-called speculative resources, 3376 MW of hypothetical resources, 9251 MW of possible reserves, 1763 MW of probable reserves and 3117 MW of proven reserves. This potential is distributed into 356 locations identified on seven islands (Java, Bali, Sumatra, Sulawesi, Nusa Tenggara, Maluku, Papua and Kalimantan) by geological and geochemical surveys, as well as geophysical surveys conducted at 45 of those locations. All the prospects are hydrothermal, and most of them are expected to have high-temperature geothermal systems. Sumatra has the largest geothermal potential, with 9.5 GW, or 40.5% of the total. The second largest potential is located in Java (7.9 GW), followed by Sulawesi (3.0 GW). The rest come from Bali-Nusa Tenggara (1.6 GW), and Maluku (1.1 GW) and a very small amount comes from Papua (75 MW) and Kalimantan (175 MW) (Darma et al. 2023; Susmanto et al. 2023).

The geothermal roadmap considers expanding the current geothermal capacity by 1234 MW for 2030 in Lumut Balai (55 MW), Rantau Dedap (134 MW), Ulubelu (10 MW), Muara Laboh (145 MW), Sorik Marapi (150 MW), Pangalengan (65 MW), Patuha (165 MW), Salak (70 MW), Kamojang (30 MW), Dieng (295 MW), Lahendong-Tompaso (35 MW), Ulumbu (40 MW), Mataloko (20 MW), and Sokoria (25 MW) (Darma et al. 2023).

More immediate projects include new power plants planned by Geo Dipa Energi in Dieng (10 MW), as well as other power plants to be installed by PGE in Lumut Balai,

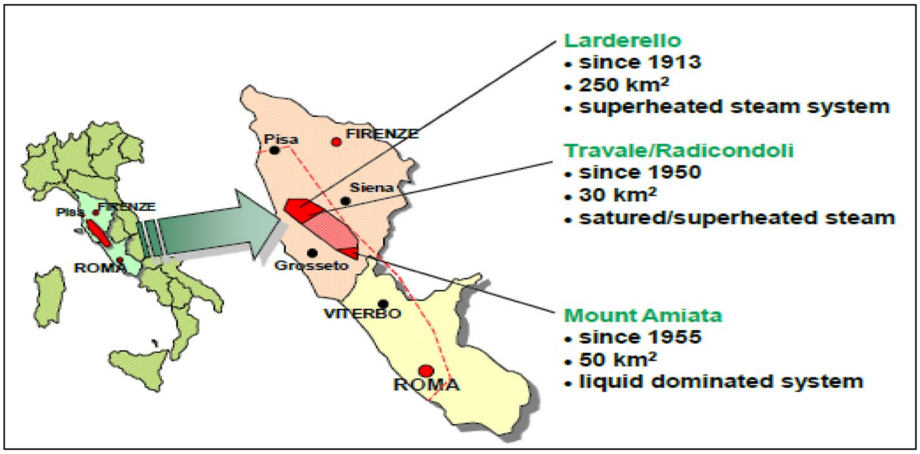

Fig. 7 General location and some features of geothermal fields in operation in Italy (taken from Della Vedova et al. 2023)

Sabang Geotermal Energi in Jaboi (5 MW and 10 MW) and Medco in Blawan Ijen (31 MW) (Susmanto et al. 2023).

Regarding incentives, the Indonesian government has made sure the geothermal electricity tariff is economically viable for developers and affordable to the public. It has also offered incentives in exploration activities and lessened the risk by assessing exploration activities (Susmanto et al. 2023).

Italy

Italy is not only the venue of the largest empire of antiquity but also the cradle of the indirect use of geothermal energy for electric generation and the site where the first geothermal power plant in the world was designed, mounted, and operated: a binary-cycle plant of 0.25 MW that started to operate in Larderello, in September 1913 (Cataldi and Suárez-Arriaga 2020). The country was also the host of the first WGC convened by the IGA, held in Florence in 1995. The status of the geothermal power industry in Italy in 2021–2022 is the same as that reported in WGC2020+1, with no changes in the installed capacity beyond the adjustments and just 1.6% less electricity generated (Table 2).

There are four geothermal fields in operation in Italy, all located in the region of Tuscany in the central-north portion of the country (Fig. 7). The fields are Larderello, Travale-Radicondoli, Bagnore, and Piancastagnaio, although the latter two are usually referred to as Mount Amiata because both are in this area. Larderello is the most known and oldest, covering a surface of ~ 250 km^2, and has been exploited since 1913. At the subsurface there is a hydrothermal, vapor-dominated reservoir, harnessed by 200 wells that produce superheated steam at 150–270 °C of temperature and 2–15 bar of pressure, with 1–10% in weight of non-condensable gases (NCG). The installed capacity is 594.8 MW, with 22 dry steam power units of 20 MW in capacity most of them, and another with capacities of 10, 14.8, 40 and 60 MW. The two oldest units were commissioned in 1991, and the two more recent were commissioned in 2009. Since the late 1970s, condensed steam has been reinjected into the shallow carbonate reservoir formation, which has been beneficial especially in the most depleted area of Valle Secolo, and has made it possible to increase the reservoir pressure and, accordingly, the steam production (Della Vedova et al. 2023).

The area explored in the field of Travale-Radicondoli is approximately 50 km^2. There are 42 wells producing superheated or saturated steam at pressures between 8 and 20 bars and temperatures of 190–250 °C. The content of NCG is 5–6.5% by weight, and the installed capacity is 200 MW with eight dry steam units in operation, 6 with 20 MW in capacity each, and two of 40 MW; the oldest unit was commissioned in 1987, and the two more recently in 2010. The deep exploration wells drilled years ago, found permeable layers within the Metamorphic Basement, located at the same depths and with the same reservoir temperature and pressure as in the Larderello area, but the deepest ones at ~ 4000 m, encountered productive layers also in the granite underlying the metamorphic basement. This and other studies, demonstrated that the shallow fields of Larderello and Travale-Radicondoli represent two discharges of a unique, wider, and deeper (3000–4000 m) geothermal system, with an extension of ~ 400 km^2. No reinjection wells have been drilled thus far in the Travale-Radicondoli geothermal field, but experimental tests performed in recent years confirmed the benefits of reinjection in the deepest parts of the geothermal system to reduce the natural decline; thus, a new project is planned to start reinjection, but no new production plants are planned until 2028 (Della Vedova et al. 2023).

As mentioned before, the geothermal fields of Bagnore and Piancastagnaio are both located on Mount Amiata. The first wells produced steam from a shallow carbonate reservoir, but a deeper exploration program was started in the late 1970s, encountering a fractured metamorphic basement underlying the shallow carbonate reservoir at depths ranging from 2500 to 4000 m. This deeper reservoir is liquid-dominated, with a pressure of ~ 200 bars and temperature of 300–350 °C at 3000 m depth, and 5–8% in weight of NCG. In this field the total installed capacity is 121 MW, with six flash units of 20 MW in capacity, and a small binary ORC power unit of 1 MW, which is the only of this type operating in the country. The oldest unit was commissioned in 1991, and the two more recent were commissioned in 2014. Mount Amiata seems to be the most promising for further development, and there are plans to install a couple of new units with combined capacity of 60 MW by 2028 (Della Vedova et al. 2023).

It is worth mentioning that all the fields are managed by Enel Green Power (EGP), which is indirectly part of the electricity conglomerate Enel Group, owned in its majority by the Italian government. The geothermal power plants in all the fields are also operated by EGP through a remote-control station located in Larderello, where approximately 12 people work around-the-clock shifts ensuring permanent monitoring. In this station, every operating parameter of each plant is monitored and analyzed, and every unit can be shut down and restarted remotely. Complex steam pipelines nets, which often include many production wells with different thermodynamic and fluid-dynamic characteristics, are managed using innovative numerical modelling tools (Della Vedova et al. 2023).

The main features of the power units are presented in Table 11.

The main geothermal power parameters for Italy in 2021–2022 are as follows:

- Geothermal fields in operation:	4
- Production wells:	279

Table 11 Number, type, capacity, and generation of geothermal power units in Italy in 2021–2022

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	6	120.0	20.0	1038.6	173.1
Dry Steam	30	794.8	26.5	4874.1	162.5
Binary ORC	1	1.0	1.0	4.3	4.3
Total	37	915.8	24.8	5917.0	159.9

- Capacity (MW)	915.8
- Generation (GWh)	5917
- Capacity factor (%)	73.8
- Average production per well (MWh):	2.4

In 2022 a new 10-MW binary geothermal power plant was authorized in the industrial area of Val di Paglia in the area of Mount Amiata, proposed by the private company Sorgenia. The project had been initially rejected by the Superintendencies for environmental reasons, but the Council of Ministers finally approved it, which would be the first geothermal power plant in Italy that is not operated by the EGP, and it would be the second plant in Italy to use binary cycle technology. It is expected that the plant will be commissioned in 2027, but first, Sorgenia will need to conduct geological investigations and provide a report on the compensatory reforestation effort including details on the choice of plant species, density, plant spacing, and care (TGE 2022b).

The so-called FER Decree regulated incentives for construction of geothermal and other renewable plants. In late 2023 it was passed the FER 2 Decree, whose last draft was awaiting approval of the European Commission, and includes an increased quota for zero-emission geothermal energy for plants up to 60 MW, up to 2018 (Zampieri 2024).

Japan

Japan is also one of the pioneer countries in using geothermal power plants. In 1925 an experimental mini plant of 1.12 kW started to operate in Beppu, Kyushu that used wet steam produced by a well drilled by Vice-Admiral Masuji Yamauchi in 1918. The plant, installed by Dr Heizi Tachikawa, was replaced in 1948 by a unit of 30 kW (Cataldi and Suárez-Arriaga 2020). After that, the first plant of commercial dimensions in the country, was commissioned in Matsukawa in 1966; it is a dry steam power plant manufactured by Toshiba that is still in operation, after 55 years of service, by the company Tohoku Sustainable & Renewable Energy Co., Inc. (Yasukawa et al. 2023).

Only four binary cycle power units (three ORC type and one Kalina type) were commissioned in Japan in 2020 and 2021, so the current installed capacity is just 0.55 MW higher than that reported in WGC2020+1 (Huttrer 2020). Thus, the current installed capacity is 545.7 MW (Table 2), composed of 91 power units operating in 40 geothermal fields and fed by 226 production wells (estimated from a total of 324 wells). The depth of the wells varies from 300 m for one well producing hot water to fed a plant of 1.9 in the Suginoi Hotel in Beppu, up to 3250 m of a well producing from a hydrothermal, biphasic liquid-dominated reservoir of medium enthalpy in the Mori geothermal field. By number, most of those plants are of binary ORC type (68 units), but single and double-flash type plants constitute most of the installed capacity (495 MW), with only one dry steam,

Table 12 Number, type, capacity, and generation of geothermal power units in Japan in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	20	495.0	24.8	2460.9	123.0
Dry Steam	1	23.5	23.5	79.4	79.4
Binary ORC	68	27.0	2.5	120.5	1.8
Binary Kalina	1	0.2	0.2	NA	NA
Other	1	0.01	0.01	NA	NA
Total	91	545.71	6.0	2660.8	29.2

one binary of Kalina cycle and one of other type, but with very small capacities. Most of the reservoirs exploited in the fields are of hydrothermal, biphasic liquid-dominated type of high, medium and some of low enthalpy, but many small binary plants are fed with hot water from relatively shallower aquifers. Only the reservoir in Matsukawa is vapor-dominated (data taken from Yasukawa et al. 2023).

The electricity generated by all the operating plants was 2660.83 GWh in 2021, corresponding to the fiscal year from April 2020 to March 2021. This amount is ~ 10% higher than the geothermal generation reported in 2018 (Table 2). More than 90% of the total geothermal generation in 2021 came from flash power plants.

The main features of the power units are presented in Table 12.

The main geothermal power parameters for Japan in 2021–2022 are as follows:

- Geothermal fields in operation:	40
- Production wells:	226 (estimated from 324 total wells)
- Capacity (MW)	545.7
- Generation (GWh)	2660.8
- Capacity factor (%)	55.7
- Average production per well (MWh):	1.4

Yasukawa et al. (2023) highlight that actual data on power plants in the country could be slightly higher than the data provided here. This occurs because numerous local companies begin small geothermal businesses installing binary systems in high-temperature hot spring wells due to the high FiT (Feed-in Tariff) price for small geothermal power. This makes it difficult to collect data from these mini power plants, and probably several of them may be missing of the total reported here. On the other hand, many small power plants do not provide data on power generation, and so the total generation must be slightly larger than reported here.

The total geothermal power potential of Japan is much higher than the current capacity, due to its volcano-tectonic framework. As pointed out by Yasukawa et al. (2023), the Japan Archipelago is located at the eastern part of the Eurasian plate on the junction of the Pacific and Philippine oceanic plates (Fig. 4). The islands are considered to have been built by the subduction resulting processes of accretion, metamorphism, magmatism, and volcanism, giving place to accretionary complexes, metamorphic rocks, plutonic and volcanic rocks, and superficial sediments, as well as 111 active volcanoes representing approximately 7% of all volcanoes on Earth, including three volcanoes added in 2011 and 2016. Therefore, most of the promising geothermal resources in Japan have volcanic origins.

Therefore, the theoretical geothermal potential of the country up to a depth of 3 km is over 20 GWe (Yasukawa et al. 2023) of hydrothermal, conventional sources, i.e., more than 36 times the current capacity. The real hurdles in Japan that explain the limited use of their geothermal resources are of legal, social, and socioeconomic types. The three major barriers seem to be the restrictive regulations on natural parks; the high risk, cost, and time for developing new power plants of several megawatts; and social acceptance. The first two problems have been largely mitigated after the nuclear accident in Fukushima in 2011 by the federal government, changing several regulations on natural parks and providing new economic incentives to promote geothermal development. However, the latter may not be easily solved, when negative campaigns for geothermal power project developments by hot spring owners tend to be so influential that geothermal projects have been delayed or even stopped in several cases. The government has begun several actions to raise the social acceptance of geothermal development, so it is expected that the last problem can also be solved (Yasukawa et al. 2023).

Kenya

Geothermal development in Kenya has experienced important growth in the current century. After a promising start in the eighties, when the three first power units, of 15 MW each, were installed in the Olkaria I geothermal field in 1981–1985, the geothermal development was stopped for more than 15 years, up to the commissioning in 2000 of Unit 1 of OrPower 4, a binary ORC plant of 13.2 MW in the same field. Thus, the country passed from 45 MW in 1985, to 58 MW in 2000, and then to 952 MW in 2022 and 972.5 in 2024: ~ 60 MW in the first 15 years, and almost 915 MW in the following 24 years (Omenda et al. 2023).

As shown in Table 2, the installed capacity in the country in 2023 was 972.5 MW, or 12% more than 3 years ago (see also Fig. 3), due to commissioning in 2022 of the Unit 6 of Olkaria I, which is a single-flash condensing plant of 86.8 MW in capacity, and the commissioning in late 2023 of five power units in the geothermal field of Menengai, with a combined capacity of almost 50 MW. Most of the power units in operation are of the single-flash, condensing type, with 27 units and 748.7 MW of combined capacity, and the rest are binary ORC units with 10 units and 200.0 MW of combined capacity, and a few power units of back-pressure type using screw expander technology of ~ 11 MW each. All of them are integrated into the electric grid, except for two, one of binary ORC type and another of back-pressure type, whose electricity is consumed by the Oserian Developing Company, Inc., to cover the electric demand of its famed flower greenhouses and their employees, in a distributed generation for self-supply (data taken from Omenda et al. 2023).

Electricity generation of geothermal origin in Kenya in 2022 was 5590 GWh (Low-Carbon Power 2023), almost 6.7% more than that generated in 2019. It is worth mentioning that the geothermal generation for Kenya reported in WGC2020+1 was expected to be 9930 GWh in 2020, with an installed capacity expected to be 1193 MW (Huttrer 2020). Both were overestimated even for 2022, with the actual figures for 2019 now reported in Table 2. On the other hand, geothermal generation in 2022 represented

Table 13 Number, type, capacity, and generation of geothermal power units in Kenya in 2022 (generation) and 2023 (installed capacity)

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	27	748.7	27.7	4473.8	165.7
Binary ORC	10	200.0	20.0	1116.2	111.6
Back-pressure	3	23.8	7.9	NA	NA
Total	40	972.5	24.3	5590.0	139.8

45.3% of the total electricity generated in the country, which was 12,310 GWh (OWD 2023), as illustrated in Fig. 2. This makes Kenya the country with the highest share of geothermal energy to supply the national electric demand. For 2023 the performance of geothermal power plants can be better in Kenya, because during the first quarter the Kenya Power and Lighting Company (KPLC) announced that the geothermal generation was 1506 GWh, which is an increase of 47% compared to the 1st quarter of 2022 when 1025 GWh were produced in the country (TGE 2023a). The KPLC had to increase the dispatch of geothermal plants, due to the drop in power generation from hydropower sources, attributed to water level problems because of prolonged drought. Hydropower output was reduced from 807.7 GWh to 424.1 GWh for the first quarter from 2022 to 2023. This is a good and practical example of the reliability of geothermal power plants as baseload sources.

The main features of the power units are presented in Table 13.

The main geothermal power parameters for Kenya in 2022 are as follows:

- Geothermal fields in operation:	3
- Production wells:	212 (estimated from 299 total wells)
- Capacity (MW)	972.5
- Generation (GWh)	5590
- Capacity factor (%)	65.6%
- Average production per well (MWh):	3.0

Although there are three geothermal fields in operation in the country by beginning of 2024, 34 of the 40 power plants are in the Olkaria field, where 99% of the whole geothermal–electric generation of Kenya is produced. The other unit is a pilot binary ORC installed in the Eburro field and generated ~ 15 GWh in 2022. The new units in the Menengai geothermal field were commissioned at the end of 2023, and are operated by the independent producer (IPP) Sosian Menengai Geothermal Power Ltd. (SMGPL). There are other units under development in Menegai, such as a couple of single flash units of 35 MW each, the first of which is under construction by Fuji Electric Co., and planned to be commissioned in 2025, with the second planned for 2027. These new projects have been granted to another private company Globelec. There are also more units planned in Olkaria to be installed between 2025 and 2027, with a combined capacity of ~ 451 MW (Omenda et al. 2023). In addition, drilling activities were resumed in a fourth geothermal field, Akiira, also within the Rift Valley, after long negotiations between the company Akiira Geothermal and local communities concerned about probable environmental impacts, that in the past had blocked access (Construction Review 2021). If all happens as planned, Kenya would reach 1180 MW by WGC2026, which will still be below the 1193 MW expectation for 2020.

The government of Kenya has laid a blueprint for the rapid development of geothermal resources, targeting installed generation of 5,000 MW by the year 2030. The additional capacity of ~ 4,000 MW will come from expansions of Olkaria and Eburru geothermal fields by the governmental company KenGen (Kenya Electricity Generation Company) and IPPs, and additional installations at Menengai by Geothermal Development Company (GDC, which is fully owned by the government). GDC is currently undertaking exploration drilling in the Baringo-Silali geothermal prospect with a plan of generating some hundreds of MW. Additional generation is planned to come from IPPs that have been granted various geothermal prospects.

The total geothermal power potential in Kenya has been estimated at ~ 10 GW, due to its privileged location within the East African Rift System, which is part of the Afro-Arabian rift system extending from the Red Sea in the north to Mozambique in the south. As the rift extends southward, it bifurcates into eastern and western branches, bordering the Late Proterozoic Tanzania craton. The eastern branch includes the main Ethiopian Rift and the Kenya Rift, and although it is older than the western branch, which comprises the Western Rift and the Malawi Rift, it is more volcanically active. All the high-temperature geothermal manifestations in Kenya are mainly associated with Quaternary volcanoes on the axis of the main rift valley, with the relatively shallow magma chambers of those volcanos being the heat sources for most of the systems (Omenda et al. 2023).

Mexico

The geothermal installed capacity in Mexico continues to be almost the same at that reported in WGC2020+1, although there were some changes: one new power unit of 25 MW net (27.2 MW gross) was commissioned in 2019 in the Los Azufres field, and some old backpressure units were decommissioned. However, the total only varied due to adjustments in the nameplate capacities. Thus, as of December 2022, there are 1001.9 MW of installed capacity and 958.9 MW of running capacity, composed of 39 power units operating in the five geothermal fields under exploitation in the country (Table 2). Most of those units (22) are single and double-flash condensing units with a combined capacity of 924 MW, 15 are backpressure units of 5 MW with a combined capacity of 75 MW, and the remaining are a couple of binary ORC-type units of 1.45 MW each, manufactured by Ormat, that are still mounted in Los Azufres but have been out of operation several years ago. The largest flash plants are 110 MW in capacity, with two 55-MW turbines ensembled in tandem, manufactured by Toshiba and commissioned in 1986–1987 in the Cerro Prieto field, the oldest and largest of the country. Another old flash plants still in operation, are a low-pressure turbine of 30 MW manufactured by Mitsubishi and commissioned in 1982 in Cerro Prieto, and a 50-MW power plant fabricated by General Electric and commissioned in Los Azufres in 1988. More recent flash plants are 5, 20, 25 and 50 MW in gross capacity, manufactured by the French and Japanese companies Alstom, Mitsubishi, and Fuji Electric, operating in all the fields. All backpressure units are of 5 MW, fabricated by Mitsubishi, Toshiba and Aco-Genova-Ansaldo-Makrotek in different years; many of them are

Table 14 Number, type, capacity, and generation of geothermal power units in Mexico in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	22	924.0	42.0	4469.6	203.2
Backpressure	15	75.0	5.0	41.9	2.8
Binary ORC	2	2.9	1.5	0	0
Total	39	1001.9	22.7	4511.5	115.7

currently only as backup for the larger units, the oldest of which is a unit operating in Los Azufres since 1982 (data taken from Gutiérrez-Negrín et al. 2023).

While the installed capacity is almost the same as that 3 years ago, electric generation presented a decrease of 16% in the period, descending from 5375 to 4511.5 GWh in 2021. The reason seems to be that two power units were out of operation in 2021: unit 1 of Cerro Prieto III, with 110 MWe of nameplate capacity, and unit 17 of Los Azufres, with 53.4 MWe of nameplate capacity (50 MW net) (Gutiérrez Negrín et al. 2023).

Net geothermal electric generation represented barely 1.3% of the total electric generation in the country in 2021, which was 323,527 GWh, but it is important to highlight the share of geothermal generation in a couple of isolated electric grids in Mexico. One of them is the Baja California electric grid (SIBC: Sistema Interconectado de Baja California), where the Cerro Prieto power plants deliver their generation. The electricity produced in this system in 2021 was 11,869.1 GWh, out of which 2363.4 GWh was delivered by the geothermal units of Cerro Prieto, representing 19.9% of the total generation. Therefore, a fifth of the electricity used in this isolated system, which includes large urban centers such as Tijuana and Mexicali, was produced by geothermal energy—excluding self-supply, co-generation and some imports from California, USA. The other isolated electric grid is Mulegé (SIM: Sistema Interconectado Mulegé), in the middle of the Baja California peninsula, which is a small electric network independent of the national grid, with an electric demand of 150 GWh in 2021; power units in the geothermal field of Las Tres Vírgenes, with only 10 MW of installed capacity, generated 36.8 GWh, i.e., 24.5% of the electrical demand. Both seem to be good examples where geothermal energy plays a determinant role in supplying the electrical demand (Gutiérrez-Negrín et al. 2023).

The main features of the power units are presented in Table 14.

The main geothermal power parameters for Mexico in 2021 are as follows:

- Geothermal fields in operation:	5
- Production wells:	225 (243 total wells)
- Capacity (MW)	1001.9
- Generation (GWh)	4511.5
- Capacity factor (%)	51.4%
- Average production per well (MWh):	2.3

All the fields are of hydrothermal type, two phase, liquid-dominated and high enthalpy, except for two (Los Humeros and Los Azufres fields), which are vapor-dominated.

In Mexico, geothermal power development has been carried out by the federal government, through the federal utility Comisión Federal de Electricidad (CFE). Thus, four of the five geothermal fields currently in operation, including the power plants, are own and handled by the CFE. Only one field, called Domo de San Pedro, is owned by a private company. However, there is a geothermal energy law, according to which 24 exploration permits have been issued as of December 2021. Approximately 11 of those permits were granted to private companies, in one of which is a geothermal power project of 25 MW that is under development (Gutiérrez-Negrín et al. 2023).

Mexico's potential for conventional geothermal resources of hydrothermal type and temperature ≥ 150 °C, is estimated at ~ 2500 MW, and the EGS potential, following the protocol endorsed by the IGA (Beardsmore et al. 2010), is approximately 2300 GW, enough to install ~ 47 GW (Gutiérrez-Negrín et al. 2023).

New Zealand

New Zealand is the most developed geothermal country located on the Australian plate (Fig. 4), with an installed capacity of 1055 MW in 2022, occupying the fifth place worldwide, between Türkiye and Mexico (Fig. 3). That is the same capacity reported 3 years ago, since no new power plant was commissioned (Table 2), although the company "Mercury Energy incrementally increased the capacity of the Rotokawa binary by 2 MW, and another 3 MW at nearby Nga Awa Purua by reconfiguring the steam field" (McLean et al. 2023). Geothermal generation in 2021 was 7820 GWh (Table 2), which represents an increase of 3.4% compared to the generation reported in WGC2020+1, though is slightly lower than the generation in 2020. The contribution of geothermal electricity represented 18.1% of the national electric generation, and 22% of the clean energy produced in the country (Fig. 2).

There are eight geothermal fields in operation in New Zealand, with 47 power units of different types and capacities. More than half of the installed capacity is composed of 13 condensing, single, double and triple-flash power plants, with a combined capacity of 662 MW, distributed in almost all geothermal fields except three (Northland, Mokai and Ngatamariki). There are also 18 binary ORC power plants with capacities from 5 to 31.5 MW, 15 hybrid plants combining binary and backpressure units, and one backpressure unit of 9 MW operating in Kawerau. Plant Tauhara II is reported in construction by the company Contact Energy, with two triple-flash units of 84 MW net (87 MW gross), that were manufactured by Fuji Electric and delivered in March 2023; these turbines have 17 stages of blades rotating at 3000 rpm. In addition, at least six binary ORC plants are planned in the fields of Northland, Tauhara, Ngatamariki and the new field of Tikitere with an additional combined capacity of 151.5 MW and tentative commissioning in 2025 and beyond (data taken from McLean et al. 2023).

There is no official report of the number of production wells currently operating in New Zealand, but the estimate is approximately 205 in 2021. They produced a total of 53.5 million m^3 of steam in that year at an average annual rate of ~ 6107 tons per hour (m^3/h). Taking the average content of CO_2 in the steam in each field, it is possible to calculate the direct emissions of CO_2eq to the atmosphere, including methane × 25 Global Warming Potentials per New Zealand's regulations, which was 479,317 m^3 in that year. Thus, the calculated median of the Operational Emissions Intensity in all the power plants in operation in the

Table 15 Number, type, capacity, and generation of geothermal power units in New Zealand in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	13	662.0	50.9	4996.0	384.3
Binary ORC	18	260.8	14.5	1992.0	110.7
Hybrid	15	123.0	8.2	811.1	54.1
Backpressure	1	9.0	9.0	21.0	21.0
Total	47	1054.8	22.4	7820.1	166.4

country during 2021 resulted in 52 gCO_2eq per kWh net generated, with a weighted annual average of 62 gCO_2eq/kWh. Of course, these are only direct atmospheric emissions, but the full lifecycle emissions for geothermal can be estimated by adding 10 gCO_2eq/kWh (net) to account for emissions associated with materials and construction, maintenance, and decommissioning. Accordingly, the full lifecycle CO_2eq emissions from geothermal power plants in New Zealand in 2021 resulted in overall MW-weighted average lifecycle emissions of 74 gCO_2eq/kWh (net) (McLean et al. 2023).

Those lifecycle emissions in New Zealand are high when compared with solar PV (44 gCO_2eq/kWh net), hydro (19) and wind (11). However, emissions from geothermal power plants can be reduced or eliminated by reinjecting CO_2. This technology diverts the CO_2 gas stream (along with CH_4 and H_2S) from venting to the atmosphere and instead dissolves the gases in the separated geothermal brine and/or condensates, and reinjects them underground to where they came from. All the major geothermal companies in New Zealand currently have active trials, or plans for, CO_2 reinjection (McLean et al. 2023).

The electricity industry in New Zealand is supporting the goal of the government of 90% renewable generation by the year end of 2025. A projection of confirmed and likely wind, geothermal and solar projects, indicates that renewable energy will rise from 82% of generation in 2021 to 88% in 2026. As part of this projection, geothermal generation would rise 23%, from 7820 GWh to 9603 GWh in 2026, based only on brownfield projects, which are known resources mostly with existing power stations (McLean et al. 2023).

The main features of the power units are presented in Table 15.

The main geothermal power parameters for New Zealand in 2021 are as follows:

- Geothermal fields in operation:	8
- Production wells:	220 (estimated)
- Capacity (MW)	1054.8
- Generation (GWh)	7820.1
- Capacity factor (%)	84.6%
- Average production per well (MWh):	4.1

Nicaragua

Data about current installed capacity and generation were gathered from Gutiérrez-Negrín (2022), Polaris Renewable Energy Inc. (Polaris 2023), and a very informative video prepared by ENEL (Empresa Nacional de Electricidad) and published on February 2023 (ENEL 2023). This country is located on the western border of the Caribbean

Table 16 Number, type, capacity, and generation of geothermal power units in Nicaragua in 2022

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	4	147.0	36.8	665.0	166.4
Binary ORC	3	18.4	6.1	115.0	38.3
Total	7	165.4	23.7	780.0	111.4

Prepared with public data from ENEL (2023) and Polaris Renewable Energy Inc (Polaris 2023)

plate, just where the Cocos plate is subducting along the Central America trench (Fig. 4), and is also a country with a long tradition of harnessing geothermal energy for power generation, considering that the first power plant was installed 40 years ago (1983) in the geothermal field of Momotombo. It was a single-flash condensing unit of 35 MW in capacity that is still operating.

The installed capacity reported in WGC2020+1 was 155 MW, with a generation of 492 GWh. Now, the capacity has grown to 165.2 MW (Table 2), with the commissioning of the newest unit in the San Jacinto-Tizate geothermal field, which is a binary ORC unit of 10.4 MW net in capacity, that started to operate in December 2022, according to a news release by Polaris Renewable Energy Inc., the parenting company of the operator of the field (Polaris Energy Nicaragua) (Polaris 2023).

There are two geothermal fields in operation in the country, Momotombo and San Jacinto-Tizate. The first one has 78 MW of installed capacity composed of two single-flash units of 35 MW each, and two binary ORC units of 4 MW each; the running capacity is approximately 24.5 MW. The other field has 87.4 MW composed of two condensing, single flash units of 38.5 MW gross each (36 MW net), and the new binary ORC power unit, of 10.4 MW net.

Geothermal electric generation in 2022 was 780 GWh, which means an important increase of 58.5% compared with 2018–2019 (Table 2). Power plants in the Jacinto-Tizate field generated 452.15 GWh, with no contribution from the newest unit, at a capacity factor of 66.9%, providing ~ 12% of the national electric supply in Nicaragua (Polaris 2023). Generation in the power plants of Momotombo was 212.9 GWh, or 31% of the installed capacity. Even with the low performance of the Momotombo plants, the geothermal electric generation in Nicaragua contributed 16.8% of the total, and 29.7% of the clean energy generation in 2021 (see Fig. 2).

The main features of the power units are presented in Table 16.

The main geothermal power parameters for Nicaragua in 2021 are as follows:

- Geothermal fields in operation:	2
- Production wells:	20
- Capacity (MW)	165.4
- Generation (GWh)	780.0
- Capacity factor (%)	53.8%
- Average production per well (MWh):	4.5

Nicaragua is traversed by a volcanic chain parallel to the Pacific coast and to the Central America trench, composed of several active volcanoes. This explains the high geothermal power potential of Nicaragua, which has been estimated to be between 1200 and 1750 MW, the highest in the subregion, including geothermal areas such as El Hoyo-Monte Galán, Managua-Chiltepe and Casita-San Cristóbal (Gutiérrez-Negrín, 2022).

Papua–New Guinea

This insular country occupies the eastern portion of the second largest island in the world, New Guinea island, located immediately north of Australia, which shares with Indonesia. Together with other islands such as Salomon, Fiji, New Caledonia, and Vanuatu, it is part of Melanesia. From a tectonic viewpoint, the island is located at the Australian plate, on its northern border where the Pacific plate is being subducted (Fig. 4).

In addition to half of the main island, Papua-New Guinea (PNG) comprises several islands such as New Britain, New Ireland, and Bougainville, as well as small groups of islands (for instance Lihir) located ~ 700 km northeast of the main island and ~ 900 km from the capital, Port Moresby. Lihir Island is part of the New Ireland Province and lies in the zone of convergence between the Pacific and Australian plates on the western side of the Pacific Rim; the Luise Volcano is located on the island, which experienced an explosive event followed by a collapse along the northeastern flank, leading to the formation of Luise Caldera and Luise Harbor. As a byproduct of this volcanic activity, epithermal gold mineralization and several geothermal manifestations formed in the Lihir Island (Lahan et al. 2020).

In 1997 the company Newcrest Mining Limited started to operate a gold mine in Lihir, and a few years later, it installed the first geothermal power unit of 6 MW in capacity. It was a single-flash backpressure unit commissioned in 2003, followed by another two units, also of single-flash but now condensing type of 30 MW, in 2005, and 20 MW in 2006. The first unit was decommissioned in 2009, and since then, the geothermal installed capacity in the island and in the country has been 50 MW (Table 2), whose electric generation is primarily used to support the electricity demand of the mine and the plant operations. Originally, the power plants provided more than half of the power requirement of the mining operations, but with the expanded operations and the decline in steam production of the wells, due to the drop in reservoir pressure, the geothermal power plants provide only ~ 15% (Lahan et al. 2020).

The electric generation from both power plants in 2021 is around 118 GWh, approximately the same as that generated 3 years ago, although it was reported 11 MW of installed capacity and 97 GWh of electric generation (Lahan et al. 2020; Huttrer 2020). Other sources report approximately 400 GWh of geothermal generation for 2021 in PNG (Low-Carbon Power 2021; OWD 2023), but this figure looks overestimated, according to the graph of net generation in PNG in 2012–2019 presented by Lahan et al. (2020).

There are no plans for new power plants in PNG, or for revamp the current installations in Lihir.

Philippines

The Republic of the Philippines is an archipelagic country composed of more than 7600 individual islands that are usually grouped into three geographical regions, from north to south: Luzon, Visayas and Mindanao (Fig. 8). The first geothermal power plant was a

Fig. 8 Geothermal fields in the Philippines (Figure by the Philippines' Department of Energy, taken from Fronda et al. 2020)

Table 17 Total installed electric capacity and geothermal electric capacity in the three electric grids of the Philippines as of December 2022

Electric grid	Total capacity (MW)		Geothermal capacity (MW)	
	Installed	Dependable	Installed	Dependable
LUZON	19,743.7	16,320.0	864.5	768.7
VISAYAS	3972.3	3340.0	975.1	887.6
MINDANAO	4542.0	3937.6	112.1	106.3
Total Philippines	28,258.0	23,597.6	1951.7	1762.6

Totals in each grid did not include Energy Storage Systems (EES), or off-grid generators. Prepared with data from DOE (2023)

single-flash wellhead unit of 3 MW in capacity installed in 1977 in Leyte and is currently retired.

As of December 2022, the geothermal electric installed capacity in the Philippines was 1951.8 MW gross, which set the country in third place worldwide (Fig. 3), only behind the US and Indonesia. The total geothermal installed capacity is the sum of the capacity reported by DOE (2023) in the three electric grids of Luzon, Visayas and Mindanao, with the following data (Table 17):

Capacities are divided into installed or gross, and dependable that seems to be equivalent to dispatchable or net capacity. In the same DOE tables the operators of the power plants in every geothermal field are reported. Accordingly, the main operator is Energy Development Corporation (EDC), with 771.7 MW in the Visayas and Mindanao grids, followed by AP Renewable Inc. (APRI) with 692.5 MW in the Luzon

Table 18 Number, type, capacity, and generation of geothermal power units in the Philippines in 2022

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	38	1734.7	46.9	10,380.0	280.5
Other (combined)	11	192.2	17.5	1140.0	103.6
Binary ORC	7	24.9	3.6	150.0	21.4
Total	56	1951.8	35.5	11,670.0	212.2

Prepared with public data from DOE (2023) and Low-Carbon Power (2023)

grid, Green Core Geothermal Inc. (GCGI) with 315.5 MW in the Visayas grid, Bac-Man Geothermal Inc. (BGI) with 140 MW in the Luzon grid, and Maibarara Geothermal Inc. (MGI) with 32 MW in the Luzon grid.

The geothermal electric capacity represents 7% of the total installed in the country but is almost the same as that reported at WGC2020+1 (Table 2) when 1918 MW gross (1770 MW running) was reported (Fronda et al. 2020; Huttrer 2020). So, there was an increase of only 34 MW in the last 3 years (see also Fig. 3). It is not clear which power plant of that capacity was commissioned in this period, since DOE reports only one new binary power plant of 3.7 MW gross, commissioned in June 2022 by the company EDC and connected to the Mindanao grid (DOE 2023).

The most recent info about geothermal electric generation found in the DOE website when writing this report was for 2020, and it was 10,757 GWh. However, Low-Carbon Power (2023) and OWD (2023) report 11,670 GWh as geothermal electric generation in the Philippines during 2022, which represents a very good increase of almost 18% over the generation reported 3 years ago (see Table 2). Low-Carbon Power (2023) reports that the total electricity generated in the country in 2022 was 112.8 GWh, so the electricity generated by geothermal fields represented approximately 13.4% of the total and 45.8% of the electricity generated by clean sources (see Fig. 2).

There seem to be approximately 56 power units operating in seven geothermal fields in the Philippines, fed by ~ 425 production wells. Most of geothermal power units operating in the country are condensing, single- and double-flash power plants, representing 89% of the installed capacity in operation with capacities between 12 and 77 MW, followed by 11 other-type (combined) plants of 6.5 to 34 MW and finally by seven small binary ORC power units of 3.6 to 6 MW in capacity. The main features of the power units are presented in Table 18.

The main geothermal power parameters for the Philippines in 2021 are as follows:

- Geothermal fields in operation:	7
- Production wells:	425 (estimated)
- Capacity (MW)	1951.8
- Generation (GWh)	11,670
- Capacity factor (%)	67.3%
- Average production per well (MWh):	3.13

The Philippines is within the southeastern portion of the Eurasian plate (Fig. 4) and is affected by the subduction processes of the Philippine oceanic plate along the

Philippine Trench and the Luzon Trough on the east, the subduction of the South China oceanic microplate along the Manila Trench, and the Sulu Sea microplate along the Negros Trench. An arc-continent collision called the Mindoro-Panay collision zone is located between the latter two trenches. The eastern and western subduction zones produced the Philippine Fault, a long (1300 km) left-lateral strike-slip fault. The total geothermal potential of the country is estimated at 4064 MW, or approximately 2000 MW to be developed, but the development of geothermal–electric projects in the country is very challenging, particularly regarding the permitting process and the environmental and sociocultural acceptability of the projects (Fronda et al. 2020).

Future geothermal power developments include a 29-MW binary plant in Palayan Bayan, scheduled to start commercial operations in the second semester of 2023, as well as the 20-MW Tanawon project and the 28-MW Mahanagdong geothermal brine optimization plant, to be online in 2024–2025; all these projects are of EDC, as well as exploration drilling in two new areas. In January 2023 APRI started the construction of a 17-MW binary ORC geothermal plant, manufactured by Ormat, in the Tiwi geothermal field, which will use the current geothermal brine with no need to drill new wells, and is expected to be completed by the end of 2023. SM Investments Corp. (SMIC), the parent company of Philippine Geothermal Production Co., Inc. (PGPC), disclosed plans to increase the current capacity of the fields Tiwi and Mak-ban by 300 MW over the next 6 years and develop 250–400 MW in other, new zones (TGE 2023c).

Portugal

Geothermal power plants in Portugal are operating in the Azores Islands, which is an archipelago part of the Autonomous Region of the Azores. It is formed by nine islands and eight islets of volcanic origin, some of which have been inactive since they were formed, and are spread over 600 km with a WNW–ESE trend. The archipelago emerges at the so-called Azores Plateau, defined by the bathymetric line of 2000 m, located at the middle of the North Atlantic Ocean, at ~ 1600 km east of continental Portugal, and formed at the triple junction where three major tectonic plates converge: North America, Eurasia, and Africa (Fig. 4). Most of the islands are on the boundary between the African and Eurasian plates, but two are on the North American plate. The main tectonic structures in the Azores include the Terceira Rift, the mid-Atlantic Ridge, and the Gloria Fault (Nunes et al. 2023).

Intense seismic and volcanic activity occurs in the Azores Islands, particularly in the Central Group islands and in S. Miguel Island, all located at the plate boundary between the Eurasian and African plates. On S. Miguel there are four active polygenetic volcanoes with explosive activity that formed calderas, and two areas of basaltic fissure eruptions. The Ribeira Grande Geothermal Field (RGGF) is located on the northern slopes of one of those volcanoes, the Fogo central volcano, and its liquid-dominated high-enthalpy system reaches maximum temperatures of ~ 245 °C. It has been developed for power generation since 1980. The other field in operation is the Pico Alto Geothermal Field (PAGF), located on Terceira Island and developed more recently (since 2017). This island has a complex tectonic setting, four central volcanoes with explosive activity that formed calderas, and the Fissural Basaltic Zone (FBZ) in the central and SE parts of the island. The Pico Alto volcano is the youngest polygenetic volcano, producing siliceous

Table 19 Number, type, capacity, and generation of geothermal power units in Portugal in 2021

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Binary ORC	6	31.8	5.3	158.9	26.5

Prepared with data from Nunes et al. (2023)

formations of pyroclastics, domes and coulées of trachytic to pantelleritic nature. At the surface, the PAGF encompasses mostly Pico Alto volcano and the FBZ, but the geothermal systems have been formed in a complex volcanological setting that includes rocks produced by the other volcanoes. The geothermal reservoir is also of hydrothermal type, liquid-dominated and high enthalpy with temperatures of ~ 300ºC in depth (Nunes et al. 2023).

The first power unit installed in the RGGF was a single-flash wellhead unit of 3 MW in capacity, which was dismantled in 2005 to be replaced the next year by the first binary ORC power unit of 10 MW, called Pico Vermelho. Afterwards, three additional binary ORC power units, all called Ribeira Grande, were commissioned in 1994 and 1998. The current installed capacity in this field (RGGF) is 27.8 MW. In the other field, PAGF, there is only a 4-MW pilot power plant of binary ORC type, commissioned in 2017 (Nunes et al. 2023). Therefore, the total installed capacity in the Azores Islands and in all of Portugal is 31.8 MW, which has not changed since WGC2020+1, although 33 MW were reported then (Table 2).

Electric generation in both Portuguese fields in 2021 was 158.9 GWh, composed of 133 GWh in RGGF and 25.9 GWh in PAGF. This represents a decrease of 26% compared to 2018–2019 (Table 2), and was due to a failure on the alternator of the Pico Vermelho power plant. During 2021 six deep wells were drilled in the RGGF to increase the total running capacity up to 30 MW, and three deep wells in the PAGF, in this case with the purpose of ensuring saturation of the power plant. Generation in the RGGF supplied 30% of the electric demand of S. Miguel Island, and the PAGF supplied 13.4% of the demand in Terceira Island.

The main features of the power units are presented in Table 19.

The main geothermal power parameters for Portugal in 2021 are as follows:

- Geothermal fields in operation:	2
- Production wells:	10 (estimated)
- Capacity (MW)	31.8
- Generation (GWh)	158.9
- Capacity factor (%)	57.0%
- Average production per well (MWh):	1.81

Romania

Even though the main use of geothermal energy in Romania is in direct use applications, a new small geothermal power plant started to operate in this country in 2020 (Gavriliuc et al. 2020). It is the Beius ORC binary plant, installed in the village of the same name, with 0.05 MW in capacity and generation of 0.4 GWh in 2020. Therefore, the current installed capacity in Romania, as of December 2020, is 0.1 MW, with two binary cycle units of 0.05 MW each, and combined generation of 0.8 GWh in 2020 (Gavriliuc et al. 2022) (Table 2).

There is little information about the power plants, but it can be assumed that the oldest plant, called CE Iosia Nord and commissioned in 2012, uses hot water from the Oradea geothermal reservoir composed of Triassic limestones and dolomites at a depth of 2000–3000 m. The new Beius plant seems to be fed by the Beius geothermal reservoir, with a similar composition and depth. There are no known plans to develop additional power plants in the country, because “the available temperature levels of deep geothermal resources in Romania do not allow power generation under reasonable technical efficiency and economic costs” (Gavriliuc et al. 2022).

Russia

Most of the data from the Russian Federation correspond to 2020, and the electricity generated by the power units in 2022 seems to be the same as that in 2020, at least as reported by OWD (2023). All geothermal power plants operating in Russia are in the eastern tip of this extended country, particularly in the Kamchatka Peninsula and in some of the Kuril Islands, which constitute the north-northwestern part of the Pacific Ring of Fire (Fig. 4). It has been estimated that this eastern portion of Russia has enough geothermal resources to install ~ 2000 MW, and it has been explored since the middle of the 1950s with geological surveys, geochemical sampling and analyses, systematic geophysical surveys, and drilling of ~ 385 wells at depths between 170 and 1800 m. At least 44 of those wells are producers of hydrothermal, two-phase fluids with temperatures ≥ 160 °C (Svalova 2022).

Approximately 18 sites of hot springs and probable geothermal fields at the subsurface have been identified and studied in the southern part of the Kamchatka Peninsula, including the Valley of the Geysers and Pauzhetsky, located northeast and south, respectively, of Petropavlosk-Kamchatsky, the capital city of the region. On March 1958 the drilling of the first deep geothermal exploration well in the geothermal field of Pauzhetsky was started, which was finished on January 1959; the well encountered a shallow interval (120–400 m depth) with overheated sodium–chloride water at 171–178 °C, but the maximum temperature was 204 °C, measured at 600 m depth. Four exploration shallow core wells were drilled afterwards (Pashkevich 2020), and finally, the first two single-flash power units of 2.5 MW each were commissioned in 1966, which are still operating after 56 years. One small binary ORC pilot plant of 0.68 MW in capacity was installed in 1967 in Paratunsky, which is another of the 18 geothermal sites, in this case located near the capital, but it was unable to operate properly and was retired soon after.

There are currently 11 geothermal power units operating in five geothermal fields, three in Kamchatka and two in the Kuril Islands of Iturup and Kunashir, the latter very near Japan. All the power plants are of the single-flash condensing type, with capacities between 1.3 and 25 MW, being the oldest the mentioned units of 2.5 MW installed in Pauzhetsky, and the newest units in the Kuril Islands, which were commissioned in 2007. The combined capacity of those 11 units is 81.9 MW, which is the same as that reported in WGC2020+1, and the electricity generation is 440.7 GWh. The running capacity is 75.4 MW (Svalova 2022). It is worth mentioning that for 2020, the electric

Table 20 Number, type, capacity, and generation of geothermal power units in Russia in 2020

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Flash	11	81.9	7.4	440.7	40.1

Prepared with data from Svalova (2022) and OWD (2023)

generation of geothermal origin in Russia is reported to be 420 GWh (OWD 2023): thus, there would be a slight increase between 2020 and 2022, but the difference is minimal.

The main features of the power units are presented in Table 20.

The main geothermal power parameters for the Russian Federation in 2020 are as follows:

- Geothermal fields in operation:	4
- Production wells:	30 (estimated)
- Capacity (MW)	81.9
- Generation (GWh)	440.7
- Capacity factor (%)	61.4%
- Average production per well (MWh):	1.6

It is estimated that there is a total geothermal power potential of 1350 MW from the fields known in the Kamchatka peninsula, of which less than 6% (76.1 MW) has been exploited up to now, and ~300 MW in the Kuril Islands, mainly in Iturup and Kunashir, with less than 2% currently harnessed (5.8 MW). One small binary ORC power plant of 2.5 was reported to be planned at the Pauzhetsky site, as well as some other unit in the Kuriles Islands (Svalova 2022).

Taiwan

There seem to be only three binary ORC power plants in operation, located in the geothermal fields of Chinshui (4.9 MW) and Shihuangping (1.2 MW), at the northern part of the island, and Jinlung (0.5 MW), at the southern tip. Thus, the installed capacity increased from 0.3 reported in WGC2020+1 to 6.6 MW, and the electric generation increased from 2.6 to 25 GWh (Table 2). Another 19 geothermal projects, with a combined capacity of 48.3 MW, are preliminarily planned to be installed in New Taipei City and in the counties of Ilan, Hualien, and Taitung, even though the Bureau of Energy (BOE) projects only 20 MW of geothermal power by 2025 (Song et al. 2023).

The main geothermal power parameters for Taiwan in 2021 are as follows:

- Geothermal fields in operation:	3
- Production wells:	6 (estimated)
- Capacity (MW)	6.6
- Generation (GWh)	25.0
- Capacity factor (%)	43.3%
- Average production per well (MWh):	0.41

Taiwan island is part of the Pacific Ring of Fire, and is located on the eastern part of the Eurasian plate, where this continental plate collides obliquely with the Philippine oceanic plate (Fig. 4). Currently, the Philippine oceanic plate is moving toward the

WNW at ~ 70 mm/year, and a mountain-building process is apparently still ongoing. A dominant collision zone frequently inducing folding and fault thrusting in the area may exist in central Taiwan since the last 5 Ma. At the latitude of southern Taiwan, the Philippine plate is riding up over the continental shelf of the South China Sea, which gives place to a rapid uplift with a high geothermal gradient. In northern Taiwan, the Philippine plate is subducting beneath the Eurasian plate, generating active vulcanism and rifting. That complex tectonic framework is favorable for high-temperature geothermal resources on the island (Song et al., 2023).

Given that volcano-tectonic setting, the total geothermal power potential of Taiwan seems to be much larger. Estimates range from 979 MW from conventional hydrothermal resources up to 36.3 GW, including EGS resources (Song et al. 2023).

It is worth mentioning that geothermal exploration started in Taiwan in the 1960s, and some small power pilot plants were commissioned in 1980–1990. However, all were decommissioned later, probably due to issues related to scaling and lack of reinjection, but also to the small scale of the plants, the high costs and a limited knowledge of underground geological reservoirs (Song et al. 2023).

Exploration and development of geothermal energy have been promoted in Taiwan through several strategies, including sharing the risk of exploration, launching a FiT scheme, simplifying administrative procedures, and subsidizing more funds. For instance, the price of electricity for public is ~ US 0.08 cents per kWh in average, but the FiT is ~ US 0.167 cents. There is also a subsidy of USD 3.2 million for exploration and drilling per project (Song et al. 2023). Thus, there seem to be enough incentives for geothermal development.

Thailand

Since 1989 a small geothermal power plant of 0.3 MW has been in operation in the northern portion of Thailand, at the Fang Hot Springs. These springs are one of the 16 known superficial manifestations in the country. Plant is of binary cycle and is fed by geothermal fluids, that downstream of the plant are also used in other facilities at the same site for dehydration, hot water pools and spas (Raksaskulwong 2008).

The hot springs are located at the Fang Basin, where they crop out from fractures in foliated granite of the basement rocks. The geothermal system was initially studied by the Electricity Generating Authority of Thailand (EGAT), and other national and foreign groups in the 1970s and 1980s. Successful wells were drilled in the 1980s and 1990s, with a combined production of 22 l/s of water at 125 °C, and then the 300-kW binary power plant, manufactured by Ormat, was installed in 1989 (Wood et al. 2018).

A very complete and detailed study comprising geology, geochemistry, and geophysics, concluded that the heat source of the Fang geothermal system is "the natural radioactive decay of K, Th, and U in the upper crustal crystalline rocks, combined with heat flow from the lower crust and upper mantle" and that geothermal systems in northern Thailand "are not associated with underlying magmatic systems". It also estimates that in this zone it is feasible to obtain a total flow of 55 l/s to generate ~ 2 MW. In 2018 the plant produced 115–250 kW (Wood et al. 2018), and more recently it produced ~ 30 kW.

Table 21 Number, type, capacity, and generation of geothermal power units in Türkiye in 2022

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Binary ORC	61	1385.9	22.7	8479.8	139.0
Other (combined[a])	2	245.0	122.5	1716.9	858.5
Flash	3	86.4	28.8	643.3	214.4
Total	66	1717.3	26.0	10,840.0	164.2

[a] Combined flash + binary plants. Data taken from (Mertoğlu et al. 2023)

Türkiye

This country occupies fourth worldwide place by its geothermal–electric installed capacity and generation, after a meteoric development in the last 20 years, a period in which the power capacity grew 86 times from 20 MW in 2005 to the current 1717 MW. In the last 3 years, the installed capacity increased 10.8% by passing from 1549 MW in 2018–2019 to 1717 MW in 2022, and geothermal–electric generation increased by more than 2600 GWh, a staggering 33%, in the same period, passing from 8168 to 10,840 GWh (see Table 2, and Fig. 3) (Mertoğlu et al. 2023).

As of December 2022, there were 66 geothermal power units installed in 27 geothermal fields in operation, out of ~ 460 fields with superficial temperatures ≥ 30 °C identified in the country. Most of the power plants are of the binary ORC type, with air-cooled condensers, and so their production efficiency and net electric generation decrease in summer due to high ambient temperatures. Geothermal operators are trying to compensate for this by installing solar hybrid plants. It is expected that production and profitability will increase, and two renewable sources will be integrated together (Mertoğlu et al. 2023).

The main features of the power units are presented in Table 21.

The main geothermal power parameters for Türkiye in 2022 are as follows:

- Geothermal fields in operation:	27
- Production wells:	330 (estimated)
- Capacity (MW)	1717.3
- Generation (GWh)	10,840
- Capacity factor (%)	72.1%
- Average production per well (MWh):	3.75

The highest measured temperature is 341 °C at a depth of 3845 m drilled in Nigde Province in Central Anatolia. The deepest geothermal well reached up to 4792 m at the geothermal field of Denizli-Tekkehamam one of the first fields to be developed. All the geothermal fields in operation are hydrothermal, of biphasic, liquid-dominated and high enthalpy. Geothermal fluids are mostly of meteoric origin, circulating through deep lateral (strike-slip) and thrust faults (Mertoğlu et al. 2023), oriented predominantly in a W–E general trend, which are the most relevant due to the tectonic framework of the country in the Eurasian plate (Fig. 4). In general, the amount of CO_2 and other non-condensable gases (NCG) in geothermal power plants in Türkiye has decreased by 50–70% in the last 15 years. Therefore, it has been necessary to install and use downhole pumps, submersible pumps and pumps resistant to high temperatures (Mertoğlu et al. 2023).

All underground resources are property of the nation in Türkiye, so geothermal springs and natural mineral waters are under control of the government and subjected to licenses and concessions to be exploited. To date, a total of 1663 geothermal exploration and 1835 operating licenses have been granted to private companies, local governments and municipalities, and individuals in the country (Mertoğlu et al. 2023), most of them concentrated in the western part, where the majority of geothermal resources are located.

Many of the operating power plants provide geothermal brine and heat supply for direct use. In the areas of Çanakkale-Babadere, Aydın-Ortaklar, Aydın-Germencik, Salavatlı and Denizli-Sarayköy, the residual geothermal fluid from the power plant is used in direct applications before being reinjected back to the reservoir (Mertoğlu et al. 2023).

There is an incentive system for geothermal investments of a certain size, implemented by the Ministry of Industry and Technology. The system includes customs duty exemption, VAT exemption, permission for credit allocation, and so on. It also includes a scheme of feed-in tariffs (FiT), which at July 2021 is approximately 6.5–8.6 cents/kWh for geothermal, as well as a 10-year purchase guarantee by the Ministry of Energy. This incentive system for geothermal energy is one of the main triggers of accelerated development in recent years. The other was the enacting of the geothermal law, and the consequent disposition of the MTA (General Directorate of Mineral Research and Exploration) to conduct geothermal exploration studies, including the drilling of 1–2 wells per concession area, and transfer of the geothermal field to a private developer, through a leasing and renting scheme (Mertoğlu et al. 2023).

The total geothermal potential for power in Türkiye has been estimated at 9000 MW for hydrothermal resources at 0–4 km depth, out of which the geothermal power target for 2030 is 3000 MW, supported by a FiT of 10.5 cents/kWh and a 10-year purchase guarantee. The geothermal technical economic potential for EGS/HDR resources in the country, at depths between 3 and 5 km, is estimated to be at least 20 GW (based on 12 cents/kWh and a 15-year purchase guarantee) (Mertoğlu et al. 2023). Thus, geothermal development has a bright future in the country.

United States

The previous US country update reported 3678 MW of geothermal gross installed capacity as of October 2019, and 2850.7 MW of net installed capacity (Robertson-Tait et al. 2020, Table 2), the latter also known as running capacity. On the other hand, the US Energy Information Administration (EIA), reports 3849.3 MW as the official nameplate (installed) capacity as of December 2019, as well as 2555 MW of Net Summer Capacity and 2980 MW of Net Winter Capacity (EIA 2023). Based on the definitions provided by the EIA Glossary, it is clear that there is no equivalence between the net installed capacity reported in the 2020 country update, and the net summer or the net winter capacity reported by EIA, since the first refers to the round year and the latter covers only 4 and 3 months, respectively. The small difference (171.3 MW) between the gross installed capacity reported by Robertson-Tait et al. (2020) and the EIA (2023) seems to be due to some plants classified as "standby/backup (…) available for service but normally not used" and other plants classified as "(OS) Out of service and NOT expected to return to service in next calendar year", as explained by TGE (2023b).

By the time this current report was written, there were no final data on geothermal nameplate capacity in the EIA databases for 2022, but for 2021, the amount was 3889.4 MW (Robertson-Tait et al. 2023). For 2022, the only new geothermal power plant commissioned in the US seems to be the 30-MW binary cycle plant Casa Diablo 4 (CD4), installed in July 2022 by Ormat in the Mammoth Lakes Complex, California, as reported by TGE (2022c). Thus, it is possible to conclude that the actual gross installed capacity in the US as of December 2022 was 3919.4 MW (Table 2), with 178 generators, 68 facilities, and 132 power plants.

Regarding geothermal electricity generation, the previous country update reported 18,435 GWh as of December 2018 (Robertson-Tait et al. 2020; Table 2). However, EIA reports 15,967 GWh as the annual net generation of geothermal plants in the same year (EIA 2023), which means 2468 GWh (13.4%) less than the gross generation indicated in the country report. In theory, the difference seems to be because Robertson-Tait et al. reported the gross generation produced by the power plants, and EIA reports the net-generation delivered to the grid, discounting the self-consumption in auxiliary power for geothermal facilities and installations. In this case, the difference in 2018 is certainly too high, because it is usually less than 10% of gross generation, but in any case, it is important to bear in mind this difference to estimate the gross geothermal electric generation for 2022.

A quick comparison between gross and net annual geothermal generation reported for the US in the previous WGCs and the EIA database between 1994 and 2014 results in differences ranging from 1% (WGC 1995) up to 13.7% (WGC 2005), with an average variation of 6.6%. On the other hand, in 2022, the net geothermal power generation in the US was 17,002 GWh (EIA), which is the highest historic record since. Thus, to estimate the gross generation produced by the 131 geothermal power plants in operation in 2022, we used a difference of 10%, which lies between the historic average and the 2018 difference. Applying this percentage to the net-generation reported by the EIA (17,002 GWh), the gross electric generation of the geothermal plants in the US during 2022 results in 18,702 GWh (Table 2).

In the last 3 years (2019–2022), there seems to be a small increase in the geothermal power installed capacity in the US of 241 MW, equivalent to 6.5% (Table 2, Fig. 3). The gross generation of all geothermal power plants in operation in the US seems to have an even smaller increase of 1.4%, passing from 18,435 GWh in 2018 to 18,702 GWh in 2022 (see Table 2). However, the net-generation increased from 15,967 GWh in 2019 to 17,002 GWh in 2022, equivalent to 6.4%. It is important to highlight that this increase occurred practically in the last year (2022), given that the net-generation reported by the EIA in 2021 was barely 15,975 GWh. That might indicate a relevant reduction in average self-consumption of geothermal power plants, a better efficiency in the operation of the fields and plants… or a glitch in the EIA data for 2022, to be adjusted later.

There are seven US states with geothermal fields and power in plants in operation, but most of the installed capacity is currently concentrated in two states, California and Nevada, with almost 95% of the national installed capacity and ~ 94% of the geothermal electric generation (Table 22). According to this table, in 2022 California had almost

Table 22 Distribution of geothermal power plants and net generation in seven states of the US in 2022

State	Facilities	Gross Installed Capacity (MW)	Share of total (%)	Net Generation (GWh)	Share of total (%)	Share (%) of state / country generation
California	32	2854.0	72.81	11,813	69.48	5.8
Nevada	25	856.7	21.86	4111	24.18	9.6
Utah	3	83.8	2.14	451	2.65	1.2
Hawaii	1	51.0	1.30	304	1.79	3.2
Oregon	2	36.7	0.94	197	1.16	0.3
New Mexico	1	19.2	0.49	46	0.27	0.1
Idaho	1	18.0	0.46	80	0.47	0.5
Total (US)	65	3919.4	100	17,002	100	0.4

Prepared with data from EIA (2023)

Table 23 Number, type, capacity, and generation of geothermal power units in the US in 2022

Type of unit	Number	Capacity (MW)	Average (MW)	Generation (GWh)	Average (GWh)
Dry steam	20	1549.9	77.5	6650.0	332.5
Binary ORC	55	1280.6	23.3	6122.0	111.3
Flash	32	1044.5	32.6	5680.2	177.5
Other (combined)	22	35.4	1.6	250.0	11.4
Backpressure	1	9.0	9.0	0.0	0.0
Total	130	3919.4	30.2	18,702.2	143.9

Prepared with data from Robertson-Tait et al. (2020) and EIA (2023)

73% of the national geothermal installed capacity and produced ~ 70% of the geothermal electricity of the country but less than 6% of the electricity produced in the state. In contrast, Nevada produced almost one tenth of the electricity produced there. At the national level, however, geothermal energy continues to be a tiny part of the total, sharing 0.44% of the 4243.1 TWh generated in the US in 2022.

The main features of the power units are presented in Table 23.

Approximately 820 geothermal production wells are estimated to be operating in the US, based on the 321 steam wells reported in The Geysers in 2021 (Calpine 2023) and on older data estimated for the US (TGE 2019).

The main geothermal power parameters for the US in 2023 are as follows:

- Geothermal fields in operation:	31
- Production wells:	820 (estimated)
- Capacity (MW)	3919.4
- Generation (GWh)	18,702
- Capacity factor (%)	54.5%
- Average production per well (MWh):	2.60

The only new geothermal power plant included in the EIA's Planned U.S. Electric Generating Unit Additions in 2023–2030 is the ORC binary cycle unit of 25 MW in North Valley, Nevada, which was effectively commissioned on April 2023 by Ormat, as part of the San Emidio project. There were no more planned geothermal power plants in the following 7 years (2024–2030), but Ormat completed a 6 MW upgrade to its Dixie Valley power plant, also in Nevada, in May 2023, and announced plans to continue the upgrading (Ormat 2023). The total geothermal potential is 9000 MW for conventional hydrothermal resources, and ~ 60,000 MW including some EGS developments (Robertson-Tait 2020).

Regarding EGS potential, a recent analysis estimated 90 GW in power plants that could be feeding the grid in 2050, mainly located in the Western US and several states like Mississippi, West Virginia, Virginia, and Pennsylvania, with estimated cost of US$ 45 per MWh by 2035, a very competitive cost considered as achievable with technology advances (Augustine et al. 2023).

Few new plants seem to be planned in the US in the near future, but things are different regarding mineral production from geothermal brines, particularly lithium. In the southern Salton Sea, the company CalEnergy, which currently operates several fields with approximately 350 MW, is planning to double that capacity and collect ~ 40 metric tons of LCE (lithium carbonate equivalent) from the brines annually. In the deepest parts of geothermal reservoirs in the Salton Sea (~ 3500 m), brines can contain 200–250 ppm lithium (Elders et al. 2023).

In March 2023, Controlled Thermal Resources (CTR) signed an agreement with Fuji Electric to install 330 MW in the next 5 years at Hell's Kitchen Lithium and Power Project, located in Imperial County, California, south of the Salton Sea. CTR plans to use the geothermal brine and a portion of renewable power generated from these facilities, to produce ~ 150,000 metric tons of lithium hydroxide annually. The long-term plans of the company comprise a total production capacity of 1100 MW of power and over 300,000 metric tons of lithium products annually (CTR 2023).

Thus, that seems to be "the start of a direct lithium extraction industry (DLE), that will be in the future the basis for manufacturing lithium-ion batteries in the Imperial Valley" (Elders et al. 2023), but also the restart of geothermal power development in California.

Other worldwide data

The current list of countries with geothermal power plants in operation as of December 2022, presented in the typical descending order by capacity is as follows (Table 24).

The order in Table 24 is more or less the same as that in WGC2020+1, except for the exit of Belgium (reported in WGC2020+1) and the incorporation of Canada, Colombia and Romania (not included before), although with very small power plants. However, the displacement of Italy by Kenya in seventh place, a country that will probably soon displace Mexico and New Zealand, and the ascent of Chile to fifteenth place, practically tied to Russia, surpassing Guatemala and Papua–New Guinea, are remarkable. It is also not too hard to forecast the next ascent of Türkiye to the third worldwide place, since its accelerated growth will probably continue in the following years.

The third column of Table 24 presents the annual capacity factor for each country in the last year available (2021 or 2022 in some cases). The highest is the capacity factor of Honduras, whose only geothermal power plant generating in the Platanares geothermal field, a 35-MW binary ORC plant operated by the private company Geoplatanares, generated 297 MW in 2021, at a staggering capacity factor of 97%. It is certainly a recent plant, commissioned in 2017, but both the plant and the field seem to be very well

Table 24 Worldwide installed capacity, generation, and annual capacity factor in 2021–2022

COUNTRY	Capacity (MW)	Generation (GWh)	C.F. (%)
1. United States	3919.4	18,702.2	54.5
2. Indonesia	2384.4	16,588.1	79.4
3. Philippines	1951.8	11,670.0	68.3
4. Türkiye	1717.3	10,840.0	72.1
5. New Zealand	1054.8	7820.0	84.6
6. Mexico	1001.9	4511.5	51.4
7. Kenya	972.5	5590.0	65.6
8. Italy	915.8	5917.0	73.8
9. Iceland	755.3	5788.4	87.5
10. Japan	545.7	2660.8	55.7
11. Costa Rica	252.5	1599.0	72.3
12. El Salvador	204.4	1575.0	88.0
13. Nicaragua	165.4	780.0	53.8
14. Russia	81.9	440.7	61.4
15. Chile	81.0	600.0	84.6
16. Papua–New guinea	50.0	118.3	27.0
17. Germany	47.0	207.7	50.4
18. Guatemala	46.5	310.0	76.1
19. China	45.1	131.2	33.2
20. Honduras	35.0	297.0	96.9
21. Portugal	31.8	158.9	57.0
22. France	17.2	127.0	84.3
23. Croatia	16.5	74.7	51.6
24. Ethiopia	7.3	0.0	0.0
25. Taiwan	6.6	25.0	43.3
26. Canada	6.3	0.0	0.0
27. Hungary	3.0	18.1	69.0
28. Austria	1.2	0.5	4.8
29. Australia	0.3	0.0	0.0
30. Thailand	0.3	0.2	7.6
31. Colombia	0.1	0.0	0.0
32. Romania	0.1	0.8	91.3
Total	16,318.4	96,552.1	67.5

operated. The only plant in Romania also shows a high capacity factor, but it is a very small (and recent) unit, while El Salvador and Iceland show capacity factors of ~ 88%, followed by New Zealand, Chile, France and Indonesia. The latter case is remarkable because in this country there are 46 geothermal power units of different capacities and years of operation.

Regarding geothermal power plants, and according to the collated data obtained for WGC2023, it is possible to say there are 673 power units in operation of mainly three basic types, condensing or flash plants, binary cycle, and combined, with a couple of important modifications of the first one: backpressure (no condensers and cooling system) and dry-steam (no separators). The summary is presented in Table 25.

Power plants of single, double and some few of triple-flash, complete with the typical separator, condenser, and cooling tower, are only 36.7% of all, but represent more

Table 25 Type, number, total, and average capacity, total and average generation, and average capacity factor of geothermal power plants in the world in 2021–2022

Type	Units (No.)	Capacity (MW)	Average Capacity (MW)	Generation (GWh)	Average Generation (GWh)	Capacity Factor (%)
Flash	247	8598	34.8	53,659	217.2	71.2
Dry Steam	60	2903	48.4	15,623	260.4	61.4
Backpressure	23	129	5.6	128	5.6	11.1
Binary ORC	288	4091	14.2	23,224	80.6	64.8
Other[a]	55	597	10.9	3,918	71.2	74.9
Total	673	16,318	24.2	96,552	143.5	67.5

[a] Other includes a combination of flash and binary plants, as well as a couple of units of binary Kalina cycle type

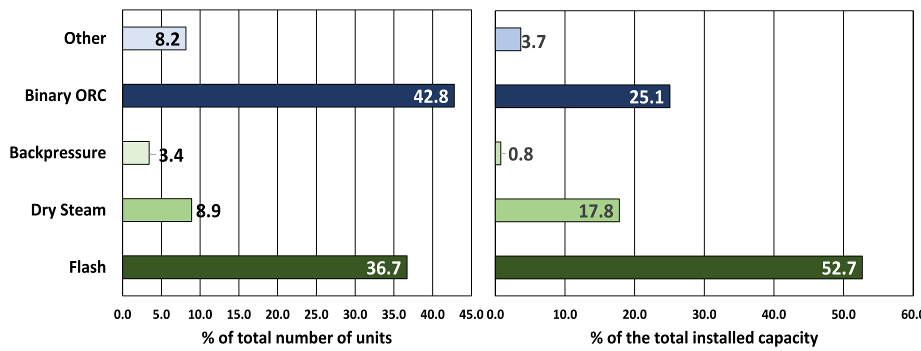

Fig. 9 Abundance of every type of power plant regarding the number units in operation (left) and the installed capacity (right)

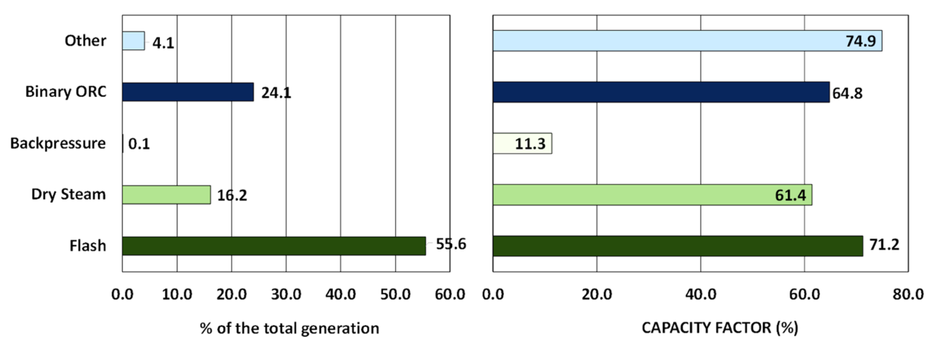

Fig. 10 Proportion of total of electric generation of every type of power plant (left), and worldwide average capacity factor (right)

than half (52.7%) of the installed capacity (Fig. 9) and generate almost 55.6% of the total electricity of geothermal origin, with the best capacity factor (~71.2%), except when they are combined with binary plants (Fig. 10). The average size of these flash power plants is 35 MW, and their electric generation is 217 GWh annually (Table 25).

The binary ORC type of geothermal power units is the most abundant (43% of total), but represents 21.7% of the total installed capacity (Fig. 9), generating approximately 21% of the electric generation, and showing almost 65% as the average capacity factor

(Fig. 10). The average size of these plants is 14.2 MW, and their average generation is 80.6 GWh (Table 25).

Deciding between flash or binary cycle power plants to be installed in a certain geothermal field, depends basically on the developer and their expectations. There was a time when the decision depended on the fluid temperature and was almost automatic: binary units were for fields with resources of ≤ 150 °C. However, for some time more binary plants have been installed in fields with high temperature, particularly in cases where environmental restrictions are stricter. On the other hand, the decision to install a dry steam plant and avoid the use of separators, depends on the features of the reservoir and specifically on the geothermal fluid composition. Thus, the number of dry steam power plants in operation is less than a tenth of the total, but the plants represent 16% of the worldwide installed capacity (Fig. 9), including the largest geothermal field in the world (The Geysers in California), and have the highest average capacity compared to the other types (48 MW, Table 25). Dry steam plants generated 16% of the electricity of geothermal origin in the world with an average capacity factor of 61.4% (Fig. 10), and the average generation of a plant of 48.4 MW was also the highest of all types, with 260.4 GWh.

Backpressure power plants have the lowest investment cost of all types since they discharge to the atmosphere and do not require condensers and cooling towers. They are also the fastest plants to be installed, are usually placed at a short distance from the production well, can tolerate more NCG content, and can be moved to other locations in a relatively short time and at low costs. However, they are the most inefficient plants, generating the lowest electric output using the same amount of steam, due to the lack of a condenser (and cooling tower). Backpressure plants are an excellent choice in greenfield geothermal projects to accelerate the start of income and simultaneously to test the behavior of the reservoir under actual conditions of exploitation. That is why there are only 23 plants of this type operating in the world (3% of the total, Fig. 9), with an average capacity of 5.6 MW, which generated 128 GWh (0.1% of the total) at the lowest capacity factor (~ 11%) Table 25, Figs. 9 and 10).

Combined plants are grouped into *Other* type, which are usually the combination of one large flash plant and one or two smaller binary plants using the residual steam or brine, but in this case the category also includes a couple of tiny binary plants of Kalina cycle of 0.5 and 0.2 MW in capacity operating in Germany and Japan, respectively. There are 55 combined power plants in operation, whose installed capacity is less than 4% of the total, but they have the highest capacity factor (75%) (Table 25, Figs. 9 and 10).

The number of production wells operating in the 198 geothermal fields in the world is estimated to be 3700, 22.2% of which are in the US, 14.1% in Indonesia, and 11.5% in the Philippines (Fig. 11), three countries that concentrate almost half (47.7%) of the total—as expected, since they have 50.6% of the installed capacity in the world (Table 24). In fact, ten countries, all with ≥ 200 production wells in operation, have 92.9% of all the wells in operation, as presented in Table 26.

Considering the total electricity generation of each country in 2021–2022 and the total number of production wells in operation around the year, it is possible to know the average production of each well. The second column of Table 26 presents this parameter in megawatts per hour. The world average results in ~ 3 MWh per production well, varying

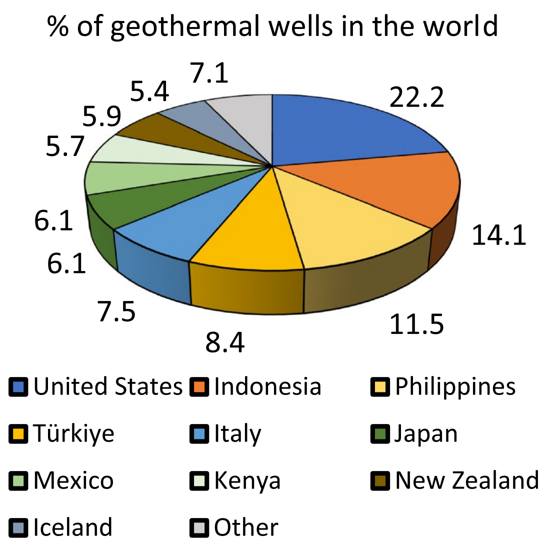

Fig. 11 Countries with ≥ 200 geothermal wells in operation

Table 26 Number of geothermal production wells and average production per well, expressed in MWh

Country	Production wells (Number)	Average well production (MWh)
United States	820	2.60
Indonesia	520	3.64
Philippines	426	3.13
Türkiye	310	3.75
Italy	279	2.42
Japan	226	1.34
Mexico	225	2.29
Kenya	212	3.01
New Zealand	220	4.06
Iceland	200	3.30
Other	262	2.89
World	3700	2.98

between a minimum of 1.34 MWh for Japan and to 4.06 MWh for the geothermal wells operating in New Zealand. In addition, it is also possible to obtain the average number of wells per power plant, and per MW installed, by dividing the total number of wells by the total number of plants and the total installed capacity. For the world, the figures are 5.5 wells per power unit, and one single well would be able to produce the required fluid for 4.4 MW of installed capacity during the year.

Final comments

The situation of the geothermal power industry in the world has not changed much in the past 3 years since WGC2020+1. Three countries, Canada, Colombia, and Romania, appeared in the scenery, the latter with demonstrative power plants in operation, but

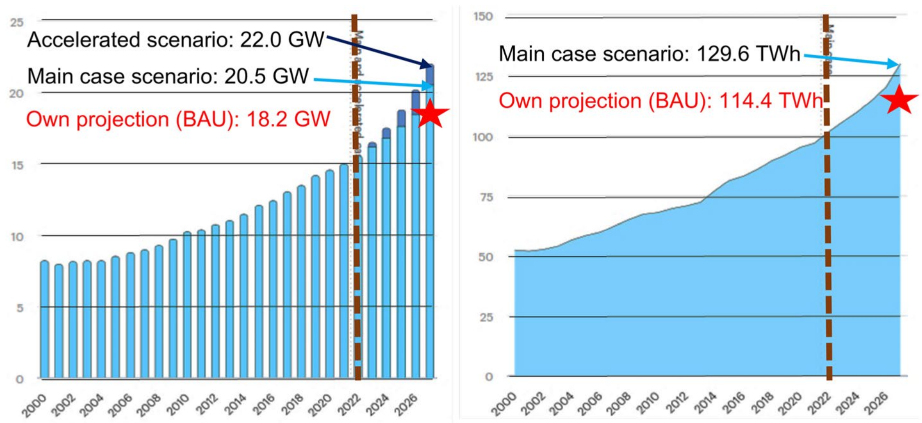

Fig. 12 IEA projections for 2023–2027 of geothermal installed capacity (in GW) in the main case (light blue) and accelerated case (dark blue) scenarios (left), and geothermal generation (in TWh) in the main scenario (right) (Taken and slightly modified from IEA (2023))

Belgium exited the list, and so the number of geothermal power countries is 32. The total installed capacity shows a modest increase of 905 MW, equivalent of 5.8% over the past 3 years, with electric generation presenting an ~ 8% increase in the same period (Table 2).

Things seem to be similar in the next few years if the current trend is projected. For instance, the International Energy Agency (IEA) projects 20.5 GW of geothermal installed capacity by 2027 in its *main case* scenario (business as usual), with 129.6 TWh of electric generation in the same year (projection increases to 22 GW in the *accelerated scenario*) (see Fig. 12) (IEA 2023).

Based on the data shown in Table 1, the projection for 2027 could be even lower: applying the same growth rate that occurred in the last 3 years, the global geothermal installed capacity in 2027 would be 18.16 GW and electric generation would be 114.4 GWh (see Fig. 12).

However, there are conditions for things to be different in the following years. For instance, in June 2023 the IEA convened its Global Conference on Energy Efficiency and released its Versailles Statement signed by 45 countries. The IEA stated that to keep the goal of limiting global warming to 1.5 °C, a full range of clean energy technologies it will be necessary, and that its Roadmap to Net Zero Emissions shows that two of those technologies are critically important: energy efficiency and renewable sources. Moving the world onto a path toward net zero emissions by 2050, means doubling the annual rate of global energy efficiency progress, and tripling the total amount of renewable power capacity worldwide by the end of this decade. The current global energy efficiency today is 2.2%, and it will need to be 4% in 2030, while the current (2022) renewable capacity of 3610 GW must grow to more than 10,000 GW (see Fig. 13).

In that context, it is worth highlight that geothermal electric generation is currently the only renewable baseload source, being able to generate 24–7 around the year, regardless of any daily or seasonal variation. Therefore, 100 MW of a new geothermal power plant, operating at a conservative capacity factor of 90%, can generate the same electricity of an onshore wind power installation of 280 MW at an annual capacity factor of 32%,

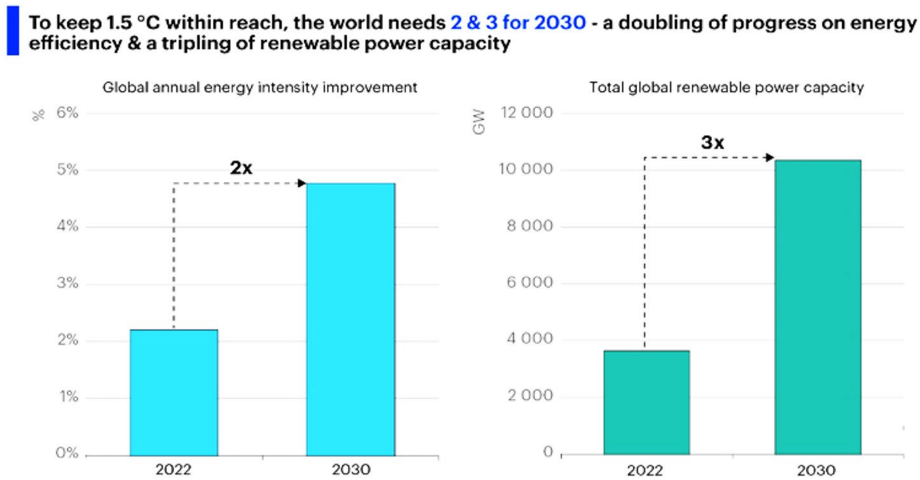

Fig. 13 Projections of the IEA about what is to be done to keep reachable the goal of limiting global warming at 1.5 °C (Taken from IEA (2023)

or of a PV solar farm of 320 MW at an annual capacity factor of 28%. Therefore, if all the current renewable capacity were geothermal, renewable generation would have tripled in 2022, and the world would be on its path toward net zero emissions by 2050. That is only a fantasy, of course, but it is a spotlight for policymakers on the importance of boosting the geothermal power development in the following critical years before 2050.

For geothermal power to reach its full potential and be able to triple its current share of electric generation worldwide, it is necessary to develop all the well-known hydrothermal, conventional potential. However, it is also indispensable to develop unconventional resources that are not limited by geography, such as the huge hot-dry rock potential, through EGS technologies. A recent report by BloombergNEF highlights the "increasing number of utility-scale, commercial projects adopting next-generation geothermal technologies, and more countries (…) embracing geothermal technologies in pursuit of their net-zero targets." By next-generation geothermal technologies, the report means EGS and advanced geothermal systems (AGS), which are capable of creating conditions for using geothermal energy in areas where hydrothermal exploitation is impossible. The report cites the US Department of Energy, who stated that next-generation geothermal energy could provide up to 120 gigawatts of firm capacity in the US by 2050, and mentions several technological companies, such as Eavor Technologies, Fervo Energy, and Greenfire Energy, which are testing their concepts not only in the US but in the EU (BloombergNEF 2023).

Of course, there are the usual hurdles. As BloombergNEF points out, geothermal power development is expensive and capital-intensive, and the cost of next-generation technologies is even higher: more than US$8.7 million/MW in capital expenditure, compared with US$1.8 million/MW for onshore wind and US$1.1 million/MW for solar plants. Financing costs are also higher: a geothermal project has a ~ 15% weighted average cost of capital at the pre-drilling stage, compared with 5% for wind and solar projects. Another problem is scalability, since the current developments have proven the technical feasibility of next-generation geothermal projects only on a small scale (BloombergNEF 2023), even though some projects currently in progress are aimed to prove the scalability of AGS, for instance the already mentioned project in Geretsried, Germany.[1]

However, the bottom line is that the geothermal power industry seems to be ushering a promising period, pulled by the world urgency to maintain global warming below the 1.5 °C threshold. So be it.

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Author's contribution
The author read and approved the final manuscript.

Declarations

Competing interests
The author declares that he has no competing interest.

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