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Geothermal Development and Use, 1995-2024

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ABSTRACT

Geothermal power generation started at Lardarello, Italy in 1904, resulting in the first commercial plant of 250 kW being installed in 1913. New Zealand came on-line in 1958 with a 1.2 MWe plant at Wairakei followed by Mexico in 1959 with a 3 MWe plant at Pathe. The first plant in the USA was at The Geysers in northern California at 11 MWe in 1960. All these plants were of the flash steam type. The first binary power plant was at Paratunka, in Kamchatka, Siberia, Russia (1967), followed by binary plants in Japan and Iceland in 1966, and China in 1970. Today (2023), 29 countries produce electricity from geothermal resources for a total estimate of 18,000 MWe generating 108,000 GWh of electricity. Geothermal direct use is one of the oldest, most versatile, and most common forms of utilizing geothermal energy. Direct use has been documented for over 2000 years throughout the world. Today (2023), it is estimated the installed capacity is 126,000 MWt and the annual energy use is 1,280,000 TJ (355,600 GWh) in over 88 countries. The average worldwide capacity factor over the past 25 years for direct use is 0.327, indicating 2,866 full-load equivalent capacity hours per year. Direct uses include bathing and swimming, space heating including district heating, greenhouse and aquaculture pond heating, industrial applications, and snow melting and cooling. Geothermal (ground-source) heat pumps using ground or ground-water temperatures between 5 and 30 degrees C for both heating and cooling are found throughout the world and are the largest direct use application. The leading countries for geothermal direct use are China, United States, Sweden, Germany, Turkey, France, Japan, Iceland, Finland, and Switzerland (>2000 MWt). In summary, lower temperature resources (<90 degrees C) are becoming more economical for greenhouses, aquaculture and drying aquacultural products such as fruit and

vegetables. Lower temperatures are now possible down to 90 degrees C for power generation with units less than 1 MWe becoming economical. Geothermal heat pumps are becoming more popular and economic with over 6.5 million units presently installed worldwide.

1. Introduction

This paper presents a review of world-wide applications and uses of geothermal energy for both electric power generation and direct utilization, including geothermal (ground-source) heat pumps, for the last 25 years (1995-2020). These data are summarized from world geothermal congresses (WGC) held every five years. These include chronologically, congresses held, in Italy, Japan, Turkey, Indonesia, Australia, and Iceland. The data included in this paper for 2020 are from 88 countries/regions; however additional areas most likely exist, but unfortunately have not been documented. We have estimated the data for 2023. See Table 1 for data from 1995 to 2023.

Table 1: Summary of geothermal capacity of production 1995-2023

Year	Installed Electric Capacity MWe	Produced Electric Energy GWh/yr	Installed Thermal Capacity MWt	Produced Thermal Energy TJ/yr
1995	6.832	38,035	8,664	112,441
2000	7,972	49,261	15,145	190,699
2005	8,933	55,709	28,269	273,372
2010	10,897	67,246	48,493	423,830
2015	12,635	73,549	76,885	592,638
2020	15,950	95,098	107,727	1,020,887
2023*	18,000	108,000	126,000	1,280,000

*Estimated

The resource temperature along with a sustainable flow rate and fluid chemistry will determine the best and most economical use of the resource. The following temperatures are general guidelines for the use of a geothermal resource. However, for these cases the temperature range can vary depending on the location.

- >175°C (350°F) – dry steam and flash steam electric power generation
- 100 to 175°C (212 to 350°F) - binary electric power generation
- 100 to 150°C (212 to 300°F) – industrial process heating/cooling
- 60 to 100°C (140 to 212°F) – space heating
- 30 to 60°C (90 to 140°F) – greenhouse and aquaculture pond heating
- 5 to 30°C (40 to 90°F) - geothermal (ground-source) heat pumps

2. Geothermal Electric Power Generation

The first geothermal power generation was from a reciprocating steam engine powered by geothermal steam at Larderello, Italy on 4 July 1904 under the supervision of Prince Piero Ginori Conti. It lit four light bulbs. By 1905 the power had been increased to 20 kWe and the first commercial power plant of 250 kWe was built there in 1913. By 1916 it distributed 2,750 kWe of electricity to the surrounding cities. Italy was the world's only industrial producer of geothermal electricity until 1958.

In 1958 New Zealand became the second country to produce geothermal electricity at Wairakei on North Island using wet steam to generate 11.2 MWe. This was followed by the first geothermal power plant in Mexico at Pathė, Acambay in 1959 at 3 MWe. In the USA, Pacific Gas and Electric began operation of the first geothermal power station in the country located at The Geysers in northern California in 1960 at 11 MWe.

The first binary cycle power plant was demonstrated in 1967 at Paratunka, in Kamchatka, Siberia, Russia at 750 kWe. Binary geothermal power was introduced in the USA in 1981 at Heber in southern California at 45 MWe. These were followed by geothermal binary plants in Japan and Iceland in 1966 and China in 1970. These plants use a secondary working fluid, a hydrocarbon, heated by low temperature geothermal fluid producing a vapor used to turn the generator for electricity (Figure 1).

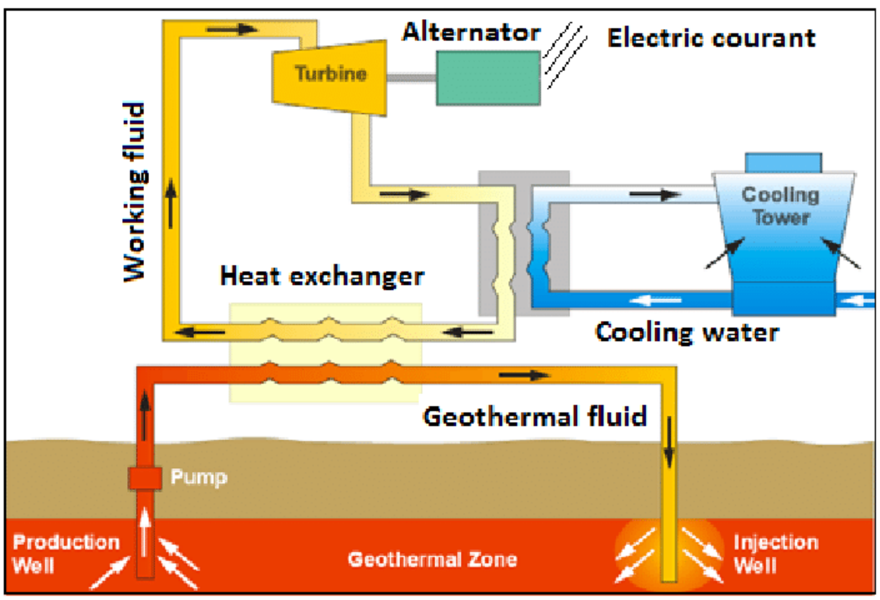

Figure 1: Binary power cycle diagram.

In 2020, 29 countries produced electricity 95,098 GWh/yr from geothermal resources, from an installed capacity of 15,950 MWe. From 2015 to 2020 geothermal electricity had the highest growth rate compared to other periods, amounting to 26.2% in MWe and 29.3% in GWh/yr. By 2023, it is estimated that geothermal power and generation has increased to 108,000 GWh/yr and 18,000 Mwe and 108,000 GWh/yr. See Table 2 for a summary of data from 2020 for countries producing greater than 100 MWe.

Table 2: Installed and generating capacity for geothermal worldwide >100 MWe in 2020

Country	MWe	GWh/yr
USA	3,700	18,366
Indonesia	2,289	15,315
Philippines	1,918	9,893
Turkey	1,549	8,168
Kenya	1,193	9,930
New Zealand	1,064	7,728
Mexico	1,006	5,375
Italy	916	6,100
Iceland	755	6,010
Japan	550	2,409
Costa Rica	262	1,559
El Salvador	204	1,442
Nicaragua	159	492
Total*	**15,950**	**95,098**

*29 countries

Electricity produced is a better measure of the geothermal contribution than installed capacity, since geothermal plants usually operate at a higher capacity factor, around 95%, than other types of power plants. Unfortunately, geothermal energy only contributes less than 0.4% of the world's electricity.

3. Geothermal Direct Utilization

Direct utilization (direct use) of geothermal energy is one of the oldest, most versatile, and most common form of utilizing this resource (Dickson and Fanelli, 2003/2013). The early history of geothermal direct use was reviewed from over 25 countries in: *Stories from a Heated Earth – Our Geothermal Heritage* (Cataldi et al., 1990). The information presented here is based on country update papers submitted to the various World Geothermal Congresses that are held every five years from 1995 to 2020. Data has been estimated to 2023 by the authors. The number of countries reporting direct use has increased from 28 in 1995 to 88 in 2020. The thermal capacity and produced thermal energy in these years have increased from 8,664 MWt and 112,441 TJ/yr to the present figure of 107,727 MWt and 1,020,887 TJ/yr (283,580 GWh/yr) with annual increases of 10.61% and 9.23% respectively. This is estimated to have increased by 2023 to 126,000 MWt and 1,280,000 TJ/yr. The average worldwide capacity factor over the past 25 years is 0.327, indicating 2,866 full-load equivalent capacity hours per year. More detailed information on geothermal direct use can be found in *Geothermics Volume 90* by Lund and Toth, 2021.

The authors have relied on country update reports from World Geothermal Congress (1995-2020), as well as from five *Geothermics* publications (Lund and Freeston, 2001; Lund et al., 2006; 2011; Lund and Boyd, 2016; Lund and Toth, 2021) along with reports from the European Geothermal Congresses in 2007, 2013, and 2019, together with information gained from personal communications.

The worldwide leaders in direct use of geothermal energy including geothermal heat pumps for 2020 are shown in Tables 3 and 4. Tables 5 and 6 show data by various categories and by regions.

Table 3: Leading countries in 2020 in terms of installed capacity including geothermal heat pumps (>2,000 MWt)

Country	MWt	Major uses
China	40,610	Bathing, district heating
United States	20,713	Heat pumps, bathing
Sweden	6,680	Heat pumps, district heatings
Germany	4,806	District heating, heat pumps
Turkey	3,488	District heating, bathing
France	2,597	Heat pumps, district heating
Japan	2,570	Bathing, heat pumps
Iceland	2,373	Bathing, district heating
Finland	2,300	Heat pumps
Switzerland	2,197	Heat pumps, space heating

Table 4: Leading countries in 2020 in terms of annual energy use including geothermal heat pumps (>12,000 TJ/yr)

Country	TJ/yr	Major uses
China	443,492	Bathing, district heating
United States	152,110	Heat pumps, bathing
Sweden	62,400	Heat pumps, district heatings
Turkey	54,584	District heating, bathing
Iceland	33,598	Bathing, district heating
Japan	30,723	Bathing, heat pumps
Germany	29,139	District heating, heat pumps
Finland	23,400	Heat pumps
France	23,280	Heat pumps, district heating
Canada	14,512	Heat pumps, bathing
Switzerland	13,292	Heat pumps, space heating
Norway	12,610	Heat pumps

Table 5: Summary of direct use by various categories for 2020

Utilization	Capacity MWt	Utilization TJ/yr	Capacity Factor
Geothermal heat pumps	77,547	599,981	0.245
Space heating/district heating	12,768	162,979	0.405
Bathing and swimming	12,253	184,070	0.472
Greenhouse heating	2,459	35,826	0.462
Aquaculture pond heating	950	13,573	0.463
Industrial uses	852	16,390	0.610
Agriculture drying	257	3,529	0.435
Cooling/snow melting	435	2,589	0.189
Others	106	1,960	0.584
Total	**107,627**	**1,020,897**	**0.300**

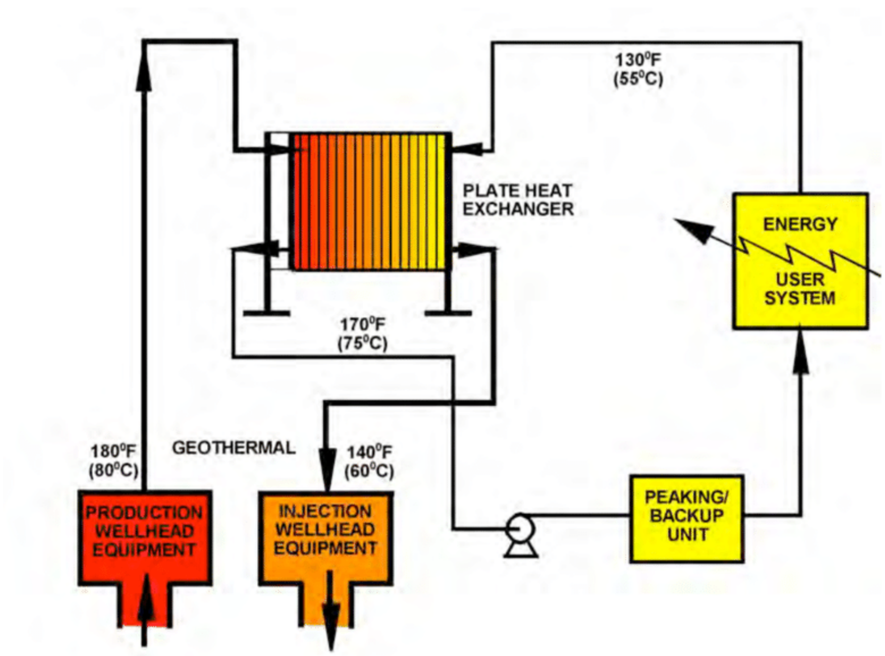

Figure 2. Geothermal direct use diagram.

Table 6: Summary of direct use data worldwide by region and continent for 2020 (Indicates number of countries)

Region/Continent	MWt	TJ/year	GWh/year	Capacity
Africa (11)	198	3,730	1,036	0.597
Americas (17)	23,330	180,414	50,115	0.245
Central America and	9	195	54	0.687
North America (4)	22,700	171,510	47,642	0.24
South America (8)	621	8,709	2,419	0.445
Asia (18)	49,079	545,019	151,394	0.352
Commonwealth of	2,121	15,907	4,419	0.238
Europe (34)	32,386	264,843	73,568	0.259
Central and Eastern Europe	3,439	28,098	7,805	0.259
Western and Northern	28,947	236,745	65,762	0.259
Oceania (3)	613	10,974	3,048	0.568
Total (88)	**107,727**	**1,020,887**	**283,580**	**0.300**

Based on data from the European Geothermal Congress (EGC) (Sanner et al, 2022), the geothermal power generation capacity of the 32 European countries, totaled about 3,496 MWe, while the geothermal heating from medium to low temperature sources exceeded 11,600 MWt. About half of that is used for district heating. Regarding shallow geothermal energy, including ground source heat pumps (GSHP) and Underground Thermal Storage (UTES), direct use capacity of at least 30,300 MWt was achieved by the end of 2021, distributed over about 2.1 million installations. In Europe, Turkey is a new leader, having very dynamic developments with 17 geothermal district heating systems in operation serving the equivalent of 116,000 residents. There are also six major greenhouse areas covering 4.3 million square meters, mainly growing tomatoes, most of which are sold internationally. In addition, twenty million local and 20,000 foreign visitors annually enjoy the balneological uses of Turkey's geothermal waters.

The former Soviet Union dominated countries in eastern Europe, comprising of Bulgaria, the Czech Republic, Hungary, Lithuania, Macedonia, Poland, Romania, Servia, Slovakia, Slovenia, and Ukraine, have never been energy independent. They have always had to import the energy they needed, mainly from Russia. Thus, these countries' overall energy consumption has dropped to levels not seen since the 1970s due to lack of funding and leadership. However, more recently, the shallow geothermal direct use sector has grown steadily, but very slowly in Eastern Europe with Poland in the lead. Hungary has shown some strong direct use development, especially in the district heating and agricultural sectors. A summary of the former Soviet Union countries in eastern Europe using ground source (geothermal) heat pumps is based on the Summery of EGC 2022 Country Update Reports on Geothermal Energy in Europe by Sanner et al, 2022. It is shown in Table 7.

Table 7: Ground Source Heat Pumps use in the leading former Soviet Union Countries in 2022 (Sanner et al, 2022)

Country	Number GSHP	Capacity MWt	Production GWh/yr
Poland	78,480	900	1,200
Czech Republic	22,740	320	472
Slovenia	14,818	237	329
Lithuania	10,647	140	314
Hungary	7,353	81	161
Slovakia	10	2	14
Ukraine	43,700	1,600	1,316
Serbia	2,850	53	117
Macedonia	1,000	3	21
Romania	600	40	100
Bulgaria	n/a	n/a	1,174

4. Summary and Conclusions

Although the number of countries now using geothermal energy to generate electricity is still small in comparison to the many countries that use geothermal resources for direct use such as for space and district heating, agricultural, aquaculture, and industrial processes, there are new nations producing geothermal electricity since 2015. These include Belgium, Chile, Honduras, and Hungary. By 2023 we may see small geothermal power on-line in Argentina, Australia, Canada, China, Dominica, Ecuador, Greece, Iran, Montserrat, Nevis, Saint Lucia, Saint Vincent, and Taiwan. In the East African Rift Zone, Malawi, Rwanda, Tanzania, and Uganda, are also trying to bring electric plants on-line. In the last five years, there has also been increased attention shown to the possibility of developing Engineered Geothermal Systems (EGS) to tap the vast thermal energy resources trapped in rocks of low natural permeability. This work is proceeding in the USA, Iceland, Great Britain, Germany, China, Portugal, Denmark, and The Netherlands.

Overall, it appears that the initial, high-risk phases of new and expanded uses of geothermal resources are being funded by federal government agencies, quasi-federal entities, and international multilateral lending banks rather than private industry. Turkey, the Philippines, and the USA appear to be the only exception to this trend. The early-stage involvement of public funds is a way to mitigate the risks perceived by private investors. Once suspected resources have been discovered, characterized and, their extent preliminarily delineated, projects can be transferred to the private sector for the necessary confirmation, development and production as the risk has been reduced.

The countries that stand out as major producers and consumers of geothermal fluids for direct use are listed in Table 3. In most countries, however, development has been slow as fossil fuels are a major competitor. Another obstacle is the high initial investment costs for geothermal projects. Countries where geothermal direct use provides a significant contribution to their energy needs are summarized in Table 8. The distribution of geothermal use by continent is shown in Table 9, indicating that Asia and Europe are the leaders, with 57 of the 88 countries reporting that they provide 77.5 % of the world's installed capacity (MWt) and 80.8% of the direct uses (TJ/yr).

Table 8: Significant contributions of direct use geothermal energy to a country's economy

Iceland	90% of buildings space heated
Japan	2,000 onsens, 5,000 public baths, 1,500 hotels serving 15 million guest/year
Sweden	40% of buildings heated using geothermal heat pumps
Switzerland	110,000 geothermal heat pumps installed (~3.7 units/sq. km)
Tunisia	244 ha of heated greenhouses
Turkey	116,000 apartments/residences heated in 17 cities
USA	Approximately 1.685 million geothermal heat pumps (4.0% growth/year)

Table 9: Distribution of direct use geothermal energy utilization by continent

Continent	Countries	%MWt	%TJ/year
Africa	11	0.2	0.4
Americas	17	21.7	17.7
Asia	19	45.6	53.4
Europe*	38	31.9	27.4
Oceania	3	0.6	1.1

* Includes CIS Countries (Georgia, Russia and Ukraine)

With the increased interest in geothermal deep drilling for direct use and ground-source heat pumps, it is now evident that geothermal energy can be developed anywhere for both heating and cooling. Heat pumps now make up 72.0% of the installed capacity (MWt) and 58.5% of the annual energy use (TJ/yr). This use has increased since 2015 by 54% of installed units reported. Low-to-moderate temperature geothermal resource are also being used in combined heat and power plants (CHP), where hot water, often with temperatures below 100ºC, is first run through a binary (organic Rankine cycle) power plant, then cascaded for direct uses, before being injected back into the aquifer. GHP projects can maximize resource use, while improving the return on investment. This has been shown in Iceland, Austria, Germany, as well as on the Oregon Institute of Technology Campus in the USA.

Approximately US$ 22.262 billion was reported as invested in geothermal energy by 53 countries during the period 2015-2019 for both electric power (64%) and direct use (36%). The average was US$ 420 million per country, with countries investing over US$ 500 million being Indonesia, Turkey, China, Taiwan, Kenya, Republic of Korea, Mexico, Chile, and Italy (in descending order). Investments were 27.9% for electric power utilization in 16 countries, 15.4% for direct use in 30 countries, 32.4% for field development including production drilling and surface equipment in 33 countries, and 24.3% for R&D including surface exploration and exploratory drilling in 47 countries. The following are the percentages of the worldwide geothermal investments and funding by continents (total US$22.262 billion). The world summary by country of ground source (geothermal) heat pumps ≥ 15.000 units are shown in

Table 10. A total of 54 countries/regions report using geothermal heat pumps, with a average unit size of 12 kW.

- 6.3% in Africa by 7 countries (US$1.412 billion)
- 10.2% in the Americas by 11 countries (US$2.275 billion)
- 74.2% in Asia by 11 countries (US$16.506 billion)
- 8,7% in Europe by 22 countries (US$1.926 billion)
- 0.6% in Oceania by 2 countries (US$0.143)

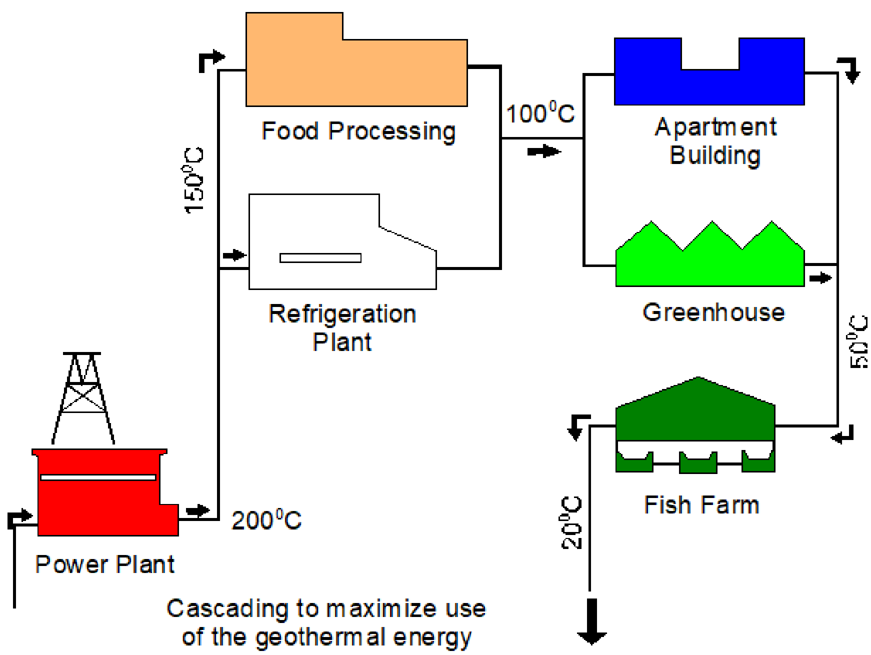

Figure 3. Cascading of geothermal power and direct use.

Table 10: Worldwide leaders in geothermal (ground-source) heat pumps in 2020 (≥15,000 units)

Country	Units	MWt	TJ/yr	GWh/yr	L.F.
United States	1,686,000	20,230	145,460	40,406	0.23
China	1,000,000	26,450	246,212	68,392	0.30
Sweden	591,000	6,680	62,400	17,333	0.30
Germany	382,000	4,400	23,760	6,600	0.17
Canada	200,000	1,831	14,512	4,031	0.25
France	174,800	2,015	12,600	3,500	0.20
Norway	150,000	1,700	10,800	3,000	0.20
Finland	140,000	2,300	23,400	6,500	0.32
Brazil	110,000	1,300	6,622	1,839	0.16
Netherlands	60,354	1,400	10,860	3,017	0.25
Poland	56,000	700	3,500	972	0.16
Denmark	40,000	350	3,500	972	0.32
Ireland	18,092	201	937	260	0.15
Austria	15.000	1,000	6,309	1,752	0.20
Worldwide total	**4,608,261**	**70,557**	**570,872**	**158,574**	**0.23**

As oil and gas supplies dwindle and increase in price, geothermal energy becomes a more economically viable alternative energy source. Even though the initial cost of developing a geothermal resource is high (exploring, drilling well, constructing pipelines and plants), the long-term cost is low. Compared to 2015, geothermal direct use has doubled its contribution to the world's annual energy mix from about 0.13 to 0.27%. As geothermal energy becomes more competitive with fossil fuels, especially if carbon penalties are applied to the price, and the environmental benefits are better understood and accepted, development of this natural "heat from the earth" should accelerate. An important task for all of us in the geothermal community is to spread the word about geothermal energy, its various applications, and the many environmental benefits that can accrue from its use.

5. The Future of Geothermal Energy.

Geothermal energy use is trending as follows (Lund et al., 2006, 2021).

- Lower temperature down to 90ºC is now possible for economic power generation
- Electrical units less than 1 MWe becoming economical.
- Lower temperature resources can be made economical such combined uses as:
  - power generation and space heating
  - power generation and industrial applications
- Lower temperature resources <90ºC, are becoming more economical for green-houses, aquaculture, and drying agricultural products such as fruit and vegetables.
- Geothermal ground-source heat pumps are becoming more popular and economic with over 6.5 million units presently installed worldwide. These units provide both heating and cooling and only need a 5º to 30ºC temperature resource, which are typical ground temperatures in most of the world.

6. References

Dickson, M. H., Fanelli, M. Geothermal Energy: Utilization and Technology, UNESCO, Paris, 2003. 205 p.

Cataldi, R., Hodgson, S.F., Lund, J.W., 1999. Storied from a Heated Earth – Our Geothermal Heritage, Geothermal Resources Council, Davis, CA, 569 p.

European Geothermal Congress 2007, Unterhaching, Germany, Proceedings.

European Geothermal Congress 2013, Pisa, Italy, Proceedings.

European Geothermal Congress 2019, The Hague, The Netherlands, Proceedings.

European Geothermal Congress 2022, Berlin, Germany, Proceedings.

Lund, J.W., Boyd, T.J., 2016. Direct Utilization of Geothermal Energy 2015 Worldwide Review, *Geothermics* 60, Elsevier, pp. 66-93.

Lund, J.W. and Freeston, D.H., 2000. World-Wide Direct Uses of Geothermal Energy 2000, Proceedings World Geothermal Congress 2000 Kyusu, Japan, May 28-June 10 2000.

Lund, J.W. and Freeston, D.H., 2001. World-Wide Direct Uses of Geothermal Energy 2000, *Geothermics*, 30, Elsevier, pp.29-68.

Lund, J. W., Freeston, D. H., Boyd, T. J., 2006. Direct Applications of Geothermal Energy, 2005, Worldwide Review. *Geothermics*, 34, Elsevier, pp. 691-727.

Lund, J. W., Freeston, D. H., Boyd, T. J., 2010. Direct Utilization of Geothermal Energy 2010 Wordwide Review, Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010.

Lund, J.W., Freeston, D.H., Boyd, T.J., 2011. Direct Utilization of Geothermal Energy, 2010 Worldwide Review. *Geothermics*, 40, Elsevier, pp. 159-180.

Lund, J.W., Bertani, R. Boyd, T.J., 2015. Direct Utilization of Geothermal Energy 2015 Worldwide Review, Proceedings World Geothermal Congress 2015 Melbourne, Australia 19-24 April 2015.

Lund, J. W., Toth, A.N., 2021. Direct Utilization of Geothermal Energy Worldwide Review. *Geothermics*, 90, Elsevier, pp. 1-31.

Sanner, B., Antics, M., Baresi, M., Urchuegula, J.F., and Dumas, F.: Summary of EGC 2022 Country Update Report on Geothermal Energy in Europe, European Geothermal Congress 2022, Berlin, Germany, 13 p.

World Geothermal Congress 1995, Roma, Italy, Proceedings.

World Geothermal Congress 2000, Kyushu-Tohoku, Japan, Proceedings.

World Geothermal Congress 2005, Antalya, Turkey, Proceedings.

World Geothermal Congress 2010, Bali, Indonesia, Proceedings.

World Geothermal Congress 2015, Melbourne, Australia, Proceedings.

World Geothermal Congress 2020+1, Reykjavik, Iceland, Proceedings.