Historical Pattern Analysis of Global Geothermal Power Capacity Development

Preprint

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Historical Pattern Analysis of Global Geothermal Power Capacity Development

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Keywords

Geothermal power plants, Historical development, Installed Power, Pattern analysis, Sustainable exploitation.

ABSTRACT

Between 1913 and 1958, Italy was the only country with an operational geothermal power plant until New Zealand installed its first plant in 1958. At present, 24 countries are involved in the geothermal power market, and they have a combined installed capacity of 16,127 GW. This study analyzes the historical patterns of geothermal power capacity in the world and in individual countries to investigate the ideal global geothermal development pattern by examining the annual cumulative capacity (ACC) and the annual capacity addition (ACA) graphs of the historical development of geothermal power capacity in 24 countries. First, the global patterns are analyzed using these graphs in five periods (1945–1957, 1958–1976, 1977–1991, 1992–2002, and 2003–2020) that are marked by a series of characteristics of ACA peaks separated by two major troughs. Then, five characteristic patterns are developed in five periods globally. These patterns correspond to the early-stage linear, the first acceleration, the first steady-state linear, the second acceleration, and the second steady-state linear developments. A positive relationship exists between global patterns and the 5-year shifted oil-price curve: two major factors influenced global development: 1) increasing oil prices and increasing awareness of global climate change, and 2) global development of geothermal power. Last, we investigate these patterns in each country. The top ten countries, which comprise 93.3% of the world's total installed capacity are separated into five groups based on the availability and characteristics of patterns globally developed in five periods. Group-1 (the United States) has an installed capacity of 3,794 MW, Group-2 (Mexico and Philippines) 963–1935 MW, Group-3 (New Zealand, Italy, Iceland, and Japan) 601–1,037 MW, and Group-4 (Indonesia, Kenya, and Türkiye) 944–2,356 MW. The remaining 14 countries (6.7%), which are called Group 5, are still in an immature stage and have installed capacities of 7–262 MW and are not involved in pattern analysis. Overall, geothermal power in the world is in its third stage of development, which had its peak development after 1977. A fourth development peak may be expected to occur after this through business-as-usual cases. The biggest barrier to the development of the global geothermal power market is the risk associated with exploration and drilling. If risk mitigation systems and funds are employed, the growth of geothermal power production projects could accelerate.

1. Introduction

Global efforts to establish a sustainable energy regime within the scope of energy transition from fossil fuels to renewables accelerated recently. The year 2015 marked a turning point in the development of a sustainable green economy in the world with internationally approved Sustainable Development Goals (SDGs) and the Paris Agreement on climate change. The 17 interlinked SDGs that were designed to achieve a sustainable future for all were adopted by all United Nations (UN) member states (UN 2015). Goal 7, which is dedicated to "ensure access to affordable, reliable, sustainable and modern energy for all," refers mostly to the infrastructure of energy, its origin, and energy consumption (SDG 2018). The Paris Agreement, which aims to limit global warming to 1.5°C, targets net-zero emission by 2050 (IPCC 2018). Several signatory states have already declared targets in line with their commitments to global climate action under this legally binding international treaty (IRENA 2021). These targets and goals were implemented for the first time by the European Green Deal program declared in 2019 (EC 2019).

The transition to sustainable energy has basically two key components: (1) increasing the use of renewable energy by accelerating the deployment of new technologies and (2) decreasing energy consumption by improving energy efficiency (Ediger 2021). Experts generally agree that geothermal energy is an attractive option to replace fossil fuels, to help mitigate climate change, and that it can play a significant role in an ongoing energy transition (Axelsson 2010; Fridleifsson et al. 2008; Khan 2021; Mock et al. 1997; Rybach 2003). Also, geothermal energy is included and encouraged in the European Strategic Energy Plan and in the Paris Agreement (Pellizzone et al. 2017).

Several authors have noted the advantages of geothermal energy, including that (1) it has benign environmental attributes with low emissions of greenhouse gases (GHGs) and a minor and controllable environmental impact from production and use (Fridleifsson et al. 2008; Linga 2019; Mock et al. 1997; Rybach 2003), (2) it is not variable and it has almost constant capacity factors throughout the year, which lead it to be used as a base load (Fridleifsson et al. 2008; Linga 2019; Mock et al. 1997; Winston 2008), (3) it is simple, safe, and adaptable with modular small-scale plants (Mock et al. 1997), (4) it has operation and maintenance costs lower than other renewables (Fridleifsson et al. 2008; Linga 2019), and (5) its resource potential is high and only a small fraction of this potential has yet been developed (Fridleifsson 2001; Mock et al. 1997). On the other hand, geothermal energy also has some disadvantages including that (1) it is limited to areas with suitable hydrothermal resources (Linga 2019), (2) it has higher capital costs (Linga 2019), (3) it carries investment risk because of long project lead times and payback periods (Linga 2019), and (4) there are concerns about local support for geothermal technologies (Pellizzone et al. 2017; Pellizzone et al. 2016).

Also, geothermal energy technologies are much less familiar to the public than other renewable technologies (Manzella 2018). Environmental organizations in various countries have warned geothermal companies about inadequately considering water and air quality impacts (Winston 2008). Public awareness and perception of geothermal energy continue to be crucial to the future of the geothermal sector. As Richter (2019) has stated, "Essentially the public is not as aware of what geothermal energy has to offer compared to other renewables." In public surveys about citizen's perception of geothermal energy in Italy, it was shown that "knowledge and understanding of the potential of geothermal are remarkably low" (Pellizzone et al. 2017) and "lack of trust in politics and unsure public communication emerged as prominent themes where the common good and community developments are sharply contrasted with corporate and private interests" (Pellizzone et al. 2016).

Geothermal energy has a history much longer than many renewable energy technologies such as solar, wind, or biopower. The first commercial geothermal power plant was established in 1913 in Italy, and by 2022, the total geothermal installed capacity of the world had increased to 16,127 MW. Though their contribution to the world's electricity generation is significant, it is still limited. According to BP energy outlook, the world's electricity generation in 2020 was 26,823.2 TWh of which 11.7% was from renewable energy sources (BP 2021). Having taken new data from World Geothermal Congress 2020 Country Update reports and from private communications with International Geothermal Association members and affiliated organizations, Huttrer (2020) calculated that geothermal power plants provide 95,098 GWh (0.35%) of the 26,823 GWh. However, geothermal energy has significant potential with 1,159 wells drilled for power projects, $10,4B project investment, and 30,491 person-years allocated to power projects between 2015 and 2020 (Huttrer 2020). The future of geothermal energy will depend on its sustainable production and utilization (Shortall et al., 2015), and by taking some measures, this can be achieved (Axelson 2012; Hackstein and Madlener 2021; Ketilsson et al. 2010; Rybach 2007).

To be able to evaluate the future development of geothermal power, its past trends at the global and country level should be well understood. Therefore, this study analyzes the historical patterns of geothermal power capacity in the world and in individual countries. We ask three main research questions: Are there some common patterns of geothermal power plant development in the world? Can countries be placed in subgroups based on these patterns? What are the factors affecting the patterns? We thus aim to investigate the ideal global geothermal development pattern by examining types of graphs of the historical development of geothermal power capacity in 24 countries such as: (1) annual cumulative capacity (ACC), which is the time series of cumulative installed capacities in each year and (2) annual capacity addition (ACA), which is the time series of yearly capacity additions. These two parameters are the most significant parameters that can be used to evaluate the success of countries' strategies and policies in developing geothermal power.

Installed capacity data for geothermal energy start in 1945 because geothermal power stations and chemical plants, which existed only in Italy before then, were heavily bombed and destroyed during World War II (Burgassi 1987; Otte 1957). All available historical data on the installed capacities of 24 countries were compiled by extensively surveying the existing sources in the field. The start dates and initial capacities of the pilot and commercial plants are given in Table 1.

Table 1. First pilot and commercial geothermal power plants by country

		Test Production	Commercial Production	
Year	Country	Pilot Plant	Geothermal Field	Installed Capacity (MW)
1913	Italy	0.1 MW in 1904	Larderello, Tuscany	0.3
1958	New Zealand	N/A	Wairakei	6.5
1960	United States	0.035 MW in 1930	The Geysers, California	11.0
1966	Japan	N/A	Matsukawa, Iwate Prefecture	23.0
1967	USSR	0.67 MW in 1967	Pauzhetka, Kamchatka	5.0
1969	Iceland	N/A	Nemafjall/Kisilidjan	3.0
1973	Mexico	3.5 MW in 1959	Cerro Prieto	37.5
1975	El Salvador	N/A	Ahuachapán	30.0
1977	China	0.3 MW in 1970	Yangbajing, Tibet	24.2
1977	Philippines	N/A	Tiwi field, Albay	3.0
1979	Indonesia	0.3 MW in 1978	Kamojang	30.0
1980	Portugal	N/A	Ribeira Grande, Azores Island	3.0
1983	Nicaragua	N/A	Momotombo	35.0
1984	Türkiye	0.5 MW in 1975	Kızıldere	17.4
1985	Kenya	N/A	Olkaria	45.0
1994	Costa Rica	N/A	Pailas	55.0
1998	Ethiopia	N/A	Aluto Lugano	7.2
2000	Guatemala	N/A	Orzunil	29.0
2003	Papua New Guinea	N/A	Lihir Island	6.0
2003	Germany	N/A	Neustadt-Glewe	0.2
2011	France	N/A	Guadeloupe	16.7
2017	Chile	N/A	Cerro Pabellón	24.0
2017	Honduras	N/A	Platanares	35.0
2018	Croatia	N/A	Velika Ciglena	10.0

Considerable literature exists on geothermal power. The Geothermal Paper Database prepared by the International Geothermal Association includes 18,157 technical papers written on geothermal power (IGA 2022). However, ours is the first study on the historical development of the world's geothermal power plants, and it will contribute to the existing literature. A complete list of installed capacities of commercial and pilot power plants established in 24 countries from 1904 to 2020 will be another important contribution of this study to the existing literature.

In this paper, the authors do not intend to give the history of geothermal energy production or the use of geothermal energy in either the world or in individual countries but instead try to investigate the correlation and the major dynamic between geothermal development in various countries. Importantly, we do not include electricity generation or capacity factor but rather deal with only installed capacities.

The paper is structured as follows. In the next section, a brief history of geothermal power in the world is given. The ranking of countries in each year from 2000 to 2020 and their changes depending on the paths they followed, as well as the pilot or demonstration plants and their roles in the development of commercial plants are investigated here. Section 3 is devoted to historical pattern analyses, which include the details of using ACC and ACA methodologies to analyze the global historical pattern and historical patterns for countries. The 24 countries are separated into 5 groups based on the availability and characteristics of patterns globally developed in Section 3. Finally, we discuss the results and conclude the paper in Section 4.

2. A brief history of geothermal power in the world

The first pilot and commercial geothermal power plants were established in Larderello, Italy, in 1904 and 1913, respectively (Otte 1957). It was not a coincidence that these plants were established in the Larderello area, as both the traditional direct use of geothermal fluid and the chemical industry started first in this region. Sulfur, vitriol, alum, and boric acid have been extracted from the hot springs in the Larderello area and marketed since the 11th century (Lund 2005).

Between 1913 and 1958, with only an interruption during World War II, Italy was the only country with operational geothermal power plants (Balddaci and Sabatelli 1999). The total installed geothermal power capacity reached 944 MW in Italy in 2020 (Huttrer 2020). In 1958, New Zealand became the second country in the geothermal market, when it established its first geothermal power plant. That plant reached an installed capacity of 1,005 MW in 2020 (Lund 2005; Thain 1998). In 1960, the United States entered the market, and in 2020, it became the country with the most capacity (3,680 MW) (Brophy et al., 2010; DOE, 2019; Robins et al., 2021).

Historical pattern analysis is conducted based on 2020 installed capacity. Number of countries involved in geothermal power increased linearly to 24 with the addition of 3 new countries each decade (Table 2). The ranking of countries in each year varied considerably, depending on the paths they followed. From 2000 to 2020, only the United States preserved its rank; four countries increased their rank, including Türkiye (up by 12 since 1984), Kenya (up by four since 1985), Indonesia (up by three since 1979), and New Zealand (up by two since 1985), and all other countries dropped in their rankings.

Only 7 of the 24 countries have established pilot or demonstration plants (PDPs). These plants have small installed capacities, varying from 35 kW (United States) to 3.5 MW (Mexico) before they start generating electricity commercially. PDPs, which operate discontinuously without being connected to the main power grid are usually established to partially demonstrate the feasibility of a technology (Hellsmark et al. 2016).

Table 2. Historical development of rankings in geothermal power capacity.

	1950	1960	1970	1980	1990	2000	2010	2020
1	Italy	N. Zealand	N. Zealand	U.S.	U.S.	U.S.	U.S.	U.S.
2		Italy	Italy	Philippines	Philippines	Philippines	Philippines	Indonesia
3		U.S.	U.S.	N. Zealand	Mexico	Mexico	Indonesia	Philippines
4			Japan	Japan	Italy	Italy	Mexico	Türkiye
5			Russia	Italy	N. Zealand	Indonesia	Italy	N. Zealand
6			Iceland	Mexico	Japan	Japan	N. Zealand	Mexico
7			China	El Salvador	Indonesia	N. Zealand	Iceland	Italy
8				Iceland	El Salvador	Iceland	Japan	Kenya
9				Indonesia	Nicaragua	Costa Rica	El Salvador	Iceland
10				Russia	Kenya	El Salvador	Kenya	Japan
11				Portugal	Iceland	Nicaragua	Costa Rica	Costa Rica
12				China	China	Kenya	Russia	El Salvador
13					Türkiye	Russia	Türkiye	Nicaragua
14					Russia	Guatemala	Nicaragua	Russia
15					Portugal	China	N. Guinea	N. Guinea
15						Türkiye	Guatemala	Guatemala
17						Portugal	China	Germany
18						Ethiopia	Portugal	Chile
19							Germany	Honduras
20							Ethiopia	Portugal
21								China
22								France
23								Croatia
24								Ethiopia

Our analysis of installed capacity data showed a relationship, but not a statistically significant one, between the year the PDP was established and the time that elapsed between the pilot plant and the commercial plant. Those establishment dates and elapsed time periods are 1930 and 30 years in the United States, 1959 and 14 years in Mexico, 1904 and 9 years in Italy, 1975 and 9 years in Türkiye, 1970 and 7 years in China, 1978 and 1 year in Indonesia, and 1967 and 0 years in Russia.

The time elapsed between the pilot plant and the commercial plant decreases as the establishment dates of the PDPs increases. The relationship represents a kind of learning curve, indicating that proficiency in technology usually increases with increased experience. However, five of these countries (United States, Indonesia, Türkiye, Mexico, and Italy) are also in the top seven countries at present, which may mean that establishing a PDP helped them develop their geothermal installed capacities more successfully than others. Another important observation is that no PDP was built after 1984, which may be related to the increasing maturation and commercialization of geothermal technologies through time.

3. Historical pattern analyses

The ACA and ACC curves are used together to analyze the global historical pattern and historical patterns for countries. In each case, the graphs are analyzed by separating them into periods and groups.

2.1 Global ACA and ACC curves

As seen in Figure 1, as ACA increases, the ACC curve naturally becomes steeper. Based on the steepness of ACC and the values of ACA, the world's historical geothermal capacity developments can be separated into 5 periods with different intervals from 1945 to 2020. Period 1 is between 1945 and 1957 (13 years), Period 2 is between 1958 and 1976 (19 years), Period 3 is between 1977 and 1991 (15 years), Period 4 is between 1992 and 2002 (11 years), and Period 5 is between 2003 and 2020 (18 years). Each period is marked by a series of characteristic of ACA peaks separated by two major troughs. These periods cover a total of 76 years and vary between 11 and 19 years with an average of 15.2 years. A total of 15,443.8 MW capacity was built from 1945 to 2020, and an average of 203.2 MW was added annually.

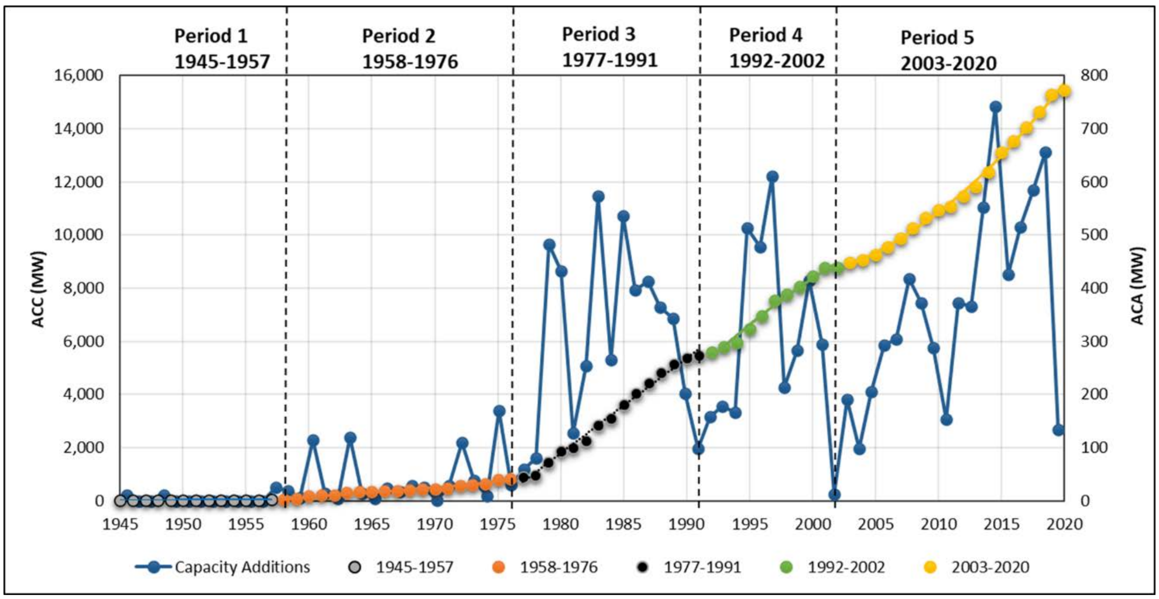

Figure 1. ACC and ACA curves, showing geothermal power development in the world between 1945 and 2020.

Significant data for the five periods are given in Table 3 Only Italy had geothermal power plants in Period 1. In this period, Italy increased its installed capacity from 11 MW to 47 MW with an annual average growth of 3.6 MW. In Period 2, the number of countries increased to 9 and a total of 776.5 MW of new capacity was added. The average annual addition increased to 40.9 MW in this period. In the following three periods, which are characterized by three irregular peaks in ACA, 94.7% of total installed capacity was made. In Period 3, the number of countries increased to 15 and capacity grew to 5,452.7 MW, of which 4,629.2 MW were new additions. The numbers of countries and new capacity additions were 18 and 3,321.2 MW in Period 4 and 24 and 6,669.9 MW in Period 5. Period 5 had the largest total and annual additions.

Table 3. Major characteristics of time periods with respect to geothermal growth.

Periods						Additions	
	Interval Years	# Years	# Countries	Beginning (MW)	End (MW)	Net Addition (MW)	Annual Average Growth (MW)
1	1945–1957	13	1	11.0	47.0	36.0	3.6
2	1958–1976	19	9	47.0	823.5	776.5	40.9
3	1977–1991	15	15	823.5	5,452.7	4,629.2	308.6
4	1992–2002	11	18	5,452.7	8,773.9	3,321.2	301.9
5	2003–2020	18	24	8,773.9	15,443.8	6,669.9	370.6

Each period is characterized by separate patterns in ACC and ACA such as the (1) early-stage linear development, (2) first acceleration in development, (3) first steady-state linear development, (4) second acceleration in development, and (5) second steady-state linear development. The average rates of growth of installed capacities are 0.6 and 10.2 MW per year in the first two periods, which are the initial stages of geothermal development in the world whereas the most noteworthy development in geothermal capacity building occurred in the remaining three periods which had average growths of 60.9, 43.7, and 87.8 MW per year.

The global ACA curve in general correlates well with the 5-year shifted oil-price curve (Figure 2). This shows that geothermal power plant investment decisions are made considering the oil prices. When oil prices increased, countries tended to substitute domestic energy resources for imported oil and gas by supporting investments in local energy resources such as geothermal. Because the average time elapsed between investment decision and commencement of power plants is around 5 years, increases in oil prices are reflected in the ACA curves 5 years later. The high ACA peaks in 1976–1991 and 2002–2020 are caused by the 1974 and 1980, and 2008 and 2011 oil crises, respectively.

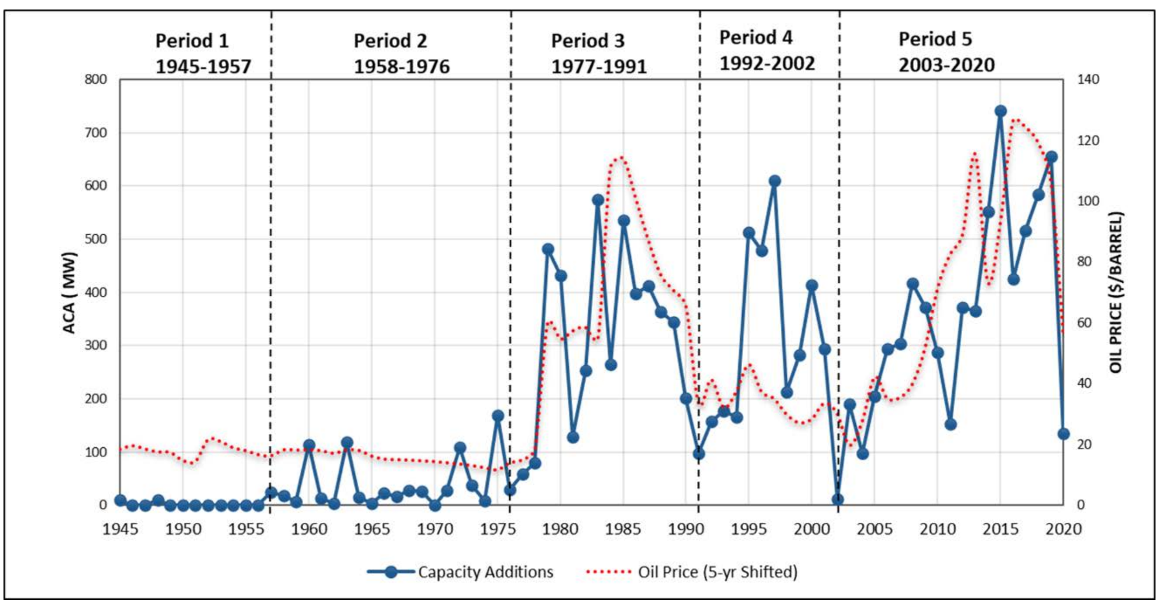

Figure 2. Correlation of global ACA curve with 5-year shifted oil-price curve.

The only period when both curves do not correlate is 1991–2002. In this period, while oil prices are stable the ACA curve has a significant peak and does not follow a similar pattern. This situation may be related to the global increase in international awareness of climate change and sustainable development as a result of several international events after 1987 such as (1) the 1987 release of Report of the World Commission on Environment and Development: Our Common Future (UN 1987); (2) United Nations Conference on Environment and Development (UNCED), informally known as the Earth Summit, in Rio de Janeiro, Brazil, in 1992; (3) the establishment of the headquarters of the United Nations Framework Convention on Climate Change (UNFCCC) in Bonn, Germany, in 1994; (4) first UNFCCC Conference of the Parties (COP 1) in Berlin, Germany, in 1995 (5) signing of the Kyoto Protocol in Kyoto, Japan, in 1997; and (6) World Summit on Sustainable Development (known as Earth Summit 2002 or Rio+10) in Johannesburg, South Africa, in 2002. The Age of Substitutability [substitution of domestic energy sources for imported oil (Goeller and Weinberg 1976)], started with oil price shocks in 1973–1974 and 1979–1980 and continued during the 1986¬1998 stable oil prices period (Ediger 2021; Ediger and Berk 2018).

2.2 ACA and ACC analysis of countries

The top 10 countries, which comprise 93.3% of the world's total installed capacity are separated into four groups based on the availability and characteristics of patterns globally developed in four periods (Fig. 3). The remaining 14 countries (6.7%), which are called Group 5, are still in an immature stage and have installed capacities of 7–262 MW. As of 2020, Group 1 (the United States) has an installed capacity of 3,676 MW, Group 2 (Mexico and Philippines) 963–1928 MW, Group 3 (New Zealand, Italy, Iceland, and Japan) 601–1,005 MW, and Group 4 (Indonesia, Kenya, and Türkiye) 861–2,131 MW.

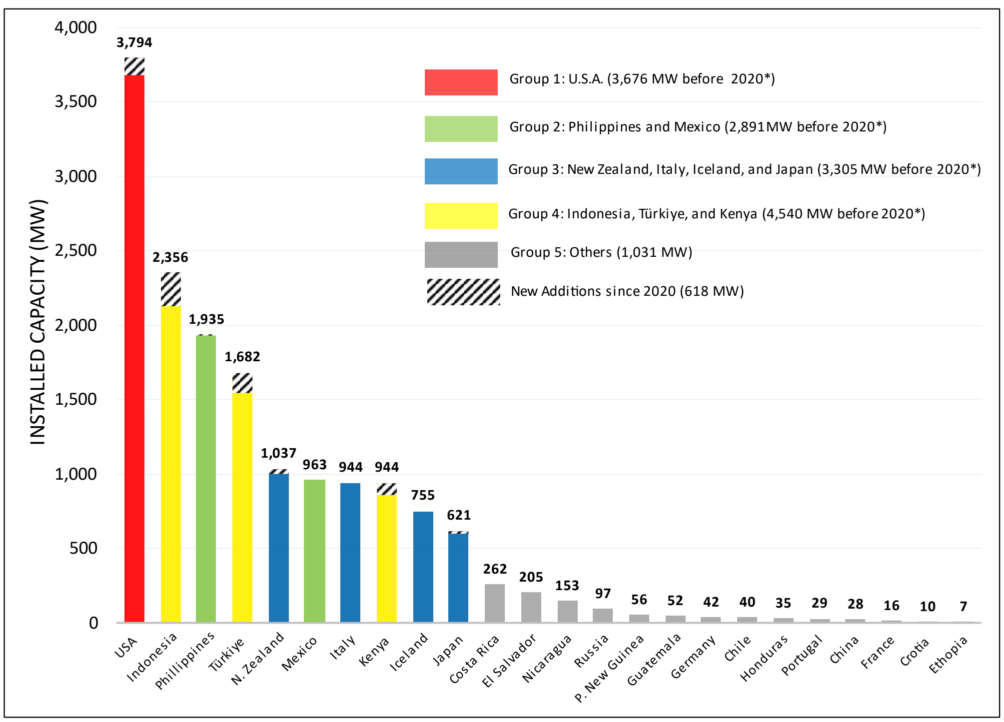

Figure 3. Selection of group of countries for ACA and ACC analysis of countries. ***(* Historical pattern analysis is conducted based on 2020 installed capacity.)***

The ACA and ACC graphs of the top 10 countries are shown in Figure 4 and Figure 5. The five periods, which were separated on a global level, do not fit exactly with all the countries because the global curves are an aggregate of 24 countries and the timing and scales of the periods are developed differently in each country because of domestic dynamics. Therefore, the geothermal development patterns of each group are analyzed separately to be able to understand whether the groups follow a similar pattern.

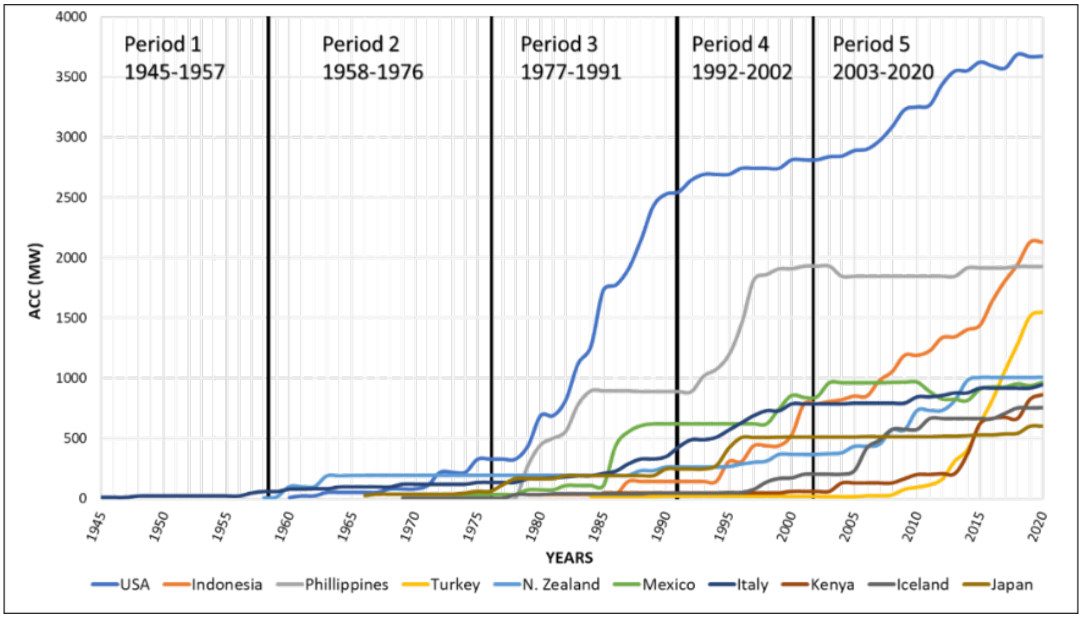

Figure 4. ACC curves for the top 10 countries overlain by global periods: Period 1 (1945–1957), Period 2 (1958–1976), Period 3 (1977–1991), Period 4 (1991–2002), and Period 5 (2003–2020).

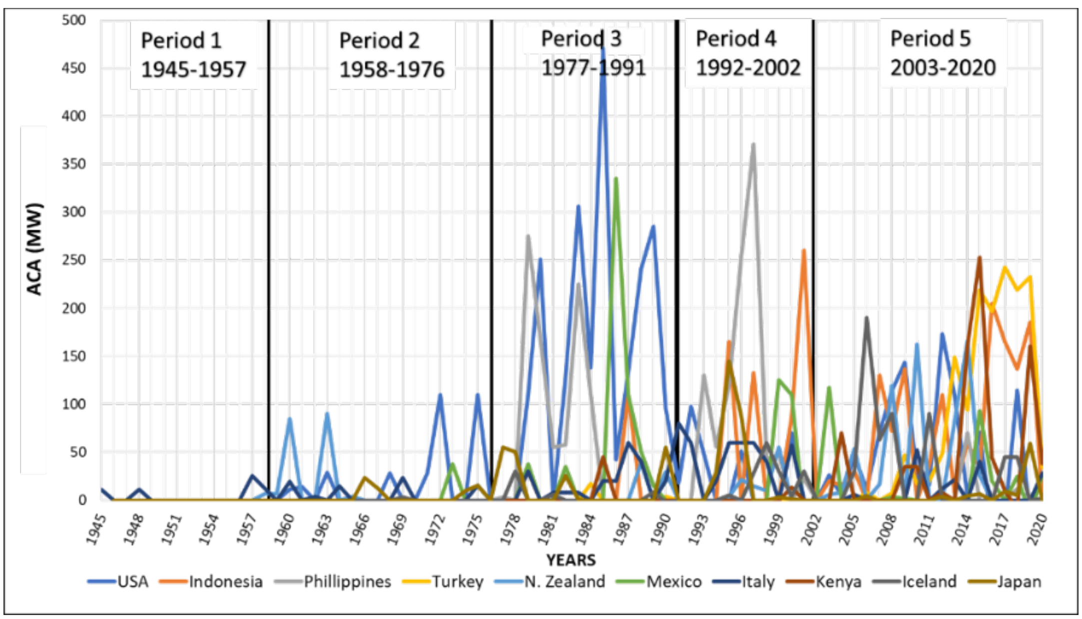

Figure 5. ACA curves for the top 10 countries overlain by global periods: Period 1 (1945–1957), Period 2 (1958–1976), Period 3 (1977–1991), Period 4 (1991–2002), and Period 5 (2003–2020).

Each period is characterized by separate patterns in ACC and ACA such as (1) the early-stage linear development, (2) the first acceleration in development, (3) the first steady-state linear development, (4) the second acceleration in development, and (5) the second steady-state linear development. The average rates of growth of installed capacities are 0.6 and 10.2 MW per year in the first two periods, which are in the initial stages of geothermal development. However, the most noteworthy development in capacity building occurred in the other three periods, where average growths were 60.9, 43.7, and 87.8 MW per year.

Table 4 summarizes the installed capacity data for the top 10 countries. The countries are grouped based on development patterns and categorized based on the total additions and the annual average addition within the boundaries of the defined periods using the ACA and ACC methods.

Table 4. Summary of installed capacity data for top 10 countries (periods are defined by ACA method and groups by ACC method).

	Period	**1st**		**2nd**		**3rd**		**4th**		**5th**		**Total**	
	Interval (years)	**1945–1957 (13)**		**1958–1976 (18)**		**1977–1991 (15)**		**1992–2002 (11)**		**2003–2020 (18)**		**1945–2020 (95)**	
Group	**Country (year of first commercial plant)**	**Addition (MW)**	**MW/Yr**	**Addition (MW)**	**MW/Yr**	**Addition (MW)**	**MW/Yr**	**Addition (MW)**	**MW/Yr**	**Addition (MW)**	**MW/Yr**	**Addition (MW)**	**MW/Yr**
1	United States (1960)	0.0	0.0	330.0	17.4	2,219.3	148.0	266.3	24.2	860.4	47.8	3,676.0	60.3
2	Philippines (1977)	0.0	0.0	0.0	0.0	888.0	59.2	1,043.0	94.8	-2.9	-0.2	1,928.1	43.8
	Mexico (1973)	0.0	0.0	37.5	2.0	582.5	38.8	223.0	20.3	120.0	6.7	963.0	20.1
3	New Zealand (1958)	0.0	0.0	192.0	10.1	69.0	4.6	104.4	9.5	639.6	35.5	1,005.0	16.0
	Italy (1913)	47.0	3.6	87.5	4.6	294.0	19.6	356.5	32.4	159.0	8.8	944.0	12.4
	Iceland (1969)	0.0	0.0	3.0	0.2	41.8	2.8	157.2	14.3	553.0	30.7	755.0	14.5
	Japan (1966)	0.0	0.0	60.5	3.2	185.1	12.3	265.6	24.1	89.8	5.0	601.0	11.6
4	Indonesia (1979)	0.0	0.0	0.0	0.0	140.0	9.3	645.0	58.6	1,345.5	74.8	2,130.5	38.7
	Türkiye (1984)	0.0	0.0	0.0	0.0	21.0	1.4	-3.0	-0.3	1,531.0	85.1	1,549.0	41.9
	Kenya (1985)	0.0	0.0	0.0	0.0	45.0	3.0	13.0	1.2	803.0	44.6	861.0	23.9
Top 10		47.0	3.6	710.5	37.4	4,485.7	299.0	3,071.0	279.2	6,098.4	338.8	14,412.6	189.6
Global		47.0	3.6	776.5	40.9	4,629.2	308.6	3,321.2	301.9	6,669.9	370.6	15,443.8	203.2

The five stages are also arranged in a periodical manner except the first one; the acceleration stages are followed by steady stages two times in both the top 10 and "global" (i.e., all 24 countries) (Figure 6). The average rates of growth increase first from Period 2 to Period 3, and then after a slight decrease from Period 3 to Period 4, they increase again from Period 4 to Period 5. The difference between the rates of growth of both the top 10 and all 24 countries also increase continuously at 0.9%, 1.3%, 3.3%, and 7.5% from Period 2 to Period 5.

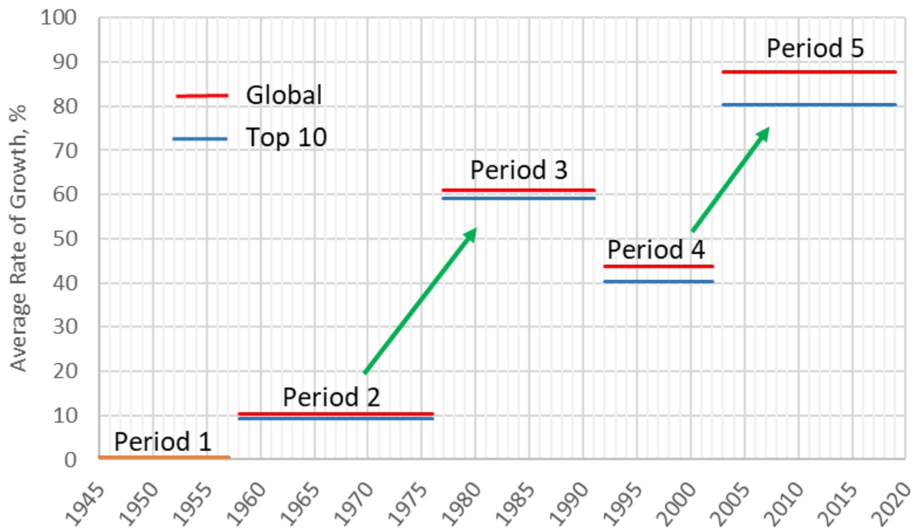

Figure 6. The average rate of growth in the top 10 and global (all 24 countries).

3.2.1. Group 1: The United States

Group 1 is represented only by the United States. Because the five complete patterns are developed well in the United States, it is used as a model country (Figure 7). The normalized curve of ACA in the United States starting from 1961 (the second year after the first operational power plant in The Geysers geothermal field in California) can be seen in Figure 8.

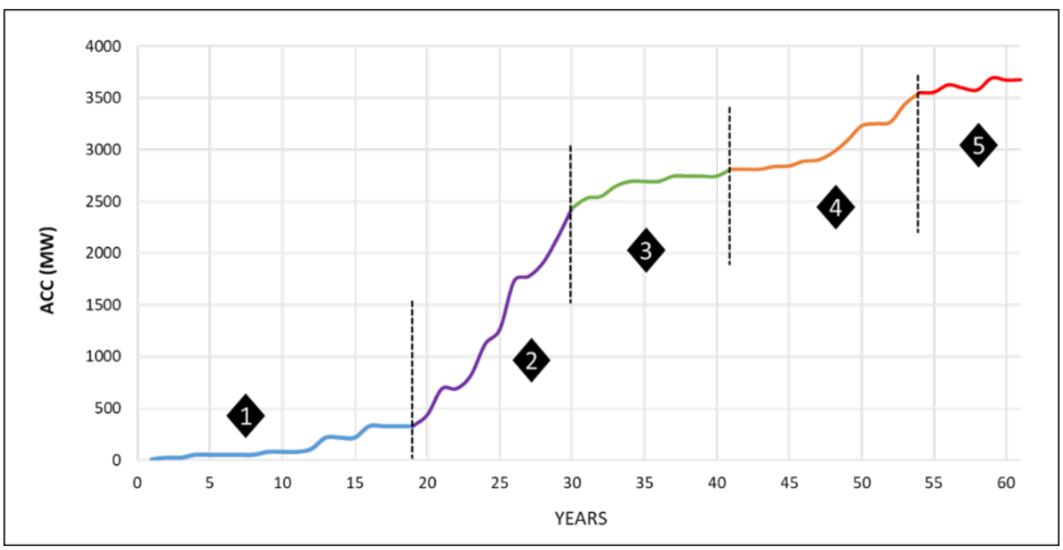

Figure 7. ACC curve and global patterns for geothermal power plants in the United States (black diamond 1 identifies the first pattern, black diamond 2 represents the second pattern, black diamond 3 t identifies the third pattern, black diamond 4 represents the fourth pattern, and black diamond 5 identifies the fifth pattern).

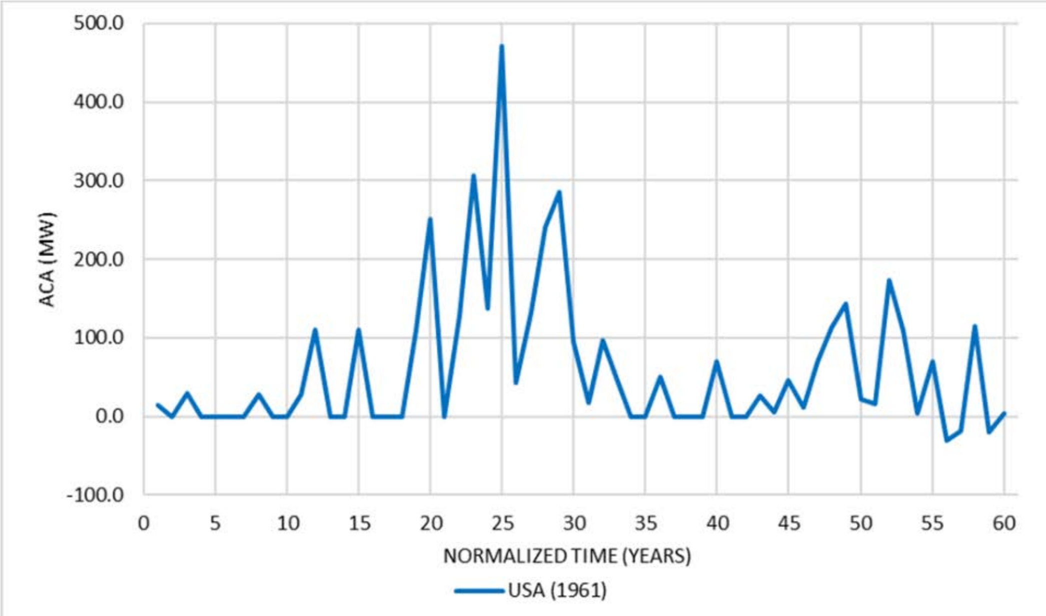

Figure 8. ACA curve for geothermal power plants in the United States (first data point corresponds to 1961 for the United States).

The United States has the highest installed geothermal power capacity and the highest proven geothermal resource potential in the world (DOE 2019). It entered the geothermal market with 11 MW in 1961(PG&E 2018), 30 years after a PDP was built in the Geysers area (Brophy et al. 2010). After 60 years of development, the total installed capacity reached 3,680 MW from 93 power plants in 2020 (DOE 2019; Robins et al. 2021). From the end of 2015 through the end of 2019, the United States brought seven new geothermal power plants online in California, New Mexico, and Nevada, adding 186 MW of nameplate capacity in that period. In the same period, 11 plants were retired or classified as nonoperational, subtracting 103 MW of nameplate capacity from U.S. capacity (Robins et al. 2021). Finally, geothermal installed capacity has been growing at about 2% per year, and it is projected to exceed 3.9 GW by 2022 (DOE 2019).

All five patterns are well developed in the United States. According to IRENA (2022), between 2010 and 2019, most of the patents on geothermal technology (106) were filed in the United States; only 40 were filed in Japan and 34 in France over the same period. The U.S. government's support of alternative energy sources after the 1973 oil crisis (following an embargo by the Organization of the Petroleum Exporting Countries) and the 1978 oil crisis (following the Iranian Revolution) has also been important in developing geothermal power in Period 3 (1976–1991). The Energy Tax Act of 1978 created the federal investment tax credit, which initially provided tax incentives for energy conservation and sources of energy alternatives to oil and gas. The investment tax credit was extended at the same level for geothermal for short periods through 1988 and 1989.

The Energy Policy Act of 1992 originally created the federal production tax credit to offer eligible wind plants tax credits in proportion to their electricity output during their first 10 years of operation. The credit originally did not include geothermal energy, but the American Jobs Creation Act of 2004 made geothermal energy and other qualifying resources eligible for the production tax credit for the first 5 years of operation. And the Energy Policy Act of 2005 increased that period to 10 years. The federal programs started in 2004 and 2005 continued to support the geothermal power development in the US. After the American Recovery and Reinvestment Act of 2009, another period of federal support for geothermal exploration and development occurred.

3.2.2. Group 2: Philippines and Mexico

Like Group 1 (the United States), Group 2 (Philippines and Mexico) has five complete patterns (Figure 9). Philippines (1977) follows the characteristics of the second pattern 6 years later than Mexico (1973). Thus, the time series data are normalized by shifting Philippines by 6 years, which results in a good correlation for the rest of the patterns. This correlation is also represented well in annual capacity additions (Figure 10).

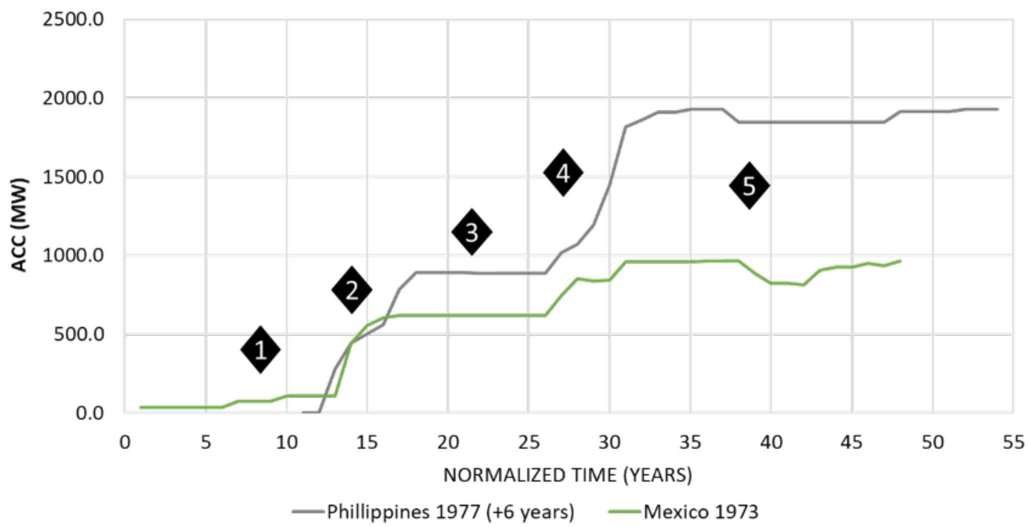

Figure 9. ACC curves and global patterns in Group 2 (black diamond 1 identifies the first pattern, black diamond 2 identifies the second pattern, black diamond 3 identifies the third pattern, black diamond 4 identifies the fourth pattern, and black diamond 5 identifies the fifth pattern).

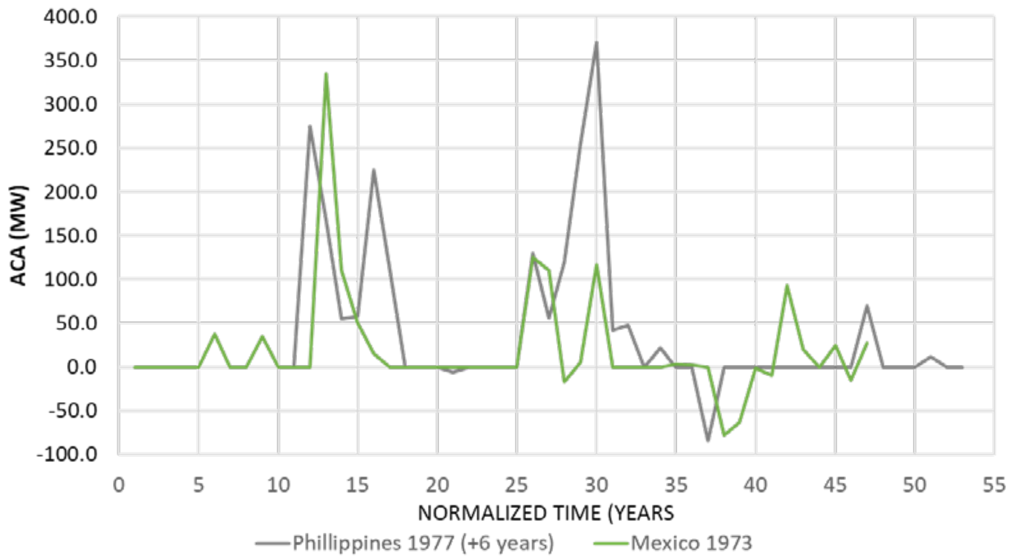

Figure 10. ACA curves for Group 2

Both countries had their maximum ACA in Period 3 (1976–1991) and Period 4 (1991–2002). In Mexico, geothermal power generation started in 1973, when the first units at Cerro Prieto and Los Azufres were installed. Though the Cerro Prieto field had 720 MW at its maximum, it now has an installed capacity of 570 MW; the Los Azufres field has 270.5 MW capacity; and Los Humeros, which came online in 1990, has a capacity of 119.8 MW. Starting with 2002, capacities drop to 10 MW (Las Tres Virgenes built in 2002) and 35.5 MW (Domo de San Pedro built in 2015) (Bertani 2016; Lund 2005; Matek 2016; Moya and Rodriguez 2009). The reason for this situation may be related to the limited potential of Mexico's geothermal resources.

Philippines is the third-largest producer of geothermal power in the world, after the United States and Indonesia. It has a total installed capacity of 1,918 MW and provides 1,770 GWh/yr to the grid with seven operating geothermal fields (Huttrer 2020). Maibarara Unit 2, which had a capacity of 12 MW in 2018, has been the only geothermal power plant established recently (Benito et al. 2005; Huttrer 2020).

3.2.3. Group 3: New Zealand, Italy, Iceland, and Japan

Group 3 includes New Zealand (1958), Italy (1950), Iceland (1969), and Japan (1966), which follow the characteristics of the first three patterns only; the fourth and fifth patterns did not develop in these countries. Therefore, these four countries have completed the early-stage linear development and the first acceleration in development, and they are in the steady-state linear development, but they have not managed to skip into the second acceleration in development or the second steady-state linear development stages.

Italy follows the characteristics of the second pattern 13 years later than New Zealand. Similarly, Japan follows the characteristics of the second pattern 9 years later, and Iceland shows the same pattern characteristics 1 year earlier than New Zealand. Thus, the time series data are normalized by shifting the time series data for Italy, Iceland, and Japan relative to New Zealand, which results in a good correlation for the first three development patterns (Figure 11 and Figure 12).

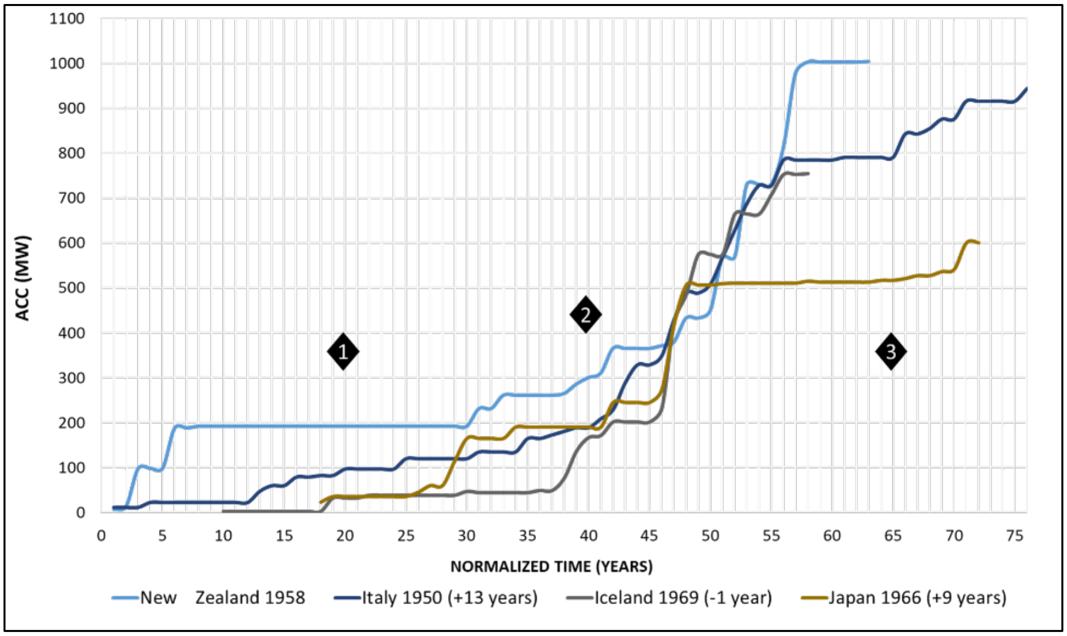

Figure 11. ACC curve for Group 3 (black diamond 1 identifies the first pattern, black diamond 2 identifies the second pattern, and black diamond 3 identifies the third pattern).

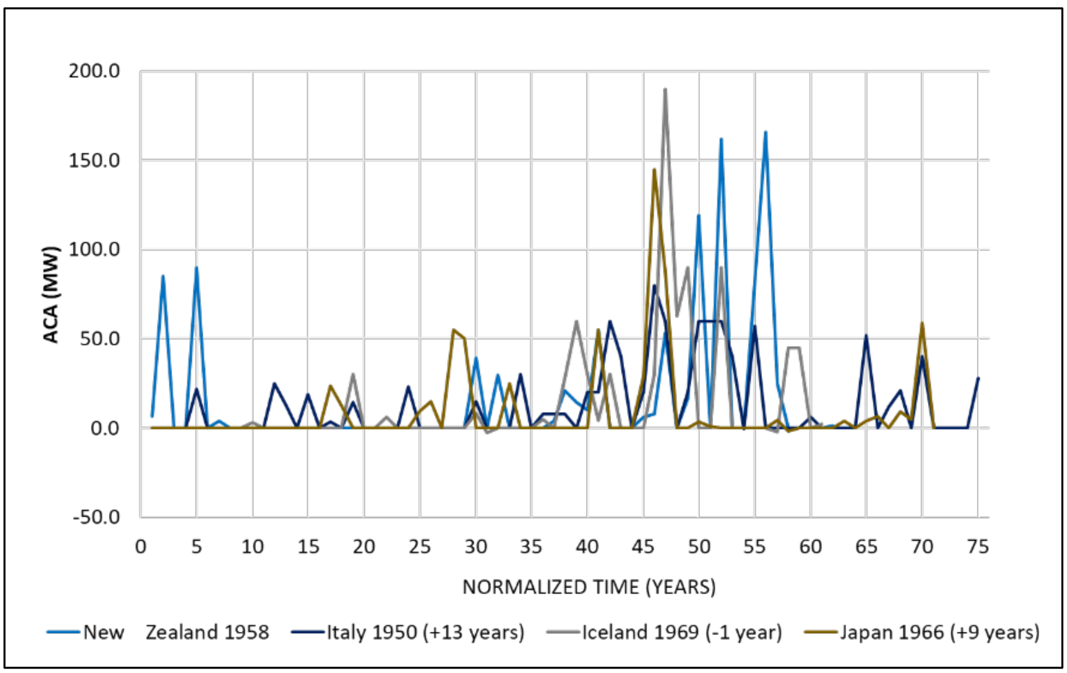

Figure 12. ACA curve for Group 3

Since experiencing rapid growth in the previous decade, New Zealand has been in a steady state in the geothermal power market since 2015. Two small power plants, which have been recently commissioned or are being constructed, have helped keep the country's total installed power constant. At Kawerau, the 25-MW Te Ahi O Maui plant was put online in September 2018, and at Ngāwha, a 31.5-MW plant is in the early construction phase (Lund 2004; NZGA 2019; Thain 1998). An addition of 32 MW of an expansion project Ngāwha did not come online by the end of

2020 as expected (ThinkGeoEnergy 2021). The Te Ahi O Maui and Ngāwha plants together produced 7,474 GWh/yr electricity by the end of 2019 (NZGA 2019), or about 18% of the national electricity in a system increasingly dominated by renewable generation (Huttrer 2020).

Although it has been increasing its installed power capacity to some extent recently, Italy is still in the first steady-state linear development stage. All its capacity (915.5 MW) is from two historical areas of Larderello-Travale (86.8%) and Mount Amiata (13.2%) locatedin Tuscany. Several old units have already been decommissioned and replaced with new ones—including a two-unit power plant at Bagnore 4, Gruppo Binario Bagnore 3 (1 MW), which is the first binary power plant in Italy, and Cornia 2, which is the first hybrid project with a biomass heater—increasing the output power from 12 MW to 17 MW (Bertani 2016; Hossain et al. 2020). The total installed capacity reached 935.5 MW after the 20 MW Monterotondo 2 plant came online in 2020 (Huttrer 2020). Recently, the gross electricity generated by 37 geothermal power plants in Italy reached 5,700 GWh, a new record (Huttrer 2020).

Japan reached its first steady-state linear development stage at lower levels than the three other countries in this group. Although the number of geothermal power plants increased from 20 to 69 between 2000 and 2018, most of these newer plants were quite small, ranging from 100 kW to 5 MW and leading to a total capacity increase of 24.4 MW. In the same period, several old and inefficient geothermal power plants were decommissioned, which resulted in a decrease in operational capacity of 68.2 MW. In 2019, construction of two larger power plants began at Wasabizawa (46.2 MW) and Matsuo-Hachimantai (7.5 MW), which boosted the existing capacity of 601 MW by 53.7 MW (ThinkGeoEnergy 2021).

Iceland is at the beginning of its first steady-state linear development stage. The country, which entered the geothermal sector in 1969 with a 3-MW Bjarnarflag geothermal power plant in the Lake Mývatn area, extended its capacity to 755 MW in 2020 (Huttrer 2020). This power plant is still producing steam for district heating, electricity, and water for the geothermal spa on Lake Mývatn (Bertani 2016; Lund 2005; Matek 2016). In 2016, Iceland reached 100% of renewables in the power sector, including 75% from hydropower and 25% from geothermal energy, and it is now producing 5,960 GWh of electricity from Hellisheidi (303 MW), Reykjanes (150 MW), Nesjavellir (120 MW), Húsavík (90 MW), Svartsengi (76.5 MW), Krafla (60 MW), and Bjarnarflag (3 MW) (Bertani 2016; Matek 2016; Mikhaylov 2020).

3.2.4. Group 4: Indonesia, Türkiye, and Kenya

Group 4 includes Indonesia (1979), Türkiye (1984), and Kenya (1985), which have completed the early-stage linear development and the first acceleration in development, but they never entered the steady-state linear development, the second acceleration in development, or the second steady-state linear development stages. However, Indonesia follows the characteristics of Türkiye and Kenya 13 years later than them. These countries are among the fastest-growing geothermal power sectors in the world increasing their ranks up by 12 in Türkiye, up by 4 in Kenya, and up by 3 in Indonesia from 2000 to 2020. They are also in the top 10 countries in terms of installed capacities; Indonesia is second, Türkiye is fourth, and Kenya is eighth (Figure 13 and Figure 14).

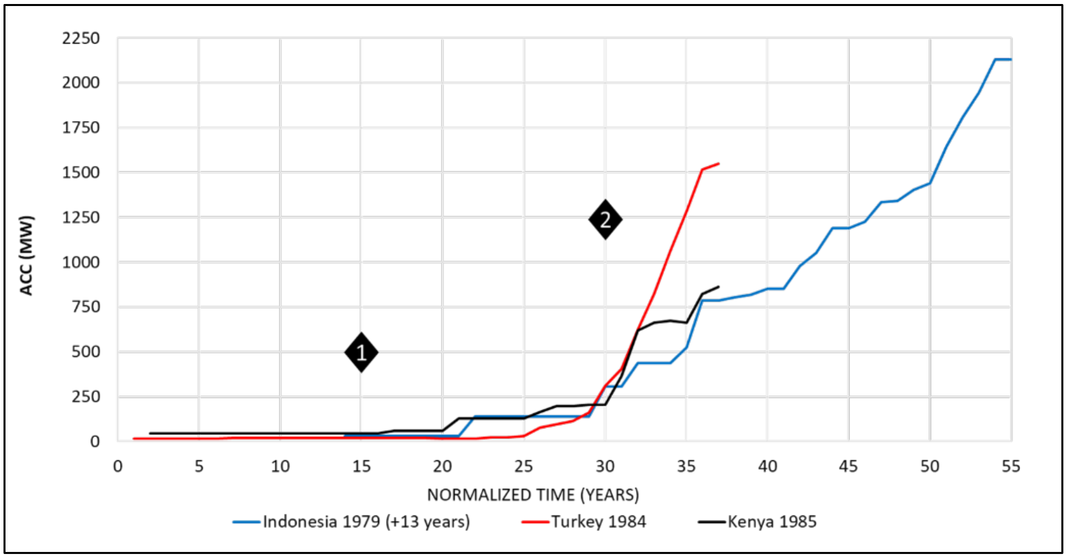

Figure 13. ACC curve for Group 4 (black diamond 1 identifies the first pattern, and black diamond 2 identifies the second pattern).

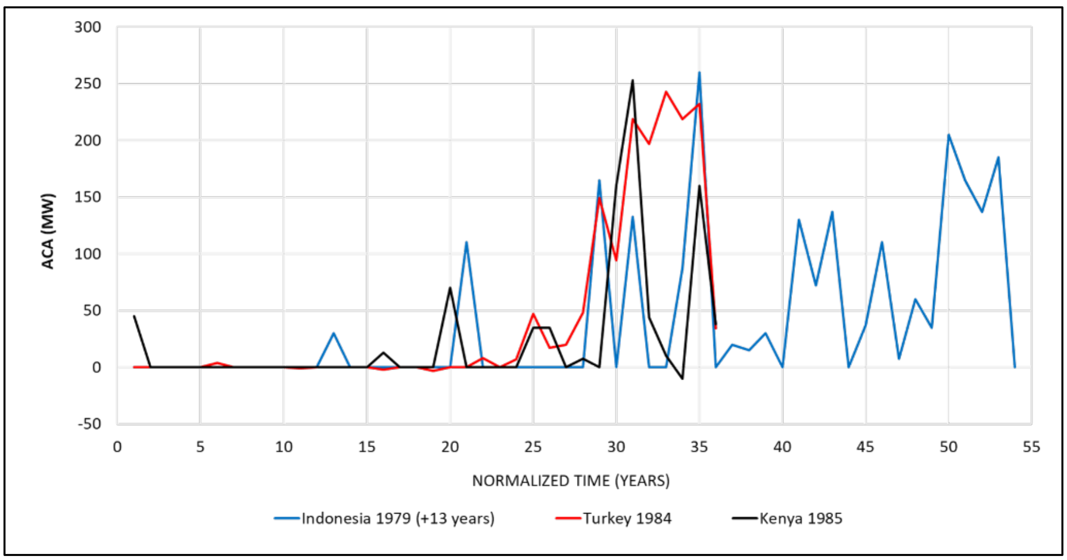

Figure 14. ACA curve for Group 4.

The fast growth of geothermal power sector appears to continue in the Group 4 countries. For instance, Indonesia's current installed geothermal power capacity is 2.13 GW, and the government has ambitious plans for 6.50 GW of total geothermal development by 2025 (Mansoer and Idral 2015; Poernomo et al. 2015). Of these three countries, Indonesia entered the geothermal power industry in 1979 with a 30-MW power plant and it reached 2,130.5 MW of capacity in 2020.

In Türkiye, the first geothermal power plant with a capacity of 17.4 MW was installed in 1984. Between 1984 and 2008, the geothermal power market in Türkiye followed a steady-state development pattern by adding only 12.6 MW until 2008 (Gokcen et al. 2004). After this, geothermal development accelerated with the implementation of a renewable energy law in 2010, which targets increasing the share of renewables up to 30% of the energy mix by 2023

(MENR 2010). This law provided for a feed-in tariff with a 10-year purchase guarantee and bonus payments for domestic hardware components made in Türkiye to support and boost the national manufacturing sector (MENR 2010). Also, as a result of exploration studies of geothermal potential, which started in 2005, the thermal potential increased to 1,900 MWt and the electricity generation potential increased to 5,000 MWe at the end of 2018 (MTA 2022). These efforts have made Türkiye the fastest-growing market in the world. The total installed capacity of Türkiye grew to 1,549 MW by the end of 2020, and 70 MW of capacity was added in 2021 (Enerji Atlasi 2021; Enerji Atlasi 2020; Huttrer 2020). The feed-in tariff, which is applied to geothermal power plants, was revised in 2021 with a lower tariff until December 2025; however, that did not slow the growth of the geothermal market.

Another fast-growing country is Kenya, which reached 861 MW of installed geothermal power capacity in 2020 by adding 198 MW of extra capacity in the last 2 years (Bertani 2016; Matek 2016; Think GeoEnergy 2020; Yee 2018). Kenya is currently in a very ambitious phase of development, with an aggressive construction pipeline of new projects in several geothermal resource areas to exploit its 10 GWe of potential (Matek 2016).

3.2.5. Group 5: Other countries

Group 5 includes 14 other countries, which do not have sufficient historical development to be involved in pattern analysis. These countries have installed capacities ranging between 7 MW and 262 MW. They established their first geothermal power plants between 1967 and 2018: Russia in 1967 (Svalova and Povarov 2015; Svalova 2012), El Salvador in 1975 (Bertani 2016; Matek 2016; Reyes 2012), China in 1977 (Huang Y. 2015; Zhu et al. 2015), Portugal in 1980 (Nunes et. al., 2019), Nicaragua in 1983 (Akar et al. 2018; Bertani 2016; Matek 2016; Zuniga and Medina 2000), Costa Rica in 1994 (Moya and Rodriguez 2009), Ethiopia in 1998 (MWIE 2015), Guatemala in 2000 (Asturias and Grajeda 2010), Papua New Guinea in 2003 (Booth and Bixley 2005), Germany in 2003 (Schellschmidt et al. 2010), France in 2011 (Boissavy et al. 2019), Chile in 2017 (Van Campen et al. 2016), Honduras in 2017 (Fercho et al. 2017), and Croatia in 2018 (Zivković et al. 2019).

Group 5 countries are using geothermal energy to generate electricity in smaller amounts than the countries in other groups, but they use their thermal resources for district or space heating, agriculture, aquaculture, and light industrial purposes. For example, China is not a significant player in the geothermal electricity market, but it ranks first in geothermal direct use (Lund and Toth 2021).

Slower rates of development in geothermal power for Group 5 countries could be related to limited geothermal resources or access to it; geothermal-specific policies, laws, rules, and regulations in some countries; and bureaucratic delays that increase the time, cost and risk in exploration, land access, mitigation of local property, environmental, spiritual, and other barriers. The slower rates could also be related to the competition from other renewable power technologies, such as wind and solar, to shorter pay-out periods, or to lower costs per kilowatt-hour. The latter can stretch the time needed to complete geothermal projects out to multiple years (6–8 years) as compared to the single year or even several months typically required to build and operate wind and solar generating stations.

4. Discussions and Conclusions

This study analyzes the historical patterns of geothermal power capacity in the world and in individual countries to be able to answer three main research questions: Are there some common patterns of geothermal power plant development in the world? Can countries be classified into subgroups based on these patterns? What are the factors affecting the patterns? The study aims to investigate the ideal global geothermal development pattern by examining the annual cumulative capacity (ACC) and the annual capacity addition (ACA) graphs of the historical development of geothermal power capacity in 24 countries. First, the global patterns are analyzed using these graphs in five periods (1945–1957, 1958–1976, 1977–1991, 1992–2002, and 2003–2020) that are marked by a series of characteristics of ACA peaks separated by two major troughs. Then, the patterns developed globally in each period are investigated in individual countries. As a result of this study, four conclusions are reached.

Firstly, although it is not statistically significant, a noteworthy relationship exists between the establishment dates of the pilot or demonstration plants (PDPs) and the time elapsed between the PDPs and commercial plants in seven countries, of which five (United States, Indonesia, Türkiye, Mexico, Italy) are in top seven countries in terms of installed geothermal capacity. As PDP establishment dates increase, the time elapsed between the pilot plants and commercial plants decreases. This may be because (1) increasing proficiency with technology—with increased experience—and (2) establishing a PDP helped the country develop its capacities more successfully than other countries. On the other hand, the fact that no PDP was built after 1978 may be due to the increasing maturation and commercialization of geothermal technologies through time.

Secondly, the five periods of the historical development of power plants at the global level are "early-stage linear development", "first period of acceleration in development", "first steady-state linear development", "second period of acceleration in development", and "second steady-state linear development pattern". The first two patterns are considered initial stages of global geothermal development whereas the most noteworthy development in geothermal capacity building occurred in the remaining three patterns in the world.

Thirdly, a strong positive relationship of global ACA curves with the 5-year shifted oil-price curve shows that geothermal power plant investment decisions are made considering oil prices: when oil prices increase, countries tend to substitute domestic geothermal resources for imported oil and gas by supporting investments. Because the average time elapsed between investment decision and commencement of power plants is around 5 years, increases in oil prices are reflected in the ACA curves 5 years later. The only exception, which occurs during the 1992–2002 ACC peak period and the 1986–1998 stable oil prices period, may be related to a remarkable increase in international awareness of climate change all over the world as a result of several international events between 1992 and 2002. Therefore, mainly two motivations influence the global geothermal power development: (1) increasing oil prices and (2) increasing awareness of global climate change. The first motivation causes policymakers to implement policies aimed at supporting domestic energy resources to decrease energy import dependency. The second motivation leads policymakers to apply policies targeting the availability of large amounts of capital.

Fourthly, the global patterns are reflected in individual countries to varying degrees depending on their specific conditions. The top 10 countries in terms of installed capacities are separated into four groups based on the availability and characteristics of patterns developed globally in the five periods. Group 1 is represented only by the United States (the first test or commercial plant in 1960), which has the five complete patterns developed. All five patterns are developed in the United States, which is a result of its success in developing geothermal power capacity and technology as well as the U.S. government's policies and support. Group 2, which consists of Philippines (1977) and Mexico (1973), has also five complete patterns but at much lower levels than the United States, possibly because of limited geothermal resources or access to it. Group 3 includes New Zealand (1958), Italy (1950), Iceland (1969), and Japan (1966), which follow the characteristics of only the first three patterns: early-stage linear development, the first acceleration in development, and the first steady-state linear development. This may be because of the limited potential of the country's geothermal resources, which does not help attract investors. Group 4 includes Indonesia (1979), Türkiye (1984), and Kenya (1985), which have completed only the early-stage linear development and the first acceleration in development. These countries are not only among the fastest growing geothermal power sectors in the world—having increased their ranks up by 12 in Türkiye, up by 4 in Kenya, and up by 3 in Indonesia from 2000 to 2020—but they are also in top 10 countries in terms of installed capacities. Although these countries are latecomers to the geothermal industry, they are applying very aggressive policies to build capacity. Finally, Group 5 includes 14 other countries that lack sufficient historical development to be involved in pattern analysis. These countries have capacities ranging between 7 MW and 262 MW, which were installed between 1967 and 2018. The slow rate of development in geothermal power in this group is related to limited geothermal resources or access to it; a lack of sound policies, including legal and physical infrastructure; and heavy bureaucracy. The slow rate could also be related to competition with other renewable power technologies such as wind and solar.

Overall, geothermal power in the world is in its third stage of development (Figure 15). The early stage was between 1913 and 1957, and the period between 1958 and 1976 can be considered a transitional stage. The real development stage started in 1977 during the Age of Substitutability (Goeller and Weinberg 1976) when countries tended to substitute domestic energy resources for imported oil and gas by supporting investments in local energy resources such as geothermal. The development stage, which is marked by three distinctive peaks separated by troughs, is continuing though at a declining pace (Fig. 6). In the near future, the fourth development peak may be expected to occur after this trough in a business-as-usual case.

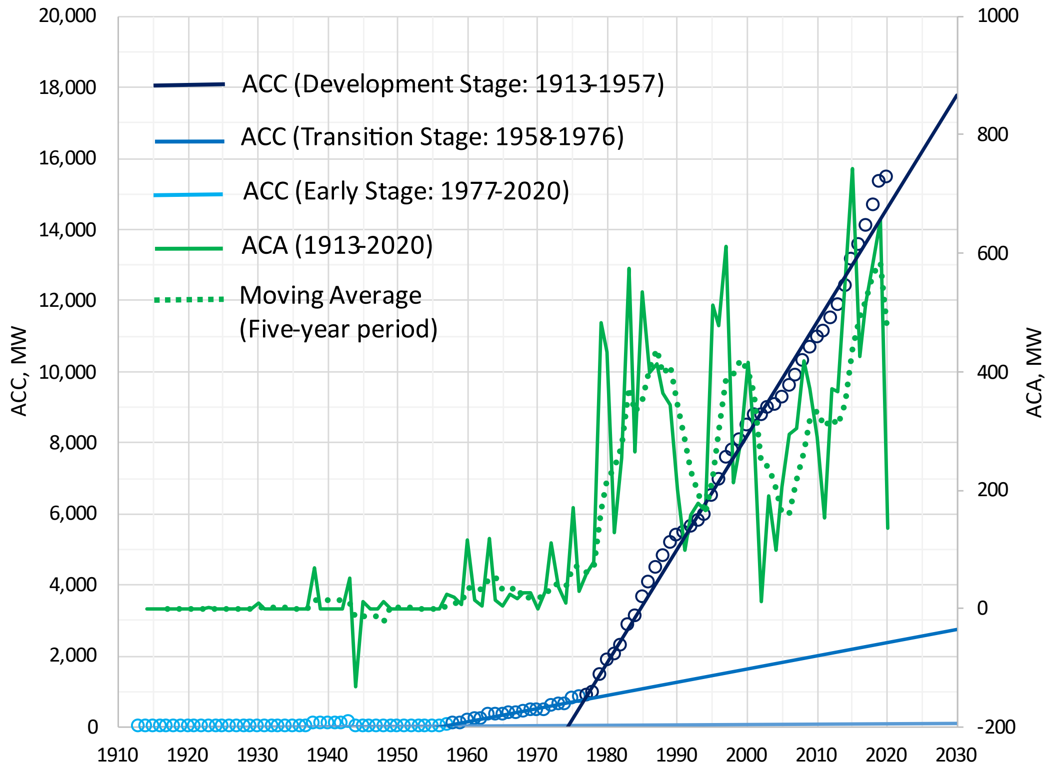

Figure 15. History of geothermal power in the world, 1913–2020.

For how long the development stage will continue will largely depend on the available resource and technological innovations. However, given the increase in global awareness of sustainable development, global climate change, and recent international events—including the adoption of SDGs by UN Member States, the adoption of the Paris Agreement, and the establishment of new programs in some countries (e.g., the European Green Deal of 2019)—the geothermal power industry can be expected to show performance better than that seen in a business-as-usual case. Alternative business models for geothermal energy include its more sustainable exploitation such as hybrid heat and power systems such as hybrid geothermal-solar thermal power plants, combined heat and power projects, hybrid revenue streams such as mineral extraction for lithium and rare earth elements, utilization of deep thermal energy storage, and hydrogen production using geothermal energy through electrolysis.

The biggest barrier to the development of the global geothermal power market is the risk associated with exploration and drilling. If risk mitigation systems (e.g., risk insurance) or risk mitigation funds are employed, the growth of geothermal power production projects could accelerate (Robins et al. 2021). Such power-focused risk mitigation systems already exist in countries like Türkiye, Indonesia, Kenya, and in Latin America. Risk insurance funds for projects also exist in some European countries like France, Germany, Iceland, the Netherlands, and Switzerland. In addition to risk mitigation systems, feed-in tariffs, exploration subsidies, production tax credits, and other incentives could also accelerate geothermal deployment (Robins et al. 2021). Other tools for mitigating risk in geothermal development include grants, loans, public and private insurance, public financing, public and private partnership, and direct government investment.

The growth of geothermal power production highly depends on its levelized cost of electricity, which, is lower than coal and gas peaking plants but higher than utility-scale solar PV, utility-scale wind, and combined-cycle gas plants. However, geothermal power plants offer several non-cost advantages such as 24-hour continuous electricity production, dispatchability, minimum CO_2 emissions, and a small development footprint. Therefore, geothermal energy plays a significant role in ongoing energy transition.

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