Geothermal development in South, Southeast and East Asia: A review

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Abstract

Global geothermal energy utilisation for power generation and direct-use applications have increased over the past 25 years, with Asia having the fastest growth in direct-use applications, which suggests a high demand for geothermal resources in Asia. This review seeks to fill a critical gap in the existing literature on geothermal development in South, Southeast and East Asia. It covers geological background, government policy, technological advancement, and socio-economic factors. This review also provides each country's current state of geothermal energy usage and insights into the respective government plans and initiatives to maintain and increase geothermal energy utilisation. The countries have been categorised into low- and high-temperature resource countries and their main geothermal heat utilisations have been identified. Countries trying to increase geothermal energy in their energy portfolios should continue to explore geothermal resources and to develop a pool of local expertise to be rightly positioned to adopt these emerging technologies.

Keywords: Geothermal utilisation, Geothermal development, Policy, Geology, Asia

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Highlights

- There has been an upward trend in geothermal utilisation in Asia since 1995.
- Geological background with graphical interpretations are summarised.
- Each country's current state of geothermal energy usage is provided.
- Continued geothermal exploration and building local expertise are needed.
- Government plans and initiatives are discussed.

Abbreviations

AGS	advanced geothermal system
EGS	enhanced geothermal system
FIT	feed-in tariff
GRC	geothermal resource category
GSHP	ground source heat pump
HDR	hot dry rock
ORC	organic Rankine cycle
ROK	Republic of Korea

Contents

1. Introduction

Worldwide geothermal energy utilisation for direct-use and power generation has been increasing since 1995 as Figure 1 shows. Utilisation for direct-use has been increasing faster than that for power generation (by 87% and 30% five-year growth for direct-use and power generation, respectively). This is partly because direct-use utilisation has lower temperature requirements on the heat resource [e.g., 1, 2]. Global geothermal energy utilisation is expected to increase as climate-related policies are passed and technology progresses [3, 4].

Figure 1A and Figure 1B show that in Asia, geothermal energy utilisation has also been increasing since 1995. Growth in direct-use installed capacities in Asia (up to 113% five-year growth) has outpaced global growth rates. Asia's share of worldwide direct-use installed capacity has increased steadily from 23% in 2005 to almost half the world installed capacity in 2020 (see Figure 1C).

However, Asia's worldwide geothermal power production share is currently decreasing as Figure 1D shows.

Globally, Huttrer [4] highlighted a decrease in the predicted growth of global geothermal power from 2020 to 2025 citing the following possible reasons: 1) increased competition from cheaper energy alternatives such as wind, solar, and natural gas-powered installations, 2) continued slow rate of adoption of geothermal-specific policies, laws, rules and regulations, and 3) bureaucratic delays that greatly increase the time, cost, and risk to obtain permits for geothermal exploration and development. These reasons would also apply to many South, Southeast Asian, and East Asian countries to a relatively greater extent as many of these countries are developing. Furthermore, Asia's worldwide share of geothermal power is also skewed towards the four largest producers of geothermal power production: China, Japan, Indonesia and the Philippines. Any delay in their respective continued geothermal development will significantly affect Asia's total installed capacity. The causes for the delay in these countries require further investigation, thus prompting this review.

About 60% of the world's population resides in Asia, and most of the countries in Asia are considered developing, according to United Nations classification criteria. Asia has also been experiencing rapid annual average economic growth of 5.3% since 2000, leading to a significant increase of energy demand and carbon emissions [16, 17]. Wei et al. [18] found that cities in Asia are leading contributors to global carbon emissions and have advocated the need for more ambitious emission reduction targets and mitigation. Literature shows that incorporating district cooling solutions [19] and geothermal applications such as ground source heat pumps (GSHPs) can not only mitigate the urban heat island effect to some extent, but also curb carbon emissions [e.g., 20, 21] and make energy usage in cities more efficient [22–24]. Large swaths of the population from urban areas depend on biofuels and coal-fired power plants to satisfy their energy requirements [25, 26]. Transitioning towards distributed grids powered by decentralised renewable sources like solar photovoltaics and geothermal has been considered an essential solution to increase electrification and reduce fossil fuel usage in Asian countries [27].

Countries have begun pledging renewable energy targets that include geothermal energy as part of their power generation mix while increasing the electrification rate of their respective populations [25]. For example, Singapore, Thailand, and the Philippines have considered including or increasing geothermal power generation in their energy portfolio to achieve their respective net zero-carbon emission targets by the

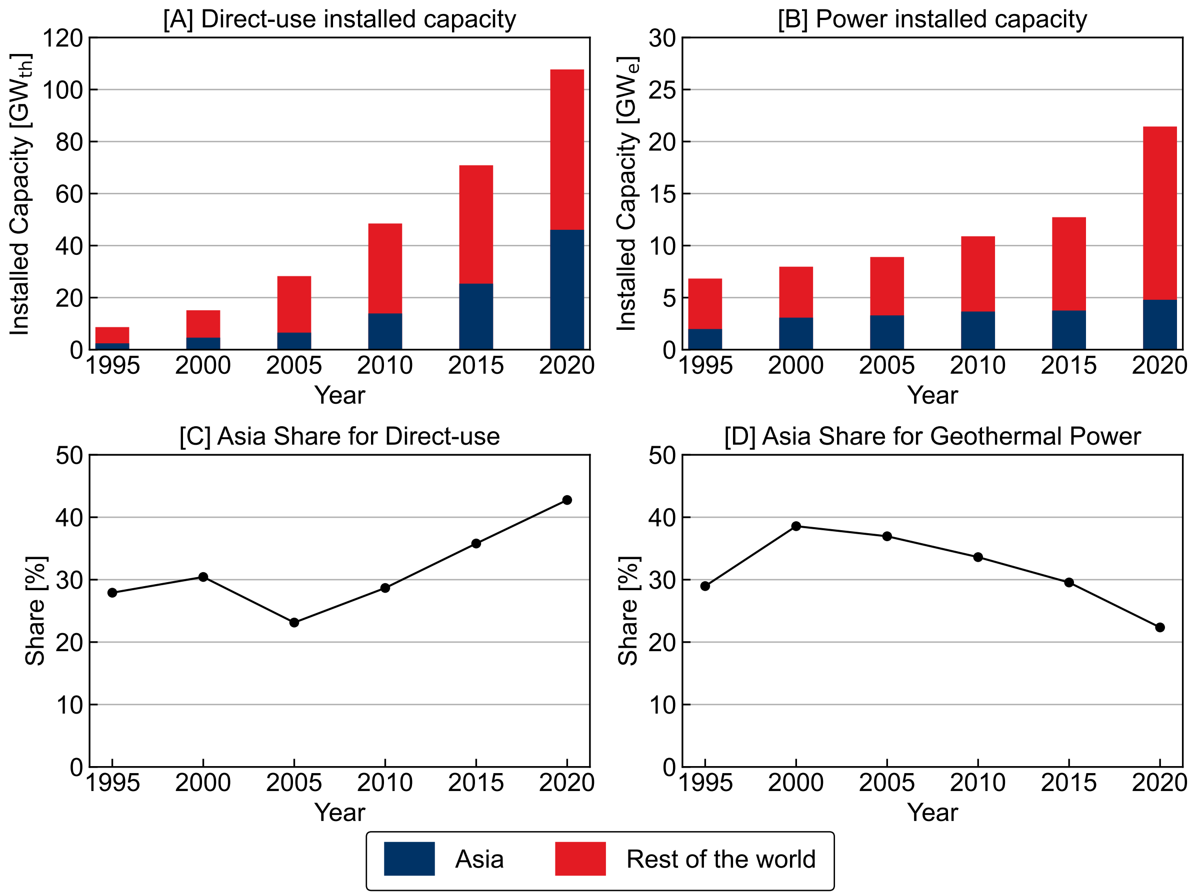


Figure 1: Summary plots for reported installed capacity figures for [A] direct-use, [B] power generation, [C] Asia's share of worldwide direct-use, and [D] Asia's share of worldwide geothermal power production. Countries categorised under Asia for direct-use by [5] are Bangladesh, China, India, Indonesia, Iran, Israel, Japan, Jordan, Malaysia, Mongolia, Nepal, Philippines, Saudi Arabia, South Korea, Taiwan, Tajikistan, Thailand, Turkey, Vietnam and Yemen. Data for direct-use are taken from [5–10]. Countries categorised under Asia for power generation by [5] are: China, Indonesia, Japan, Philippines, Taiwan and Thailand. Data for power generation are taken from [4, 11–15].

year 2050 [28–31]. However, progress on the energy transition within the Association of Southeast Asian Nations (ASEAN) has been slow because of insufficient annual investments into renewable energy and the lack of clarity from government policies [32, 33]. The likelihood of missing the 1.5 °C climate target is also increasing [34]. Time grows shorter to meet the countries' decarbonisation and renewable energy targets.

This study seeks to fill a critical gap in the existing literature on geothermal energy resource development by focusing on Asia, with a special emphasis on South, Southeast Asia, and East Asia. While the existing literature comprises country-specific reviews such as Yadav and Sircar [35] for India, Darma et al. [36] for Indonesia, Yasukawa et al. [37] for Japan, Tian et al. [51] for China, and Amoatey et al. [38] for the Middle Eastern region, there is a noticeable scarcity of comprehensive studies that delve into unique challenges, opportunities, and advancements in geothermal energy in South, Southeast, and East Asia.

The novelty of this paper lies in its dedicated exploration of geothermal energy utilisation within the dynamic and rapidly evolving energy landscapes of South, Southeast, and East Asia. This region presents a distinct set of circumstances, including geological diversity, regulatory frameworks, technological advancements, and socio-economic factors, which significantly impact the feasibility and scalability of geothermal projects. The review includes an overview of geothermal resource utilisation in the respective countries, with an extension on low-temperature utilisation. The latter is important to explore as high-temperature geothermal development is already quite well established. However, the location of these high-temperature resources is constrained by geological and hydrogeological parameters. On the other hand, low-temperature geothermal resources are not constrained by similar parameters and are potentially more abundant and accessible to countries. However, countries urgently need to accelerate their energy transition plans to reduce the impacts of climate change. There have been advances in technology such as advanced geothermal systems (AGSs) and enhanced geothermal systems (EGSs) that can effectively utilise these low-temperature or less productive geothermal regions. Lastly, this review also seeks to present the current state of geothermal energy developments, challenges, policy interventions, technological innovations, and/or best practices that can be adopted to promote geothermal energy utilisation.

The structure of this review is as follows. Section 2 explains the methodology used. Current geothermal applications and geothermal resources found in published literature for South, East and Southeast Asian countries are discussed in Section 3. Each country review is structured to include a short geological overview, known geothermal provinces/fields, current applications, and any initiatives/challenges the country faces to increase and/or deploy geothermal technologies. Concluding paragraphs are added for each reviewed country, summarising the authors' recommendations to improve the country's uptake for geothermal development. Section 4 discusses the results and concludes the study.

2. Materials and methods

The methodology for literature review in this study involves gathering, analysing, and synthesising relevant literature and data. The steps implemented allow a comprehensive coverage of the subject matter while maintaining objectivity in the review process.

2.1. Literature research strategy

To compile relevant literature for this review, a comprehensive search strategy was developed to identify relevant literature, including academic journals, conference proceedings, reports from reputed organisations (e.g., ASEAN Centre for Energy and International Renewable Energy Agency), and government publications. Google Scholar, Science Direct, and International Geothermal Association databases were used to carry out the search by utilising a combination of keywords such as '*geothermal energy*', '*utilisation*', '*low-temperature*', '*resource potential*', '*[country name]*', '*geology*', '*geothermal energy applications*', '*geothermal energy policy*', '*renewable energy policy*' and variations thereof. Boolean operators (AND, OR) were employed to refine the search results, ensuring the inclusion of relevant studies. The literature research was conducted in 2023.

2.2. Inclusion and exclusion criteria

Studies are included in this review if they have been published in peer-reviewed journals, conference proceedings, or reports from reputable and government organisations. Where primary literature sources are unavailable, newspaper articles and slide decks have also considered to provide the recent status of a particular project or policy.

2.3. *Data acquisition and interpretation*

Finally, data are extracted from various publications over the following topics: geological background of the respective countries, geothermal potential, existing low-temperature geothermal projects, their locations, installed capacities, and respective technical aspects. Details on some policy frameworks, government initiatives, and incentives that promote geothermal uptake within the respective countries are also acquired. The findings from the literature review are synthesised to form a comprehensive understanding of the current state of the high and low-temperature geothermal applications in the given country. Interpretations are then formed to draw logical conclusions, identify problems, propose recommendations for policymakers, and suggest areas for future development in the use of geothermal energy.

3. Current geothermal development and utilisation in Asia

In this section, the geothermal development and utilisation in selected countries in South, Southeast and East Asia are reviewed. The countries are divided into two groups according to their temperature classification.

3.1. *Classification of geothermal systems*

Several classification schemes have been considered over a few decades that cater to a wide variety of criteria such as temperature, geothermal play type, enthalpy, exergy, and the mobile fluid phase in reservoirs [e.g., 39–43].

The most common approach is to use the averaged temperature of a geothermal reservoir either measured from exploration wells or estimated by geothermometers [44]. Relying on reservoir temperature as a basis for resource classification is insufficient to identify the phase of the fluid produced at the wellhead. Depending on the pressure, two reservoirs with the same temperature can produce either liquid or steam at the wellhead. Steam has a significantly higher heat content than liquid, which will affect the utilisation and management of the resource. Despite its simplicity, the range of temperatures to classify geothermal systems remains undecided despite many decades of study (see Figure 2). For example, temperatures considered by Sanyal [41] as low-temperature resources begin at 190 °C, which is significantly higher than other classifications [e.g., 45, 46].

In this study, we have selected 150 °C as the temperature threshold. A country with resources below 150 °C is categorised as low-geothermal resource category (GRC), while a country with resources above 150 °C is categorised as high-GRC. The choice of 150 °C as the threshold is supported by four out of seven previous classifications, as evidenced in Figure 2, where 150 °C is commonly used to differentiate high- and non-high-temperature resources. The measured temperature refers to either the measured reservoir temperature or the highest down-hole temperature, whichever is available or the highest.

The following subsections review the reported geothermal development and utilisation in South, Southeast and East Asia. Figure 3 displays the countries considered

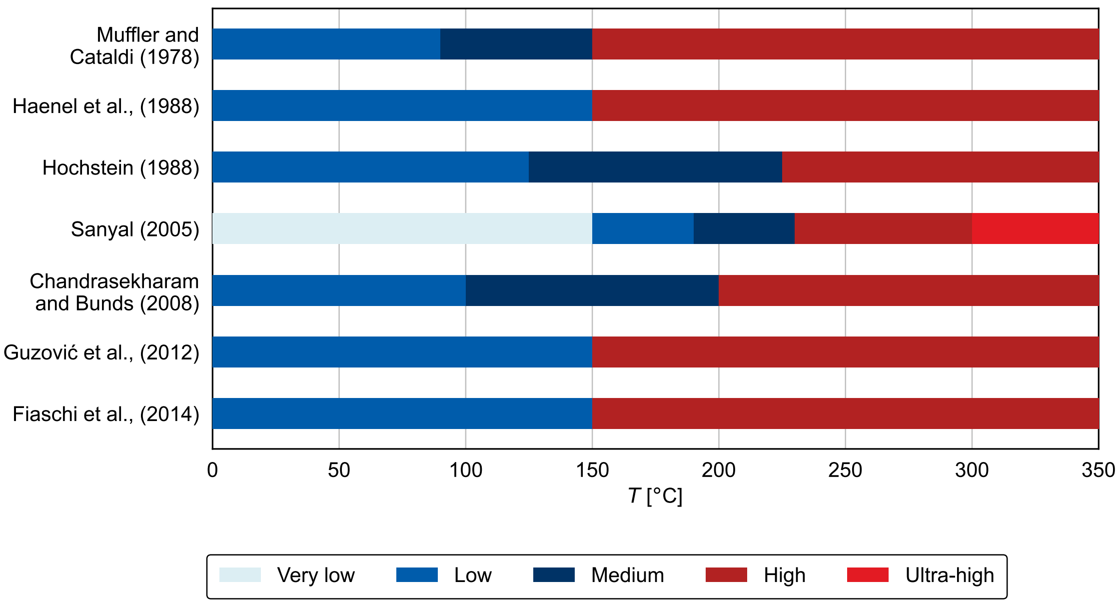


Figure 2: Summary of some published geothermal resource classifications based on averaged reservoir temperature. Modified from [42] and data taken from [39, 41, 45, 47–50].

in this study and their GRC. In an effort to consolidate the published works, the country's geological setting, current status of geothermal power generation, direct-use applications, geothermal energy-related policies depending on data availability are summarised under each country. The countries are grouped according to their respective GRC. Literature review on Bangladesh, Bhutan, Brunei, Cambodia, Hong Kong, Lao People's Democratic Republic, Myanmar, Nepal, North Korea, Sri Lanka, Timor-Leste for this study has revealed no deployment of and/or no rigorous plan to utilise geothermal heat conversion technologies. Although Singapore has not deployed any geothermal heat conversion technologies, a substantial research effort is ongoing to include geothermal energy as part of Singapore's future renewable energy portfolio [30].

3.2. High-GRC countries

3.2.1. China

The territory of China resides within the southeastern edge of the Eurasian Plate, where it borders the Indian plate towards the southwest, the Philippine Sea and the Pacific plates towards the East as shown in Figure 4A. China and the adjacent regions have undergone complex tectonic processes throughout its long and ancient geological history [51]. Currently, strong tectonic activity persists in regions close to these plate boundaries as seen in the formation of the Himalayan mountain range and the central mountain range in Taiwan, at the Indian-Eurasian Plate (see Section 3.3.1) and Philippine Sea-Eurasian Plate boundaries (see Section 3.2.6). As such, geological settings favourable for geothermal resources have been formed [52]. Figure 4B highlights that geothermal resources are found in two distinct geological settings: sedimentary basins and apophysis mountains [53]. The first type is the sedimentary basin type, characterised by a stable continental block deposited by thick sedimentary layers as seen in Tianjin within the North China Plain [54]. The second type of geothermal resource is associated with uplifted mountains found in active structural belts formed by orogenic processes. Examples of such geothermal resources are in the Tibet province and the Tianshan orogenic belt.

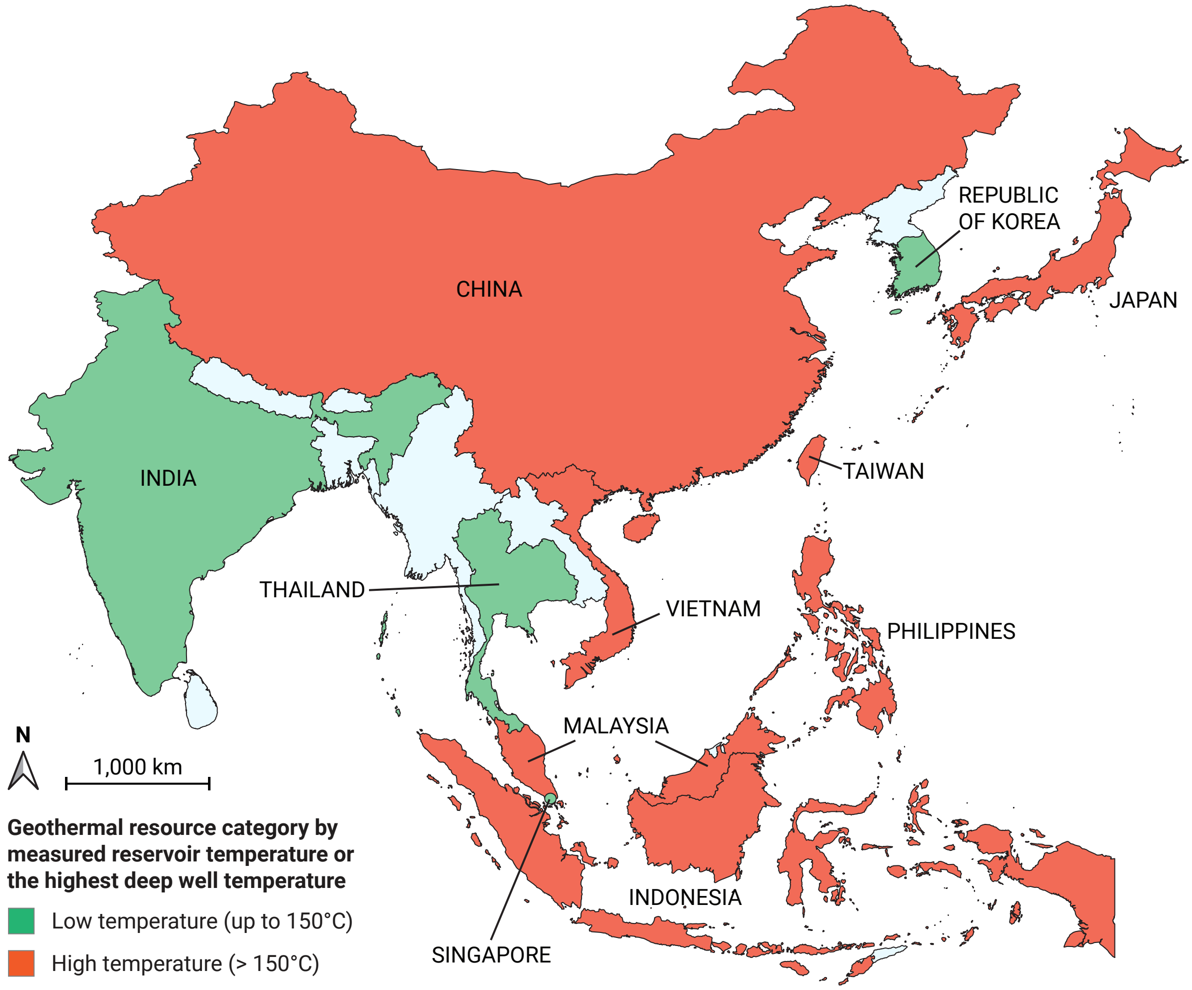


Figure 3: Asian countries covered in this review with the geothermal resource category based on the highest measured temperature identified. Temperature details are found in references in the respective country subsections. Countries in grey are not covered as there is no indication of deployed geothermal heat conversion technology.

In 2016, China had over 2300 thermal springs and more than 5800 geothermal wells [56]. Low-temperature waters (≤150 °C) are found almost everywhere [57], but more concentrated clusters can be found in several areas: in the eastern coastal provinces; at Tibet and western Yunnan where some waters are above 150 °C.

Geothermal gradients in China are generally higher in the north than in the south, with average values of 30 °C/km in the north and 24.5 °C/km in the south [58]. The average gradient at sedimentary basins is 32 °C/km with maximum values of 30 °C/km to 40 °C/km in areas like Songliao Basin, Yunnan, most of North China Plain etc.

The high-temperature geothermal resources are found in the southwestern parts of the country, like southern Tibet, western Sichuan, and western Yunnan. The low-temperature resources are mainly identified in the eastern parts of China, like the North China Plain, Hehuai Plain, Songliao Basin and other sedimentary basins and mountainous fault zones. The high- and low-temperature geothermal resources have a total power generation potential of 1.5 GW and 7.1 GW respectively [59].

Utilisation of the high-temperature resources is mainly for power generation, while the low-temperature resources are for direct use. High-temperature power plant pro-

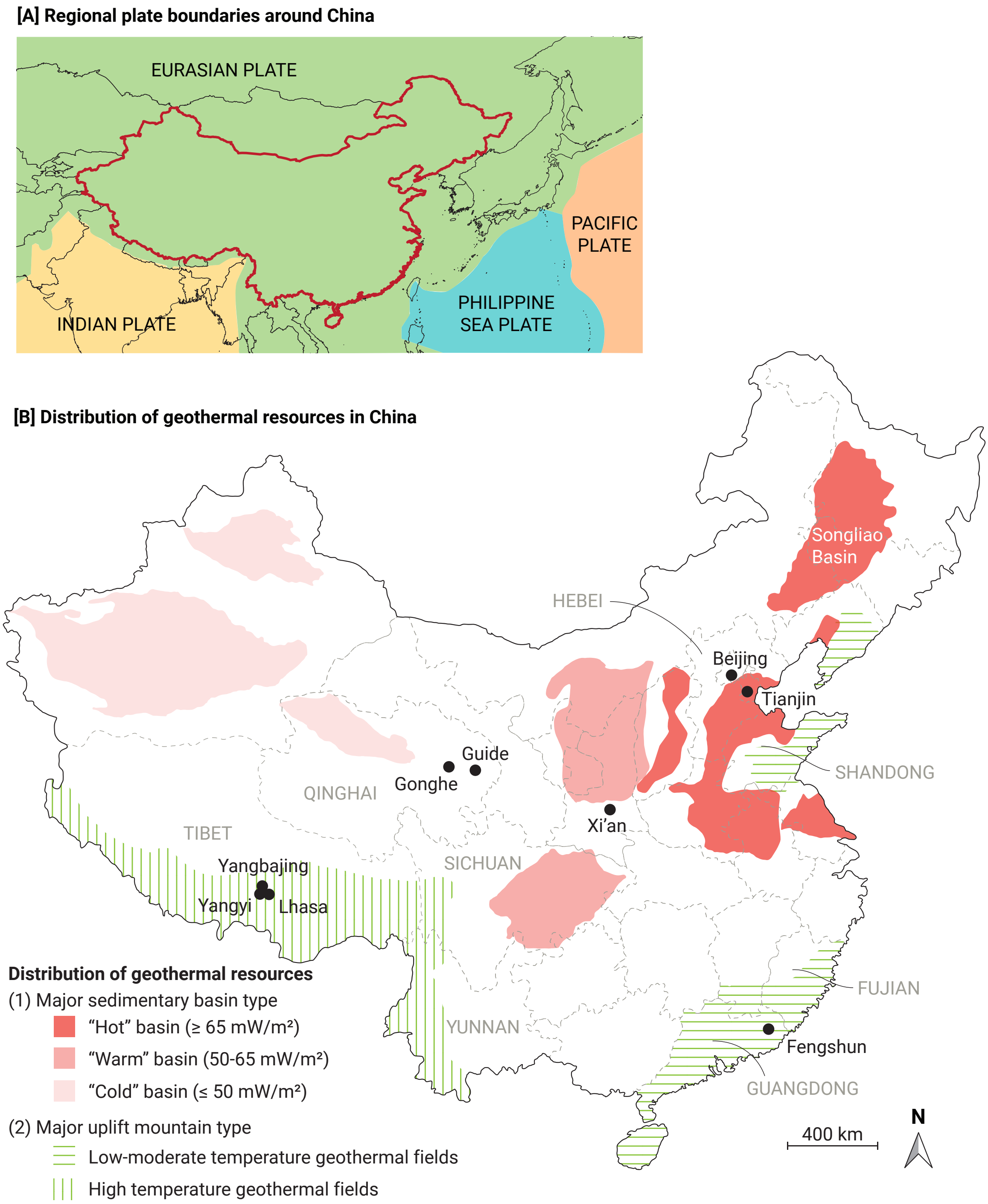


Figure 4: [A] Regional plate boundaries around China adapted and modified from [55]. The solid red line demarcates the territory of China. [B] Distribution of geothermal resources in China adapted and simplified from [56].

jects have been developed since the 1970s and began in Tibet [51]. The country's total installed capacity reached 43 MW_e in 2018 (see Table 1) and has remained at a similar level since. The Yangbajing geothermal field in South Tibet, with an installed capacity of 27 MW_e, has been experiencing sharp declines in production well pressures, temperatures and flow rates in recent years, partly due to the limited recharge to its shallow geothermal reservoirs (less than 450 m deep) [60, 61]. In 1996, the deep exploration well ZK4001 was drilled, and a naturally fractured deep reservoir at depth 950 m to 1350 m was discovered with high temperatures, reaching 250 °C. Flow tests to extract groundwater stored in the fractured granite reservoir stabilise at 84 kg/s of 200 °C two-phase flow at the wellhead. Yuan et al. [61] proposed to exploit the deep reservoir through fracturing and expected to generate 66 MW_e. In other parts of China, several low-temperature geothermal power plants have been built, but most have been decommissioned due to ageing equipment and economic reasons. Only one test power plant—in Fengshun—is still active with a total installed capacity of 0.3 MW.

Table 1: Detailed information on installed geothermal power plants in China in 2019, adapted from [62].

Power plant	Location (province)	Construction year(s)	Capacity [MW]	Temperature [°C]	Status
Fengshun	Guangdong	1984	0.3	92	operational
Yangbajing	Tibet	1977	1.0	181*	retired
		1981–1991	24.2		operational
		2008–2010	2.0		retired
Yangyi	Tibet	2018	16.0	160*	operational

*denotes averaged value

China has consistently been among the top ranks in the world in direct utilisation of geothermal energy. Low-temperature resources are widely used for various applications like space heating, bathing, medical treatment, industrial heating, aquaculture or leisure tourism, with a total installed capacity of 14,160 MW_t in 2019, excluding GSHPs [51]. The installed capacity of GSHPs has been increasing rapidly in China, especially in Beijing, Tianjin, Hebei and Shandong. The total installed capacity of GSHPs in China is the highest in the world at 26,450 MW_t [5].

Shen and Liu [58] presented the challenges for geothermal development in China. Some of these are the low survey accuracy for geothermal resources, the extensive development and utilisation of a geothermal resource in an area that has caused the water level to drop (e.g., the water level of a geothermal well in Xi'an has decreased by more than 200 m), the immature equipment technology to withstand high temperatures, and the low local talent reserve to support the rapid growth of geothermal development. Despite these challenges, continuous research efforts are ongoing to study the hot dry rock (HDR) potential in China [56, 59, 63] and geothermal development at abandoned oil reservoirs [64]. Liu et al. [59] indicated that the HDR resources at depths of 3 km to 10 km in mainland China are equivalent to several thousand times of China's total energy consumption in 2017. From 2014 to 2016, some exploratory boreholes were drilled to depths up to 3.7 km at the Qinghai Gonghe Basin, Guide Basin and Fujian. The bottomhole temperatures are measured to reach 151 °C to 236 °C.

China's government recognises the significant potential of low-temperature geothermal resources within the country [65]. During the 13th Five-Year Plan period (2016 to 2020), there was substantial growth in low-temperature geothermal utilisation. Specific standards were formulated for the geothermal energy industry, facilitating its growth and operation within the legal framework for resource development and utilisation.

However, government policy support during the 14th Five-Year Plan period seems less rigorous. With rather sufficient energy supplies in most regions, the government is less inclined to provide incentives to promote geothermal energy utilisation. Many geothermal wells were closed in the Hebei and Shandong provinces in 2020 due to the competition with inexpensive gas and coal heating sources.

Except for a few areas like Tibet and Hebei, excessive use of geothermal resources has led to significant drops in groundwater levels. Strengthening government policy to regulate excessive geothermal heat utilisation practices is essential. Adding to the challenges, the reduction in reservoir pressure has led to the shutdown of many operating power plants, especially those relying on high-temperature resources. This has prompted the industry to shift focus towards deeper geothermal resources. Where groundwater is scarce, hot dry rock resources are available, distributed on the edges of continental plates and in areas with thinning crust. These resources include high heat flow granite found along coastal areas in southeast China and sedimentary basins in Guide, among other locations.

In light of these developments, it is clear that robust government policy support is still needed to encourage further development of the geothermal industry in China.

3.2.2. Indonesia

The tectonic and geological conditions of Indonesia are largely associated with a protracted and complex movement of continental plates that form tectonic boundaries and major fault zones. Figure 5 displays a map of Indonesia with simplified tectonic setting and geothermal areas. Towards the west, a series of continental blocks were joined by suture zones that led to the formation of the Sundaland [e.g., 66, 67]. Indonesia is blessed with abundant volcanic activities as the volcanic islands are part of a long chain of islands known as the Circum Pacific Ring of Fire which begins in Sumatra in the west [36], extends towards the Banda Arc in the East [68], and extends towards the north that traverses over other countries such as Philippines (Section 3.2.5) and Japan (Section 3.2.3). Seismic and volcanic activities remain high as trenches are still tectonically active [69], setting favourable conditions for many high-temperature geothermal resources to form. As such, Indonesia has identified over 312 geothermal locations distributed along seismic lines corresponding to subduction zones between the Indo-Australian and Sunda continental plates [36]. The maximum reservoir temperatures of the existing wells in the archipelago vary from 230 °C to 327 °C. To reach the target reservoir temperatures, most geothermal wells drilled in Indonesia have depths in a range of 1200 m to 2800 m [70].

Indonesia's geothermal resource potential is about 29 GW_e, the highest geothermal potential for any country in the world [71]. The temperature gradient and the heat flow vary across the country, with high heat flow found in the north of Sumatra island and in the eastern part of the country [72]. In the Central Sumatra basin, the temperature gradient is in a range of 35 °C/km to 191 °C/km [73]. The heat flow in Sumatra ranges from 37 mW/m^2 to 369 mW/m^2 with Central Sumatra having the highest heat flow followed by South and North Sumatra. The high heat flow regions are associated with volcanic activity.

The archipelago has an installed capacity of 2289 MW_e, which shows low utilisation compared to the available resource potential [4]. The installations are spread over different islands of the archipelago like Java-Bali (1539 MW_e), Sumatra (617 MW_e), Sulawesi (120 MW_e), and Flores (12.5 MW_e). All of the existing power plants are utilising high-temperature resources.

The estimated potential of low-temperature resources is limited to 8000 MW_e, but the actual potential could be much lower, as some of these resources are intended

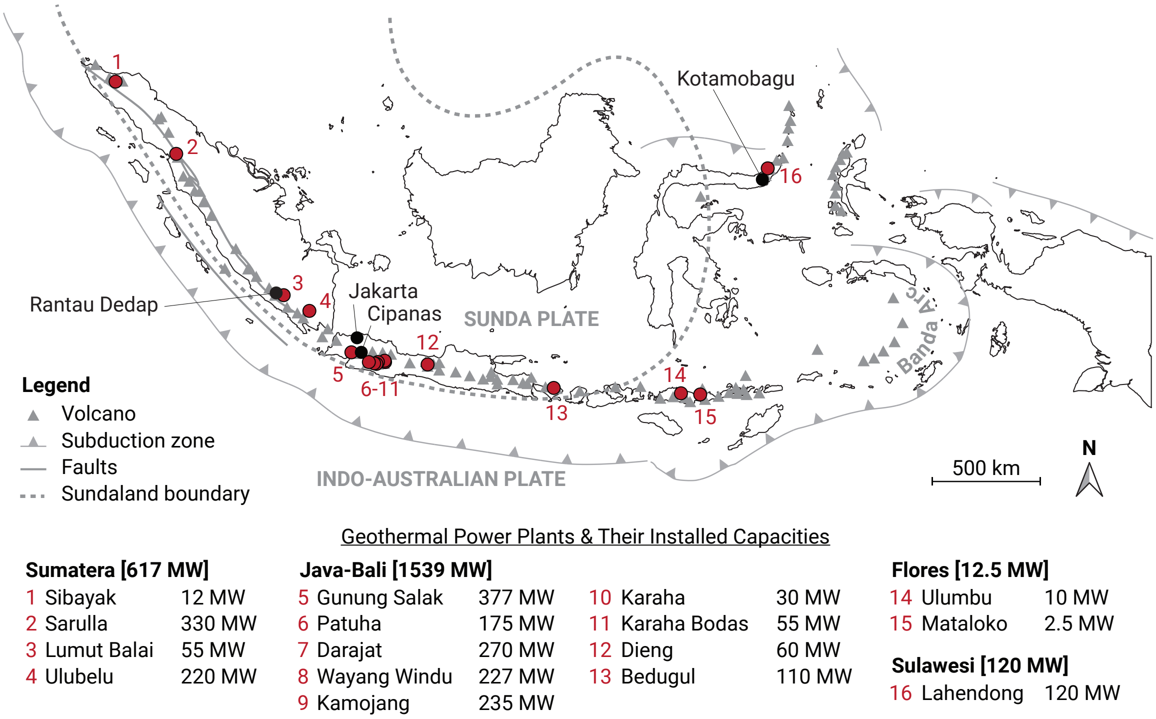


Figure 5: Composite map of Indonesia with simplified tectonic setting and geothermal areas. Locations of geothermal power plants and respective installed capacities are from [36]. Locations of faults, subduction zones, and volcanoes are adapted from [69, 74].

for direct-use applications and are not considered suitable for power generation [75]. Febrianto et al. [76] inferred that out of the 8000 MW_e, geothermal resources with temperatures of 100 °C to 150 °C account for 2660 MW_e and those with temperatures of 150 °C to 190 °C could contribute 4175 MW_e. Given Indonesia's less developed mountainous terrain, many of these resources are not easily accessible, resulting in high mobilisation and drilling costs when compared to other more developed volcanic countries, like Iceland and New Zealand [70].

A German-Indonesian collaboration project was initiated in 2013 and successfully installed a binary power plant in 2017 [77]. This 0.5 MW_e plant in Lahendong harnesses power from a 170 °C geothermal resource that is formed due to lateral fluid outflows from a high-temperature system. The collaboration implemented several initiatives, such as setting up PhD programmes, student exchange programmes, workshops and field camps, enabling knowledge transfer and local expertise development [78]. Studies indicate that similar resources are also available in other locations, like Ulubelu in South Sumatra [79], Rantau Dedap system [80], and Kotamobagu resource in North Sulawesi [81]. This type of low-temperature resource is attractive for Indonesia as it allows the expansion of existing high-temperature fields [76].

The direct-use potential has not been widely realised in the archipelago. Assessments show that the provinces Banten and West Java have a direct-use potential of 6.6 MW_t and 62.2 MW_t respectively [82].

The archipelago's most common direct usage type is for balneology and recreational purposes like heating swimming pools (e.g., the swimming pool in Cipanas) [83]. A mushroom farm from the same province uses a geothermal resource to sterilise and warm the incubation room. This system has substituted kerosene usage at this farm, leading to cost and emission reductions [84]. A farmer at an aquaculture facility in

Lampung reported that mixing hot geothermal water with fresh water improved fish growth. Other possible direct-use applications in this agricultural nation include Vetiver oil distillation, brown and palm sugar processing, as well as drying cocoa, coffee seeds and tea [36].

Several installed capacity targets have been set over time, for example 10 GW_e by 2030 [36] or 3.3 GW_e by 2030 [85]. The growth of geothermal power installations is rather slow due to challenges like the economic viability of the projects, lack of human resources, and handling social concerns (e.g., delay in Gunung Talang due to violent clashes [86]), among others [36]. The local geothermal research community is focusing on enhancing exploration techniques and learning from global geothermal drilling projects to overcome these hurdles. The government is also intervening through policies like the Clean Technology Fund which aims to de-risk the developers and promote geothermal energy. Coal power generation is highly incentivised in Indonesia, as evidenced by the capping of coal prices to meet local electricity cost expectations. However, Presidential Regulation Number 112/2022, issued in 2022, has delinked renewable energy tariffs from coal prices, setting a better ceiling tariff to accelerate geothermal development to meet the capacity targets [87]. sustainable transition.

In the authors' view, Indonesia is at a critical juncture to enhance its geothermal energy utilisation. Indonesia should continue fostering collaborations with leading geothermal utilisation nations to strengthen exploration techniques, share best practices, and leverage the latest advancements in drilling technologies. The country should also focus on expanding low-temperature geothermal power generation technologies, particularly by implementing binary technology in existing high-temperature geothermal fields. This approach presents a lesser risk for developers as it leverages known geothermal resources while diversifying the energy mix. Additionally, Indonesia can boost its local economy by adopting community-level direct utilisation of low-temperature geothermal resources. Applications such as balneology, agriculture, and industrial processes offer sustainable and cost-effective solutions that can benefit local communities and industries. Despite the high initial costs associated with low- and high-temperature geothermal energy utilisation, Indonesia can explore opportunities for green electricity exports to neighbouring countries or consider producing green hydrogen and ammonia for export markets. This not only contributes to regional energy security but also positions Indonesia as a leader in sustainable energy solutions on the global stage.

3.2.3. Japan

The Japan archipelago resides within the Eurasian and North American Plates, and these plates are located close to active subduction zones generated from the movements of the Philippine Sea and Pacific Plates [Figure 6, 37]. The geological history of Japan began with the breakup of the supercontinent Rodinia (ca. 750 million years ago) and the formation of the Pacific Plate [88, and references therein]. The westward motion of the Pacific Plate then collided and subducted beneath the plates around the eastern margin of the Eurasian Plate, forming a convergent margin for the next 500 million years. The protracted convergent movement led to the formation of multiple islands and volcanoes, which the Japan archipelago is part of. The protracted tectonic activity and island and volcano formation have led to favourable conditions for geothermal fields. The geothermal resources are largely concentrated in a variety of plutonic, volcanic and metamorphic rock formations, which are then categorised as Arima-type, Green-tuff type, Coastal and Volcanic [89, 90].

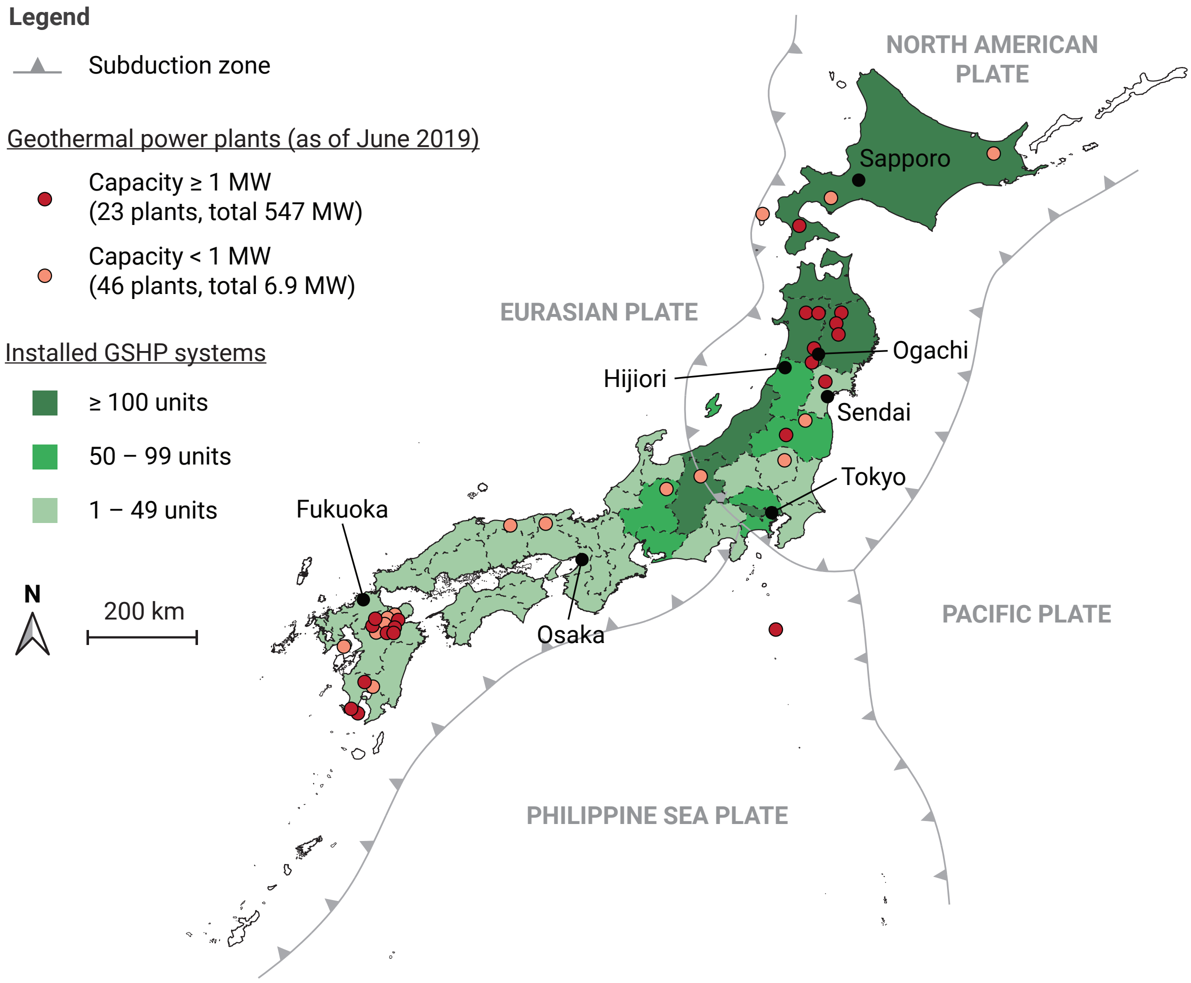


Figure 6: Distribution of installed geothermal power plants and GSHP systems in Japan (modified after Yasukawa et al. [37], Farabi-Asl et al. [91]). Tectonic plates around Japan and locations of subduction zones are adapted from [92].

Figure 6 indicates the distribution of installed geothermal power plants and GSHP systems in Japan, as well as tectonic plates and subduction zones. In 2019, there were 69 geothermal power plants in operation in Japan [4, 37], many of which are found at locations with high geothermal gradients and heat flows. Anomalous high heat flows in Japan generally coincide with volcanic and geothermal areas [93]. The first experimental geothermal power generation occurred in Beppu in 1925, and the first commercial geothermal power plant opened in the Hachimantai Plateau in 1966 [94]. The total installed power capacity has increased over the years and then remains at approximately 550 MW_e despite the implementation of a series of incentives (since 2012) to support the geothermal industry [37, 95].

The potential for geothermal power generation of up to 3 km deep is estimated to be over 20 GW_e [96]. The estimated potential for EGS electricity generation for Japan is between 8954 GW_e and 24,952 GW_e [97]. Despite the high potential, the installed capacity of geothermal power was about 550 MW_e in 2019.

Slow growth in the geothermal power industry is partly due to low public acceptance, especially from owners of *onsens* (hot bath facilities) as indicated in previous studies [98–100]. Development for geothermal power production is feared to dry out the hot water that supplies the *onsens*, increase pollution and ruin the relaxation experience. Since 2012, the government has allocated a budget to support public acceptance activities by private sectors. One effort to improve public acceptance is to learn from overseas examples like Iceland, where the "Blue Lagoon", the world's largest hot bathing facility, has been developed and operated successfully next to a geothermal power plant.

The government has instituted at least two financial incentives for geothermal projects. One is feed-in tariff (FIT) and another one is exploration drilling support covering up to 50% of the cost [96]. The FIT is JPY 26/kWh (approximately USD 0.23/kWh) for $\geq$15 MW_e plants, and JPY 40/kWh (approximately USD 0.35/kWh) for <15 MW_e plants.

Another initiative by the government is in the research and development area. Two HDR or EGS projects have been developed in Ogachi and Hijiori, northern Japan, since 1986. The reservoir temperatures were measured to reach 228 °C at Ogachi and 270 °C at Hijori. One notable feature of these EGS projects is that the injected water recovery is up to approximately 32% and 70.4% for the Ogachi and Hijori projects, respectively [101].

There are three main categories for direct utilisation: hot springs for bathing, geoheat pumps and thermal use of hot water [102]. The most used direct-use utilisation is bathing. However, these bathing facilities are usually managed by private enterprises, making statistical data sparse. Nevertheless, Yasukawa et al. [37] collated data from various sources to estimate the total installed capacity as 2570 MW_t, of which 78% is used for bathing and swimming, 6% for geothermal heat pumps, and the remainder for other usages (e.g., district heating, greenhouse heating, fish farming, and snow melting [103]). Despite the challenge of high drilling costs in Japan [91], the installed capacity of GSHPs increased multiple times from 62 MW_t in 2015 to 163 MW_t in 2019 [37, 96]. Figure 6 indicates the distribution of installed GSHP systems in Japan, with higher installations found in the northern part of the country where heating demands are higher due to colder climate conditions. Locations with higher GSHP installation are also associated with locations of higher groundwater flow in the country. The advection effect of groundwater flow is beneficial for GSHP systems.

The government has announced a 'Green Growth Strategy' to spearhead decarbonisation efforts and reach carbon neutrality by 2050 [104]. Under this strategy, geothermal energy is identified as one of the 'next-generation renewable energy' sources. To encourage geothermal development, the government plans to improve on existing geothermal-related technologies, conduct exploration programmes and establish deep drilling technologies. Through subsidies and debt guarantees, financial aid will also be provided to absorb some risks from geothermal power project developers through the Japan Organization for Metals and Energy Security.

In Japan, despite an abundance of high-temperature geothermal resources, geothermal power development has been stagnant at approximately 550 MW_e. Opposition from local communities, particularly *onsen* owners, poses a significant barrier, as there are concerns that large-scale geothermal operations might undermine their businesses. This challenge extends to the exploitation of low-temperature geothermal resources as well.

Deployment of modular systems with higher heat-to-electricity conversion efficiencies for low-temperature resources has started to gain traction. On the other hand, the depletion of some geothermal reservoirs, due to substantial pressure drops from mass withdrawal, calls for alternative extraction methods. Closed-loop heat extraction systems can be deployed at these depleted reservoirs [105] to enable residual heat utilisation.

The utilisation of low-temperature geothermal resources for heating through GSHPs has grown rapidly. To support the expansion of geothermal energy and achieve a three-fold increase in capacity by 2030, the Japanese government has introduced policy reforms, including relaxing restrictions on geothermal development in national parks and streamlining environmental assessments. Moreover, a financial policy providing above-market tariffs for geothermal electricity has encouraged many new small scale geothermal projects, which are largely unaffected by the stringent environmental regulations applicable to larger developments. Despite the great support, large geothermal project development remains slow in Japan.

3.2.4. Malaysia

The territory of Malaysia consists of two parts: Peninsular Malaysia towards the west and East Malaysia towards the east. Figure 7 displays the two parts, including the locations of hot springs. The general geology of Peninsular Malaysia is characterised by the three approximately north-south trending granite plutons overladen with Cenozoic sedimentary rocks: Western, Central and Eastern Belts [106, 107]. From a broader tectonics context, the Western Belt represents the Sibumasu continental block [108]. In contrast, the Central and Eastern Belts consist of metasedimentary and magmatic rocks corresponding to the East Malaya-Indochina tectonic terrane. The Bentong-Raub suture zone is regarded as a collisional boundary that resides in-between the Western and Central Belts [108]. East Malaysia occupies Northern Borneo, a landmass within the Eurasian Plate and is in-between the Indo-Australian and the Philippine Sea Plates. Northern Borneo is formed by a mountain-building process known as the Borneo orogeny that involves a complex interaction of microcontinental terranes, producing a series of sedimentary basins and fold belts [67, 109].

Over 60 natural hot springs have been identified in Malaysia [113, 114]. In Peninsular Malaysia, 55 hot springs are located along two main trends: the West-East and the North-South [111]. The hot springs associated with the West-East trend extend from Langkawi island in the west towards the state of Terengganu in the East. The North-South trend contains most hot springs and is associated with the NNW-SSE tectonic trend of the Main Range Granitoid batholith and the sedimentary rocks near the granites. The surface temperature of these hot springs range from 27 °C to 104 °C. Silica geothermometer showed that reservoir temperatures range between 93 °C and 154 °C. In particular, the hot spring in Ulu Slim has the highest surface temperature of 104 °C, which warrants further exploration. The estimated geothermal potential around Ulu Slim is 148 MW [115]. The heat sources for these hot springs are suggested to be of tectonic rather than volcanic origin [114].

In East Malaysia, Tawau remains the only high-temperature geothermal resource identified [116]. A 1400 m deep slimhole has been drilled with a measured temperature of over 200 °C with neutral pH hydrothermal water. Surface temperatures of hot springs here are up to 78 °C. The conceptual hydrogeological model suggests that the hot springs are recharged by meteoric water, being heated by a magmatic heat source at depth before circulating towards the surface [116]. This magmatic heat source is understood to be an extension of a volcanic arc complex from the Western Philippines, potentially sharing similar characteristics of volcanic-hosted geothermal systems in the Philippines (see Section 3.2.5). Malaysia has oil and gas wells that have been depleted

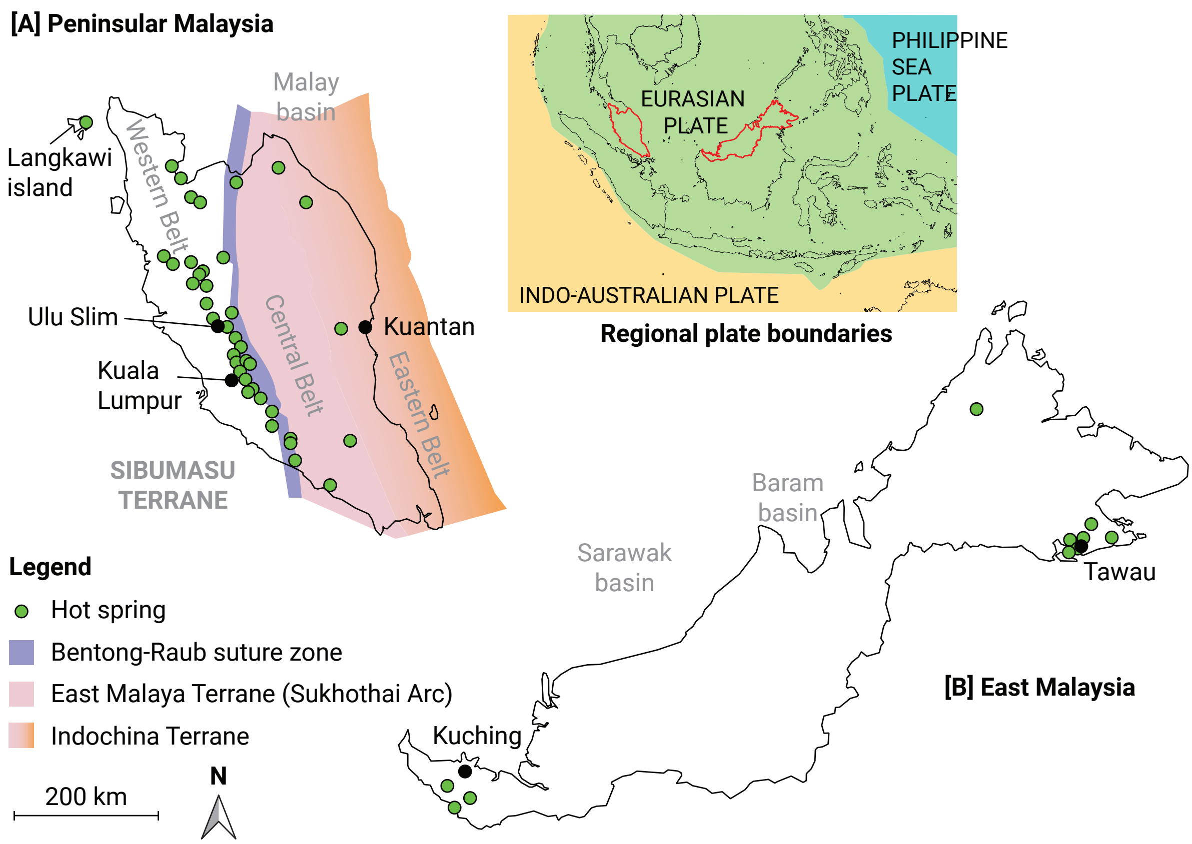


Figure 7: [A] Generalised tectonic setting of Peninsular Malaysia adapted from [67], with hot springs along the peninsular. The eastward boundary of the East Malaya Terrane is poorly constrained. [B] East Malaysia with hot springs. Locations of the Peninsular and East Malaysia in the Southeast Asia region are indicated with red lines in the regional plate boundaries inset (modified after [110]). Hot spring locations have been taken from [111, 112].

and need to be decommissioned. Feasibility studies, such as those conducted in the Baram Basin oil and gas region [e.g., 117], have explored the repurposing of the depleted wells for geothermal heat extraction. Recent temperature measurements from oil and gas wells show that the sedimentary basins located offshore, such as the Malay Basin and the Sarawak Basin, have geothermal gradients ranging from 35 °C/km to 75 °C/km that may have potential for heat extraction [118]. However, no field test has been conducted, yet.

The power potential for the Tawau geothermal field is estimated to be 85 MW_e, leading to a planned construction of a 37 MW power plant. However, the project was later found abandoned, resulting in the government's decision to revoke the power plant construction approval in late August 2018 [119]. The current utilisation of geothermal energy in Malaysia is only direct-use; mainly for hot spring bathing facilities [114]. Simulation-based studies suggest that deploying vertical GSHPs in cities in tropical and subtropical climate regions to provide cooling is not economically feasible and not able to keep up with the high cooling demand [e.g., Kuantan, Malaysia in 21, 120].

Policies considering renewable energy were passed in 2011 that include the setting up of a FIT scheme and the formation of the Sustainability Energy Development Authority of Malaysia office [121]. Currently, the FIT mechanism is being utilised for selected renewable sources, including biomass, hydro, solar and geothermal energy. The now-defunct Tawau geothermal power plant was one of the projects that benefited from the FIT. Current FIT rates for geothermal are higher than other supported renewable energy sources, showing government's continued support for geothermal energy development. Under the National Energy Policy 2022–2040, the Malaysian government has plans to increase electrification rate, fuel diversification and renewable penetration to the current energy generation portfolio, of which geothermal and wind have been selected for study and potential development [122].

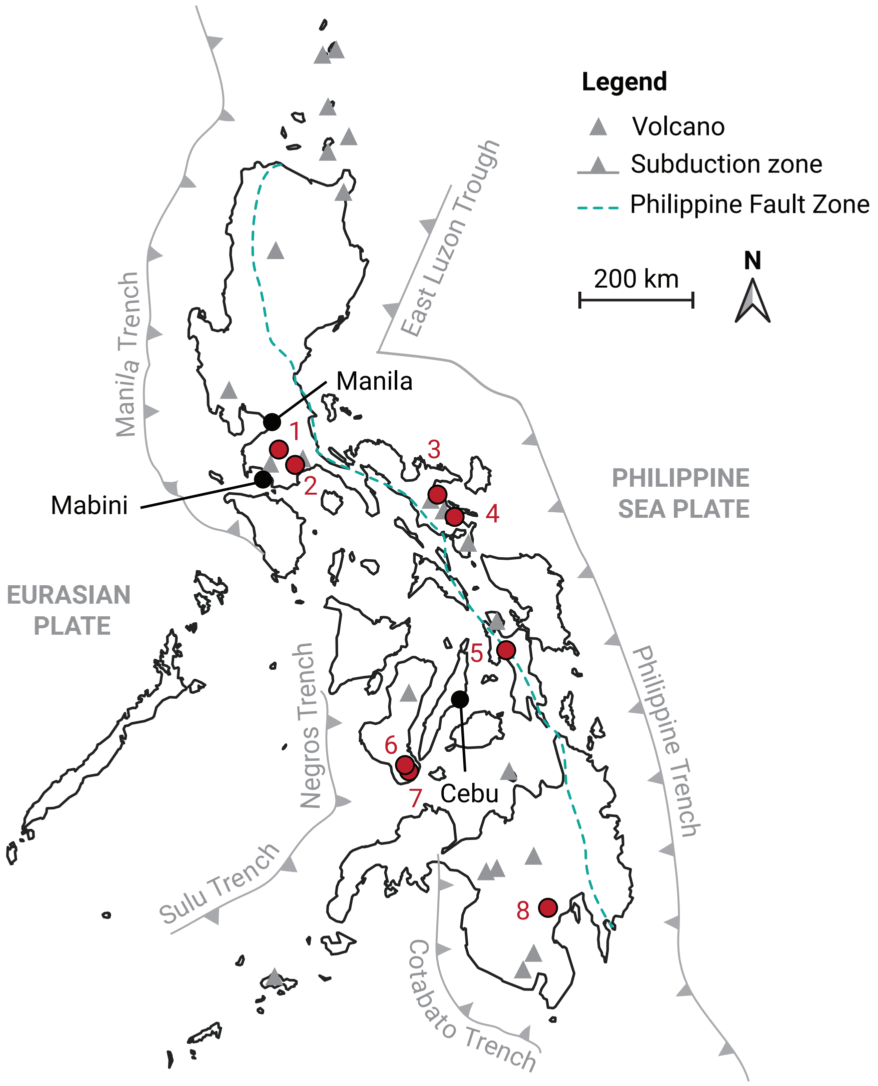
Malaysia's geothermal potential, highlighted by its hot springs and the Tawau field, remains integral to its energy strategy despite the Tawau plant's cessation. Details on achieving geothermal objectives are unclear, but prior studies in Ulu Slim and the Baram Basin show promise, particularly Ulu Slim's hot springs—the hottest surface temperature in the peninsula. Currently underutilised for bathing, these springs could support district cooling and aquaculture or even electricity generation. Since the country has an oil and gas industry, decommissioned wells could be repurposed for geothermal heat extraction. Pilot tests should also be considered to verify heat potential and to understand field specific geothermal reservoir response and challenges to heat extraction.

3.2.5. Philippines

The Philippines is an archipelago complex that consists of more than 7600 islands that reside in-between the Manila-Negros-Sulu-Cotabato Trenches in the west and the East Luzon Trough and Philippine Trench in the east. Figure 8 shows a simplified tectonic setting of the Philippines with installed geothermal generation capacity. The territory of the Philippines resides in seismically active zones attributed to the convergence of the Eurasian and Philippine Sea plates, forming subduction zones [123, 124]. This convergence occurred ca. 56 million years ago, leading to the generation of the Philippine Fault Zone, which now traverses the archipelago complex longitudinally. Continued crustal-scale movement at the subduction zones since the Tertiary would be capable of intense faulting and folding leading to several bathymetric highs and intense volcanic-plutonic activity within the island clusters. Many of the geothermal areas and related young volcanoes are located in regions near the Philippine Fault Zone, its branch faults and along the fringes of the batholiths.

The Philippines is the country with the third highest installed geothermal capacity worldwide (1918 MW_e in 2020), behind the USA and Indonesia [4]. The highest measured well temperature in the Philippines is 339 °C (with a temperature gradient of 141 °C/km) recorded in the Tongonan geothermal field [127]. According to Fronda et al. [29], it is envisioned to increase the Philippines' installed geothermal power capacity by 75% in 2030, as compared to 1848 MW in 2013. The largest power plants are Tongonan, with an installed capacity of approximately 720 MW in the centre of the Philippines, and Makiling-Bahanaw in the north, with an installed capacity of 460 MW. Most of the geothermal potential is used for electricity generation from high-temperature geothermal systems, with most of the resources being fully developed [128]. The reservoir temperatures of the high-temperature resources in Philippines are in a range of 170 °C to 325 °C [129].

Aside from high-temperature geothermal systems, of which most have been developed, low-power geothermal power resources are considered, too. Halcon et al. [130] analysed projects funded by the Department of Energy on low-temperature geothermal power resources with temperatures between 90 °C and 150 °C. The authors concluded that geology, geochemistry and geophysics surveys should be carried out at the be-



Geothermal power plants installed capacity

1	Maibarara	32 MW	5	Tongonan	722.7 MW
2	Makiling-Banahaw	458.5 MW	6	Nasulo	222.5 MW
3	Tiwi	234 MW	7	Palinpinon	
4	Bacon-Manito	140 MW	8	Mindanao	108.5 MW

Figure 8: Simplified tectonic setting of the Philippines with geothermal power plant installed capacity, adapted from [124–126].

ginning of such projects. Two of these projects were found to offer good prospects for exploiting geothermal energy, and further studies are necessary. Dela Cruz III and Manuel PhD [131] compared Ormat and Kalina Cycle for a geothermal installation in Mabini, Batangas. Using the Kalina Cycle, they concluded that the power output could be more than 10 MW.

Two organic Rankine cycle (ORC) binary plants of ≈28 MW are under construction at Bacon-Manito [132] and Mahanagdong geothermal plants [133] which are existing high-temperature geothermal power plants similar to the binary plant application in Lahendong of Indonesia. The planned binary plants utilise the brine discharge from the high-temperature plants.

The Philippines, like Indonesia, also faces challenges due to its complex terrain and the remote location of its geothermal resources. This poses a significant challenge in mobilising drilling equipment to the sites, leading to high specific drilling costs in the country [70]. The Philippine government has implemented several policies to promote geothermal energy utilisation. One of its recent policy implementations was to allow 100% ownership of the large-scale geothermal projects by foreign investors [134]. Recently, the Philippine Board of Investment has awarded green lane certificates for multiple geothermal energy projects whose combined capacity is around 272 MW. The green lane certificates are aimed to streamline and expedite the permitting process for geothermal projects, which significantly reduces the lead project development time.

The Philippines stands as a promising player for geothermal energy, characterised by its abundant high-temperature resources and a commitment to bolstering their utilisation through strategic policies and expanded deployments. Notably, the nation is exploring the potential of harnessing low-temperature geothermal sources for power generation, akin to successful models seen in countries like Indonesia. Concentrated efforts in international collaborations to implement advanced drilling techniques like directional drilling can play a key role in accessing remote and challenging geothermal reservoirs.

3.2.6. Taiwan (China)

Taiwan is located at the junction of the Eurasian Plate and the Philippine Sea Plate. Figure 9 shows a simplified tectonic setting of Taiwan, including hot springs locations. The Philippine Sea Plate collided against the Eurasian Plate, forming the Central Mountain Range and subduction zones such as the Ryukyu and Manila Trenches. Cenozoic deposits surrounding the Central Mountain Range are thick (>10,000 m) and have been subjected to varying grades of induration or metamorphism [135]. The general geology of Taiwan is diverse. The rocks in the west consist of exhumed Eurasian Paleozoic to Mesozoic metamorphic basement [136, 137], Neogene to Paleogene slate belts at the centre, and sediments from continental shelf deposits due to an active fold-and-thrust belt found in the east [138]. Taiwan has over 100 hot springs and multiple geothermal fields. The fluids are found to circulate through slate/schist rock formations and are heated by the thermal blanketing effect of the thick sedimentary basin [137]. As such, the geothermal play type in Taiwan is categorised as a conduction-dominated system with an active orogenic/belt foreland basin terrane [42].

The hot springs are being utilised for bathing and spa-related tourism activities. However, data concerning direct-use applications is not available [10]. Previous exploration efforts have identified several regions, including Tatun, Yilian, Hualien-Taitung and Lushan, for future geothermal power development [139–141]. The estimated country's electricity generation potential from geothermal power at identified hot potential sites is significant ranging from 0.75 GW_e to 33.6 GW_e, and is capable of replacing up to the country's one-third of coal-fired power plants [139, 142, 143].

The Tuchang-Qingshui geothermal area is the most studied out of all the named geothermal areas in Taiwan, leading to the construction of Taiwan's first geothermal power plant in 1981. Hot springs observed around the geothermal area have a surface temperature between 60 °C and 99 °C and have a flow rate of around 3 kg/s [148]. Geothermal wells in this area have depths of 1505 m to 3000 m, bottom hole temperatures of 201 °C to 225 °C, and total flow rates of around 11 kg/s to 35 kg/s [149, 150]. However, the power plant ceased operations in 1993 due to low well and power productivity

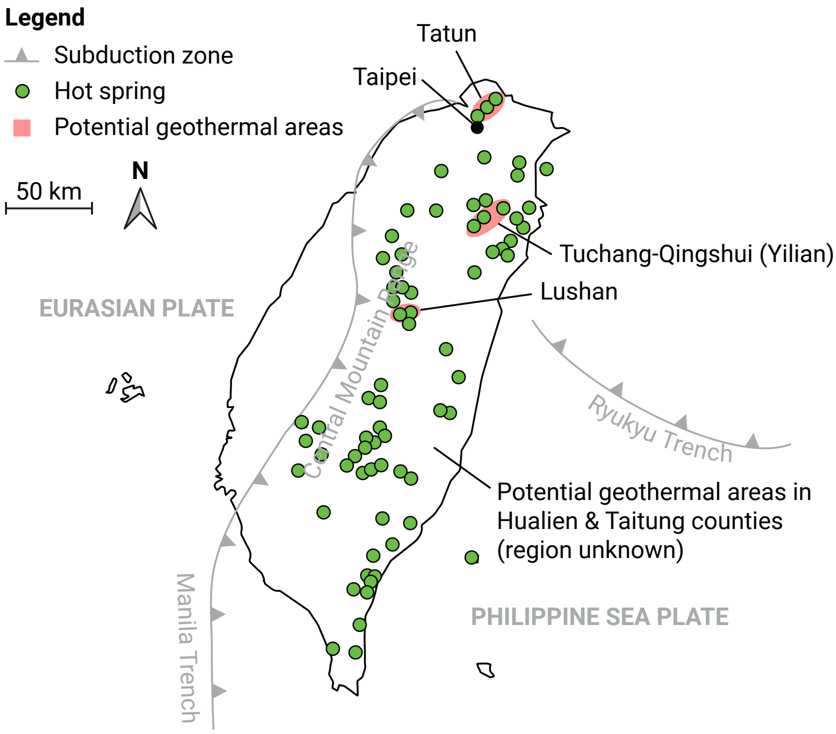


Figure 9: Simplified tectonic setting for Taiwan as adapted from [144, 145]. Compilation of hot spring locations and geothermal areas adapted from [142, 146, 147].

due to carbonate scaling.

The Qingshui power plant was redeveloped and relaunched with an installed capacity of 4.2 MW and is capable of meeting the demand of about three quarters of households in Datong and Shanshing Townships [151]. The plant utilises water with temperatures of up to 180 °C that is drawn from depths of 1200 m to 2100 m to generate electricity before re-injecting the water back into the ground [152]. According to Chen et al. [142], the used hot water is further utilised through a multi-function demonstration system, of which details have not been made available.

Geothermal is considered a part of Taiwan's 2050 net-zero transition policy [153]. The policy aims to increase the proportion of energy generated from renewable sources from 9.6 GW to 46 GW in 2030. Geothermal energy's contribution is to increase the installed capacity for geothermal from 20 MW in 2025 to 3 GW to 6.2 GW in 2050. To facilitate the growth of geothermal power, multiple partnerships have been established with industry players including Ormat [154], GreenFire [155], and GNS Science [156] to support Taiwan's geothermal ambitions. Taiwan also introduced a FIT system and financial subsidies to encourage and accelerate private and national geothermal development efforts [143]. Results and data concerning ongoing geothermal exploration initiatives have been made available to the public as part of a public education effort on geothermal [157].

Taiwan has significant geothermal energy potential, given the presence of many hot springs and geothermal fields. A power plant was built in Qingshui to test its feasibility, and it can be viewed as a catalyst for revitalising Taiwan's geothermal industry. A three-decade gap existed between the plant's closure in 1993 and its relaunching in 2023, suggesting technological limitations to overcome high-temperature geothermal fluids and scaling issues. If the Qingshui geothermal fluids have a sufficiently high concentration of silica, silica recovery would be an added benefit to the profitability and maintenance of the power plant. On policy, it is encouraging and ambitious that geothermal energy is incorporated into Taiwan's overall net-zero transition plans. Multiple industry partners have been engaged to provide the needed technical expertise and technology. However, we opine that geopolitical relations between Taiwan and China have become increasingly tenuous, which has the greatest potential to unravel Taiwan's geothermal ambitions. Efforts should be made by both countries willing to refocus efforts to combat climate change.

3.2.7. Vietnam

Figure 10 shows that the territory of Vietnam can be subdivided into five tectonic blocks: Northeast, Northwest, Truong Son, Kontum and Nambo [158, 159]. The rocks associated with the Northeast block consist of various plutonic and volcanic rocks [160]. The Northwest and Truong Son blocks contain the thickest strata containing marine fossils in the country and are recognised as NW-SE trending folded systems. The Kontum block relates to an uplifted massif, which comprises a variety of metamorphosed granites and magmatic-related intrusions. The Nambo block contains mainly deltaic sediments at the southern end of Vietnam. Major structures have been formed within and in-between the structural blocks, providing structural conditions favourable for hot springs and geothermal reservoirs to manifest [160].

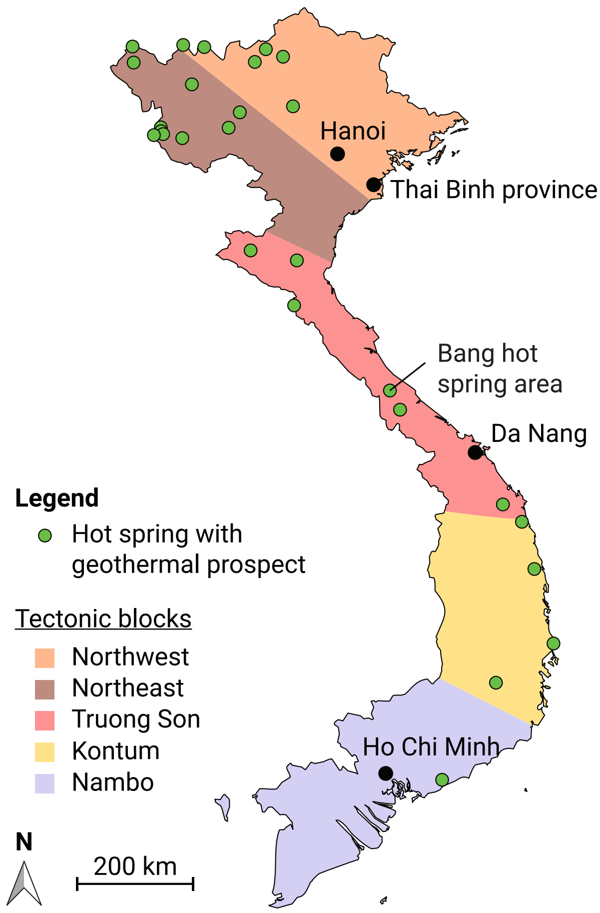


Figure 10: Simplified tectonic block divisions of Vietnam adapted from [158]. Locations of hot springs with geothermal prospects are adapted from [159, 161].

Nearly 300 hot springs with surface temperatures of >30 °C have been identified and categorised geographically by these structural blocks [159, 162, 163]. The hottest spring is at the Bang hot spring area within the Truong Son block, with a measured temperature of 105 °C at 24 m depth, and an estimated reservoir temperature in a range of 167 °C to 200 °C at >2 km depth [163, 164]. As such, the estimated country's geothermal potential that can be developed is 680 MW_e [159]. Regional simulation studies suggest Vietnam's geothermal potential for electricity generation is significantly higher than previous estimations if EGS is considered, namely 2106 GW_e to 7466 GW_e [97].

Current utilisation of geothermal energy in Vietnam is for direct-use applications such as GSHPs, spas, farming, bathing, and heating of swimming pools [5, 159]. The total direct-use installed capacity and utilisation excluding GSHP are about 18 MW_t and 187 TJ/yr. There are two pilot GSHPs installed in Hanoi, but only one is monitored at the Vietnam Institute of Geoscience and Mineral Resources. The GSHP has an installed capacity of 5 kW_t. Additionally, the locals of the Thai Binh province have used the hot water to warm fish breeding ponds and chicken or pig farms during winter.

According to the Vietnam Renewable Energy Policy 2022, significant efforts are placed to increase the installed capacity for renewable energy [165]. For instance, the projected growth in installed capacity from 2025 to 2045 is about 9 times for wind and 8.6 times for solar photovoltaics. Current high FIT and legislative support have driven current Vietnam's rapid growth in solar and wind energy [e.g., 33]. However, future geothermal energy development remains unclear as it is categorised as 'other renewable energy sources' together with biomass. Additionally, the lack of local expertise, pricing and financial assistance to lessen the high-risk profile of geothermal exploration are cited to be caused for this [159, 162].

Current utilisation of geothermal energy in Vietnam is direct-use and within local communities. Although previous studies have identified multiple hot springs with geothermal potential and conducted successful demonstration projects, the current energy policy focuses disproportionately on solar and wind projects compared to other renewable energy sources. The data and potentials for solar and wind energy projects are more established, and implementing them carries less risk than geothermal. Similar pricing and financial assistance policies are needed to reduce the high-risk nature of geothermal energy and may spur the implementation of private and public geothermal projects. Like Malaysia (in Section 3.2.4), Vietnam has a well-established oil and gas industry and may have wells that require decommissioning. If the well's temperature and thermal gradients are high, reusing them should be considered for geothermal heat extraction. Furthermore, conducting a pilot test would give further insights into the heat extraction potential in Vietnam.

3.3. Low-GRC countries

3.3.1. India

The territory of India consists of the amalgamation of several ancient cratons that have undergone multiple deformation cycles throughout geologic history [e.g., 166–169]. The basement rocks consist of various magmatic rocks interlayered with metamorphic clastic and carbonate sediments [170]. Sediments are then deposited on top of the basement, which either ended up as variably metamorphosed and deformed mobile belts or remained as undisturbed intracratonic basins [e.g., 168, 171]. Major structural lines in India formed from the generation of horst and graben structures at ca. 180 million years ago [166]. Widespread volcanism occurred at ca. 145 million years ago, forming volcanic-associated plateaus. The most recent tectonic activity is the collision and docking/subduction of the Indian plate with the Eurasian Plate leading to the formation of the Himalayan mountain range. Figure 11 displays the geothermal provinces of India and a simplified tectonic arrangement. This long geological evolution has led to the formation of various geological features and associated structural patterns that are favourable for geothermal regions and mineral deposits to form [e.g., 170, 172].

At this time, around 340 hot springs have been identified with surface temperatures in a range of 32 °C to 97 °C [35, 173, 174]. These hot springs are spread over seven geothermal provinces, namely the Himalayas, Sohana, Cambay, Son-Narmadah-Tapi rift zone (So-Na-Ta), West coast, Godavari basin, and Mahanadi basin. The combined geothermal potential of these provinces is estimated to be around 10.6 GW_e [35, 175]. The reservoir temperatures in these provinces are in a range of 102 °C to 260 °C [174]. The Himalayan in the north and the Cambay province in western India are the two most-studied provinces with some geothermal heat utilisation activities.

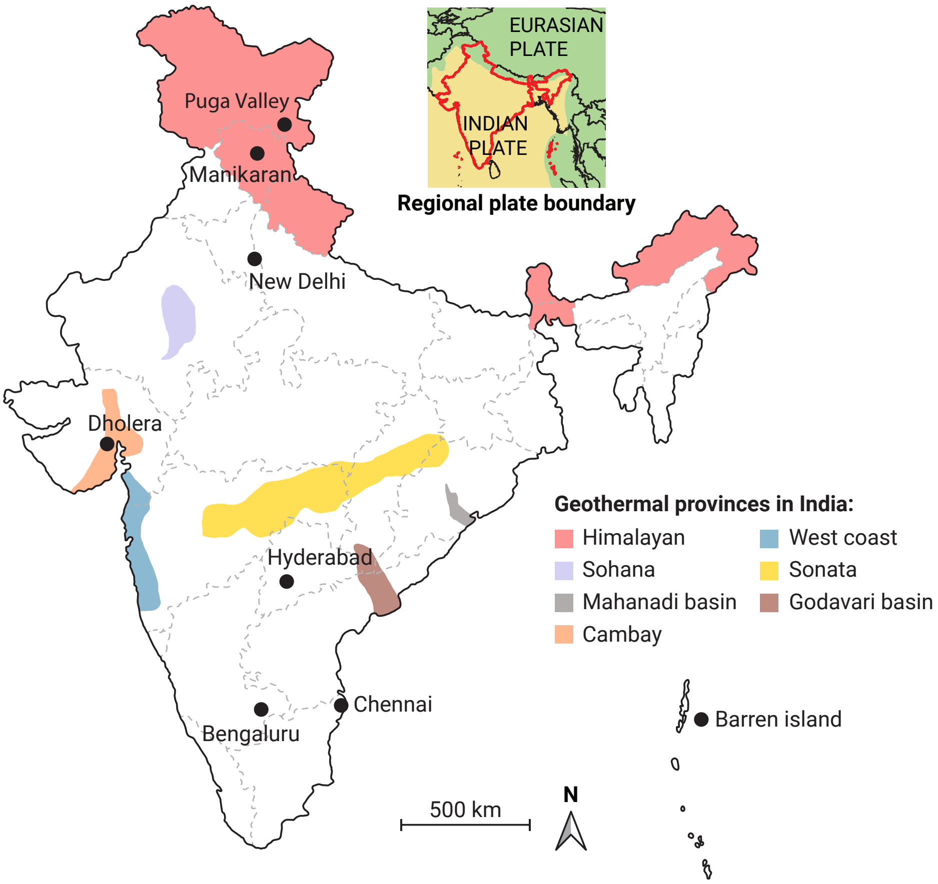


Figure 11: Geothermal provinces of India adapted and modified after [35, 172]. Simplified current plate tectonic arrangement around India as inset, adapted from [55]. Solid red line demarcates the territory of India.

The Himalayan province is mainly associated with post-tertiary granite intrusions blanketed with sedimentary cover. This region has thermal reservoirs within hot granite. Chandrasekharam et al. [176] suggest that these heat-generating granite rocks can make India one of the major electricity producers from EGSs. Previous studies show that the Puga geothermal field in this province could power a 20 MW_e power plant. The power generation in this field could curtail power shortages in Jammu and the Kashmir region, dependent on hydropower stations that do not work at full capacity during winters [174]. The state-owned company Oil and Natural Gas Corporation (ONGC) started to drill exploration wells in the Puga geothermal field. In the first phase of exploration for a 1 MW_e pilot plant, drilling of two 1 km deep wells began in August 2022. After one week of drilling, high-pressure steam of 100 °C with a flow rate around 27.7 kg/s was encountered. Successful implementation of this pilot plant in this geothermal field could pave the way for constructing a deeper reservoir, leading to a commercial-scale geothermal power plant [177].

Successful geothermal utilisation was conducted to extract mineral resources, such as borax, sulphur and potentially caesium, from the hot springs located in the Puga geothermal field. Greenhouse cultivation, incubating poultry and mushrooms, and space heating applications have been effectively demonstrated in this region [174].

The Manikaran geothermal field is in the Himachal Pradesh state, known for its apple farms. This field has a small geothermal-driven absorption chiller of 7.5 t capacity (1 refrigeration ton is about 3.5 kW_t). A trial run of a 5 kW_e binary cycle power plant was also carried out [35]. Such utilisation cases could support cold storage of apples grown in this region. One of the direct-use applications is cooking rice with geothermal water to serve millions of worshippers visiting Gurudwara [172].

Cambay geothermal province is among India's main oil and gas regions. It has sedimentary deposits blanketing simple lava flows. Research suggests that this province is an ideal candidate to harness geothermal energy from abandoned oil and gas wells in India [178]. The reservoir temperatures are in a range of 150 °C to 175 °C. Two geothermal wells of 457 m were drilled at Swaminarayan Temple in Dholera. The geothermal resource temperature is around 47 °C, which is supplied to a simultaneous heating and cooling heat pump. This heat pump increases the water temperature to make it suitable for processing honey and pasteurisation of milk. The cooling side of this heat pump supplies chilled water to meet the space cooling demand of the auditorium at the temple [179].

The Western Coast province is a large graben in India, covered by thick Deccan flood basalts which are affiliated with massive volcanic eruption activity. The area has a high heat flow anomaly, a possible magma conduit structure and an unusually shallow Moho layer [35, 180]. The reservoir temperatures are in a range of 102 °C to 137 °C. The So-Na-Ta province has a strong tectonic reactivation with reservoir temperatures of 105 °C to 217 °C [35]. The predicted reservoir temperatures of the hot springs in Godavari basin are 128 °C to 184 °C. The reservoir temperatures of the resources in the Sohna province range from 45 °C to 147 °C. The geothermal surface manifestations in Mahanadi basin could have reservoir temperatures up to 144 °C [181].

The geothermal policy drafted by the government in 2016 envisioned geothermal deployments of 1 GW_t and 20 MW_e by 2022 and an increase to 10 GW_t and 1 GW_e by 2030 [182]. The policy subsidises the installation of GSHPs. This policy document claims that direct-use applications like balneology, swimming, bathing, and cooking have a combined capacity of 986 MW_t. There has not been any update on this policy since 2016. Currently, India does not have any operational geothermal power plants. For reservoir depth ranges of 3 km to 7 km, the estimated EGS electricity production potential for India is 30,082 GW_e [97].

The Barren Island in the Bay of Bengal hosts India's sole active volcano. The geothermal potential on this island is unknown due to the lack of exploration [175]. The presence of the active volcano suggests that it could be worthwhile for further exploration.

India has vast untapped geothermal potential. Implementing GSHP technology could efficiently harness this energy for space heating, replacing harmful practices like charcoal burning in northern regions. To deploy these technologies, awareness drives are essential to inform local communities about government policies. The same low-temperature technology can be implemented in other parts of the country for space cooling applications. Decentralised geothermal power plants offer a promising solution to improve electricity supply to remote villages. A promising future path involves strategic investment in geothermal exploration and development, especially in regions like the Himalayas and Cambay. Harnessing geothermal energy from abandoned oil and gas wells, for example in the Cambay region, can be regarded as a potential path for cleaner power generation in India. Further, EGSs offer significant electricity production capacity positioning India as a major clean energy producer and reducing reliance on fossil fuels. India should prioritise geothermal energy development, update policies, and invest in infrastructure for a greener and more resilient energy sector. Consequently, geothermal energy can play a pivotal role in India's sustainable energy transition.

3.3.2. Republic of Korea

The Republic of Korea (ROK) is located in the eastern continental margin of the Eurasian continental plate and is a composite landmass. Figure 12 shows a simplified tectonic map of ROK and locations of hot springs. Starting from the north to southward direction, the Precambrian Kyeonggi and Yeongnam massifs are separated by the Okcheon Fold Belt, and followed by the Gyeongsang sedimentary basin in the southeastern part of the landmass [183]. The rocks in ROK consist of metamorphosed gneiss and schists, sedimentary rocks, granites, and some young volcanic rocks [e.g., 184]. The source for geothermal waters is strongly related to the widespread distribution of the granites and their associated deeply-connected fracture network [183, 185]. The non-volcanic geothermal waters are distributed throughout the country and are categorised into two types according to Lee et al. [186]. The first group is the residual magma-type geothermal waters that have a temperature range of around 35 °C to 77 °C and are associated with igneous intrusions. The second group are the deep groundwater type geothermal waters having a temperature range of 24 °C to 35 °C.

Geothermal waters in ROK have been used for public baths and spa-related facilities for over 2000 years [e.g., 187]. These spas utilise hot spring water temperatures ranging from 23 °C to 76 °C. Lee et al. [183] indicates that ROK has 233 geothermal wells and 452 hot spring facilities.

The use of GSHPs has rapidly increased in public and commercial applications since 2000 [188]. The increase in the number of GSHP installations is also attributed to existing infrastructure and historical groundwater usage, and ongoing government subsidies that kept drilling and installation costs low [185, 189]. The latest total installed capacity for GSHPs is estimated to be 1579 MW_t [147]. These GSHPs installations provide space heating and cooling to buildings. Despite this positive uptake of GSHPs, there is growing concern that the groundwater is becoming environment unstable and unsafe for the general population [e.g., 189].

The only known attempt to generate geothermal power is the Pohang EGS project, a proof-of-concept to construct a 1.5 MW binary power plant [190]. The project was conceived to exploit the heat flow anomaly associated with a major fault system and a

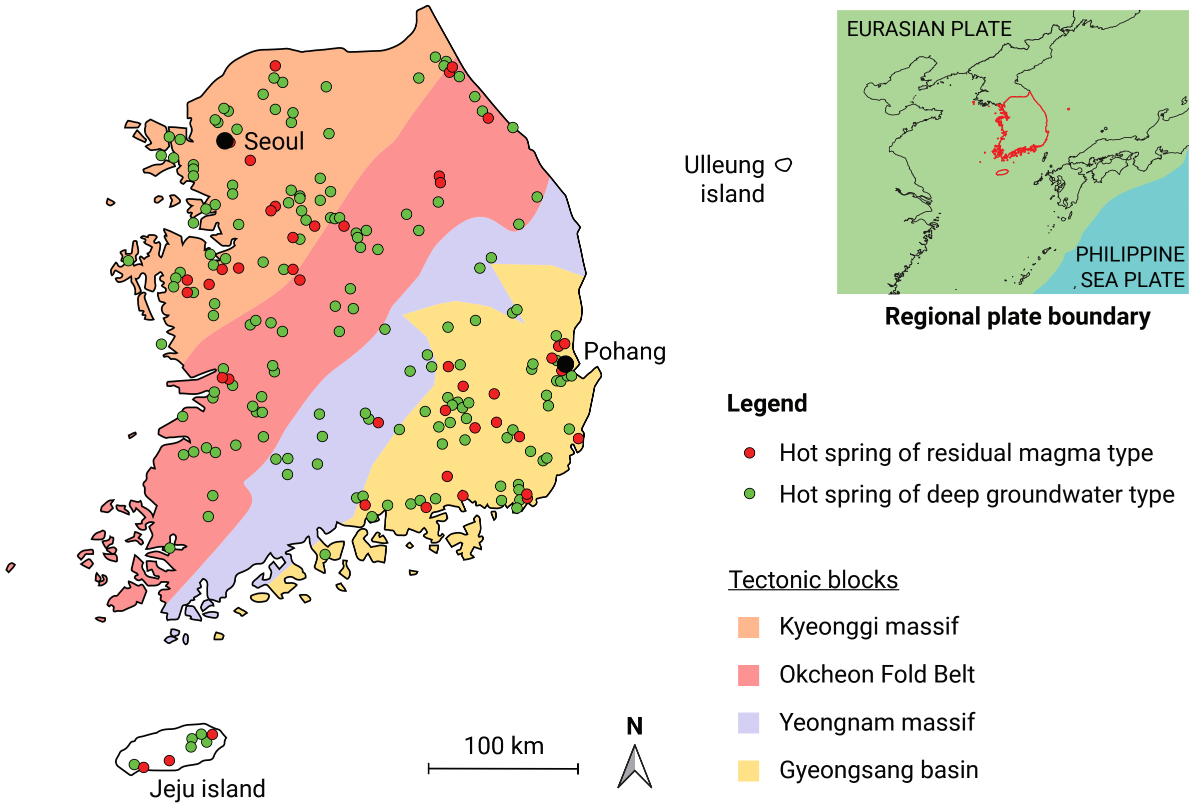


Figure 12: Simplified tectonic map of ROK, adapted from [183]. Simplified current plate tectonic arrangement around ROK as inset, adapted from [55]. Locations of hot springs have been adapted from [186].

sedimentary basin [185]. Previously drilled petroleum-related wells at Pohang indicate that the geothermal gradient there is above 30 °C/km, which is higher than the national average of 25 °C/km [191]. Two deeper wells were then drilled after the exploration well in 2010 to depths of 4.1 km and 4.3 km for EGS stimulation experiments in 2016 [192]. The project was then discontinued after it was determined that the project caused the 2017 Pohang earthquake [e.g., 193]. Public perception of geothermal energy has decreased significantly. Pohang residents view geothermal power as negatively as nuclear power [194].

The government of ROK has passed a series of policies since 2000 to encourage the adoption of new and renewable energy systems [e.g., 185]. For instance, the Promotional Law of New and Renewable Energy Development, Use and Dissemination law ensured the mandatory installation of renewable energy systems such as GSHP into newly constructed and reconstructed public buildings and facilities [188]. Furthermore, the government has also introduced financial support for new installations of these renewable energy systems. However, significant policy changes have been made to the policies concerning geothermal energy after the 2017 Pohang Earthquake. Other forms of renewable energy, including solar, wind and nuclear power, are being pursued to increase power generation from renewable sources from 30% to 35% by 2040 [195]. Funding new research and development projects and exploration activities involving geothermal energy and GSHPs were significantly reduced for projects developing hybrid renewable energy systems involving GSHPs. Geothermal exploration activities have received no updates following the conclusion of investigative efforts on Ulleung and Jeju islands [196].

Since the 2017 Pohang Earthquake, geothermal exploration in ROK has reduced significantly to the point that GSHPs are only considered with hybrid systems. Other renewable sources are considered to meet their energy and proposed targets by 2040. Undoing negative public perception on geothermal will be challenging. Despite the challenges, cities such as Seoul have made plans to grow their current installed geothermal heating and cooling capacity from 278 MW_t to 1000 MW_t and to construct a large 23 MW geothermal plant by 2030 [197]. Therefore, we opine that ROK will not completely abandon geothermal power.

3.3.3. Singapore

Singapore is located at the southern edge of Peninsular Malaysia within the Eurasian tectonic plate. Figure 13 displays its simplified geology with variegated arc-derived granites and dykes [198], very-low metamorphic grade sedimentary rocks with pyroclastic-tuff related rocks towards the east [199, 200], and a series of marine and terrestrial sedimentary rocks to the west [201]. The near-surface geological features are well understood up to the first few hundred metres deep, partly due to the abundance of shallow boreholes and building works [202]. Regional heat flow maps indicate anomalous heat flows ranging from 110 mW/m^2 to 130 mW/m^2 located towards the west of the island [203]. The cause for the anomaly could be attributed to nearby subduction-related arc magmatism and extensional deformation in Sumatra and Java [204].

Singapore has several naturally occurring spring systems, of which the Sembawang and Tekong island hot springs have the highest measured temperatures. The waters of the Sembawang hot spring reach a surface temperature of at least 70 °C. A mean reservoir temperature of 163 °C has been estimated by applying a Na/K geothermometer proposed by Santoyo and Díaz-González [206] on the Sembawang hot springs. The estimated reservoir temperature suggests being hot enough to generate electricity and district cooling schemes in Singapore [207]. Numerical simulations indicate that subsurface temperatures of 125 °C to 150 °C could be found at a depth of 1.25 km to 2.75 km beneath the Sembawang hot spring [208]. The Sembawang hot spring also resides within the Simpang granite pluton, one of the variegated granites with elevated concentrations of radiogenic heat elements (Uranium, Thorium and Potassium). The heat production of this granite can be estimated by applying the method described in Rybach [209] on the concentrations of the radiogenic heat elements at 100 m to 200 m deep [198]. The calculated radiogenic heat production is from 7 $\mu W/m^3$ to 8 $\mu W/m^3$, which is around twice the mean global granite heat production [210]. The current geothermal reservoir model suggests that the Sembawang hot spring is part of a hydrothermal system where meteoric water percolates to about 5 km deep, gets heated and flows upwards due to thermal buoyancy through faults to form hot springs at the surface [207, 211].

The second confirmed hot spring, Unum, is located towards the northern extent of Tekong island, the second largest offshore island located at the north-eastern extent of Singapore. The general geology of the island is understood to be a layer of volcanic-related rocks deposited over moderately deformed and very-low grade metamorphosed sedimentary rocks [199]. Similar volcanic rocks can also be found in south-eastern Johor, Malaysia, sharing similar ages, corresponding to a period of active volcanism [212]. These volcanic rocks have been proposed to provide a thermal blanketing effect over the possible granitic basement. The heat source could be derived from radiogenic heat

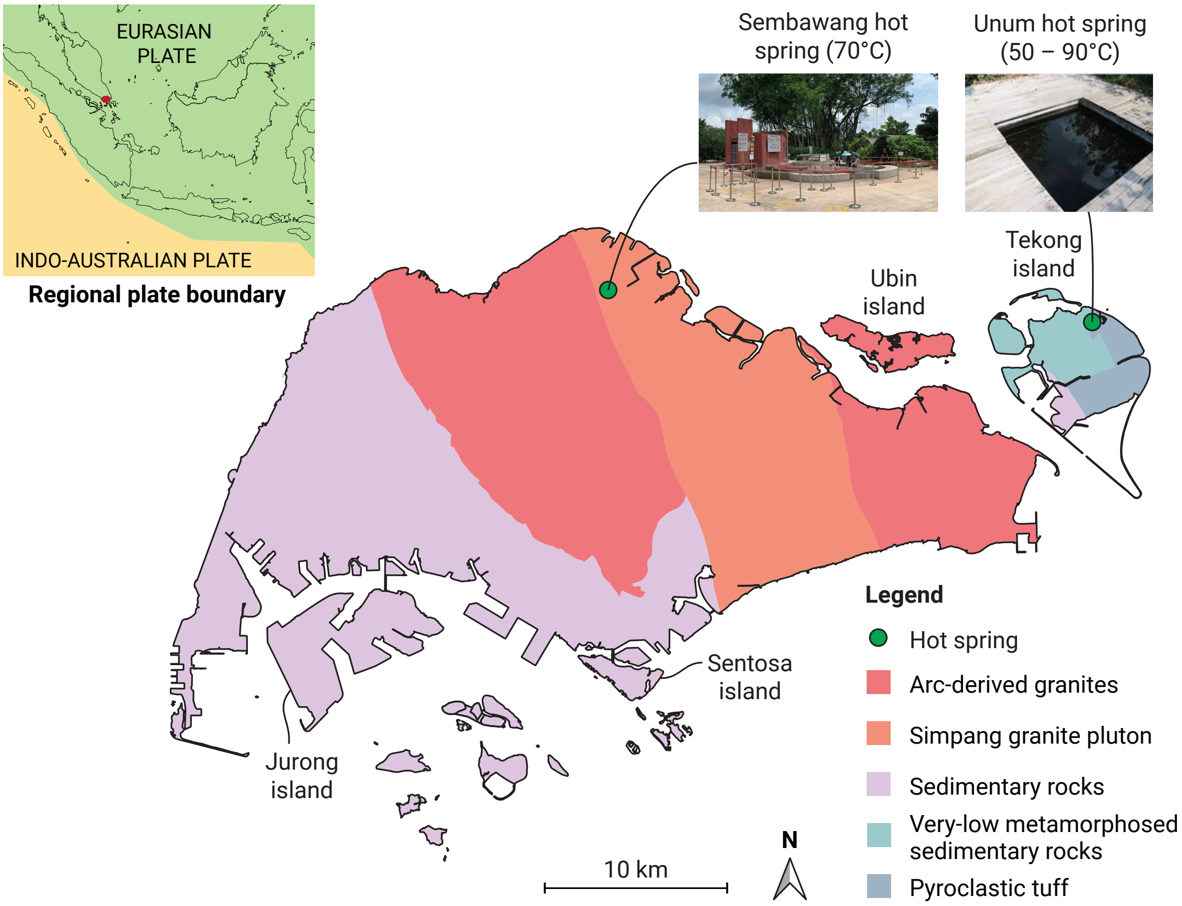


Figure 13: Simplified geological map of Singapore with the locations of the Sembawang and Tekong Island hot springs adapted from [198, 205]. The location of Singapore in the Southeast Asia region is indicated with a red dot in the regional plate boundary inset (modified after [110]).

production within the granite and high heat flow from the mantle [207]. The measured surface temperatures of the water and wet soils around the hot spring are 50 °C and >90 °C, respectively. Other hot springs on Tekong Island might exist, but their locations may be lost due to ongoing land reclamation activities.

The amount of stored heat in place in Singapore within the regions of Simpang granite pluton (where the Sembawang hot spring resides and the shallow granite radiogenic heat production is high) and Tekong island (where the Unum hot spring resides) can be estimated by using the volumetric method [213–215]. The available thermal energy can be determined to amount to 5×10^{19} J, with the following assumptions: 1) the hot rock has a vertical extent of 2 km at a depth of 3 km to 5 km which Qiu et al. [97] describe as zones applicable for relatively simple practical applications, 2) total hot rock plan area of 175 km^2, 3) a 60 °C temperature difference exists between the working fluid at production (150 °C) and injection (90 °C) wells, and 4) the volumetric heat capacity of the rock is 2.5×10^6 J/(°C m^3). The power potential can be estimated—using the method described in Quinao and Zarrouk [216] and Ciriaco et al. [217]—as 1 GW$_e$ for 30 yr.

A recent geothermal exploration effort has drilled two deep slimholes to acquire temperature measurements towards the island's north. The measured temperatures at 1.1 km depth are among the highest when compared with measured temperatures in other countries with non-volcanic geological setting [218].

The Singapore government has initiated several measures to accelerate its energy transition ambition. One such initiative includes a nationwide non-invasive survey aimed at exploring the potential for geothermal development and carbon sequestration. Another initiative is establishing a Future Energy Fund of SGD 5 billion by the end of 2024. This fund is intended to support the country's energy transition towards a net-zero future and could potentially expedite the development of geothermal energy in the country. Singapore's geothermal energy resource can be harnessed for various uses, including power generation, space cooling, industrial preheating and dehydrogenation processes.

3.3.4. Thailand

The tectonic setting of modern Thailand is caused by the movement and merging of regional tectonic plates, similar to those of previously discussed neighbouring Southeast Asian countries. Figure 14 shows a simplified tectonic setting of Thailand, including hot springs locations. In Northern Thailand, the most recent regional tectonics is attributed to the collision of the Indian Plate that uplifted oceanic crusts and sedimentary basins through a series of continental thickening events and the reactivation of existing structural zones [219]. The topography of Southern Thailand is defined by a central mountain range that forms the spine of the peninsula, and it extends northwards into Myanmar [e.g., 220, 221]. In-between this mountain range are the Ranong and Khlong Marui fault zones that traverse in a Northeastern-Southwestern orientation.

There are about 120 hot springs scattered from northern, western and southern Thailand with surface temperatures ranging from 40 °C to 100 °C [224]. Based on the surface temperatures of these hot springs, geothermal prospects have been identified as low and medium potential (≤80 °C) and high potential (>80 °C) as shown in Figure 14 [223].

In Northern Thailand, these hot spring systems are located on fault systems within the Paleozoic and Mesozoic plutonic rocks, Paleozoic metavolcanic rocks, or along the edges of Cenozoic basin sediments against pre-Cenozoic rocks [225]. In the Fang geothermal field, exploration wells were drilled into low resistivity anomalous zones that discharged hot water of 125 °C with a total flow of 22 kg/s [e.g., 226]. These wells underwent a successful production test, leading to the procurement of a 300 kW binary power plant to become Thailand's current geothermal power production. Deep exploration wells conducted at the San Kamphaeng geothermal field indicate geothermal gradients up to 130 °C/km [227]. One of these wells intersected a fracture zone at depth and generated a 125 °C water discharge at around 11 kg/s [228]. These high measured geothermal gradients and heat flows in Northern Thailand could be attributed to local structures and their subsequent reactivation caused by regional extensional tectonics during the Miocene [229, 230].

In Southern Thailand, surface temperatures of the hot springs range from 40 °C to 80 °C, and hot springs are located in proximity to fault zones [231]. Reservoir temperatures are estimated to be in a range of 73 °C to 143 °C based on applied geothermometers. The chemical composition of the geothermal waters indicates that the reservoir is likely a zone of mixing hot waters with existing groundwater or seawater intruded in near-coastal aquifer. These hot springs in southern Thailand have been identified to be hot enough to run and produce electricity through binary power plant systems [231].

Thailand uses geothermal energy for both power generation and direct-use applications through the demonstration binary cycle system at the Fang geothermal field.

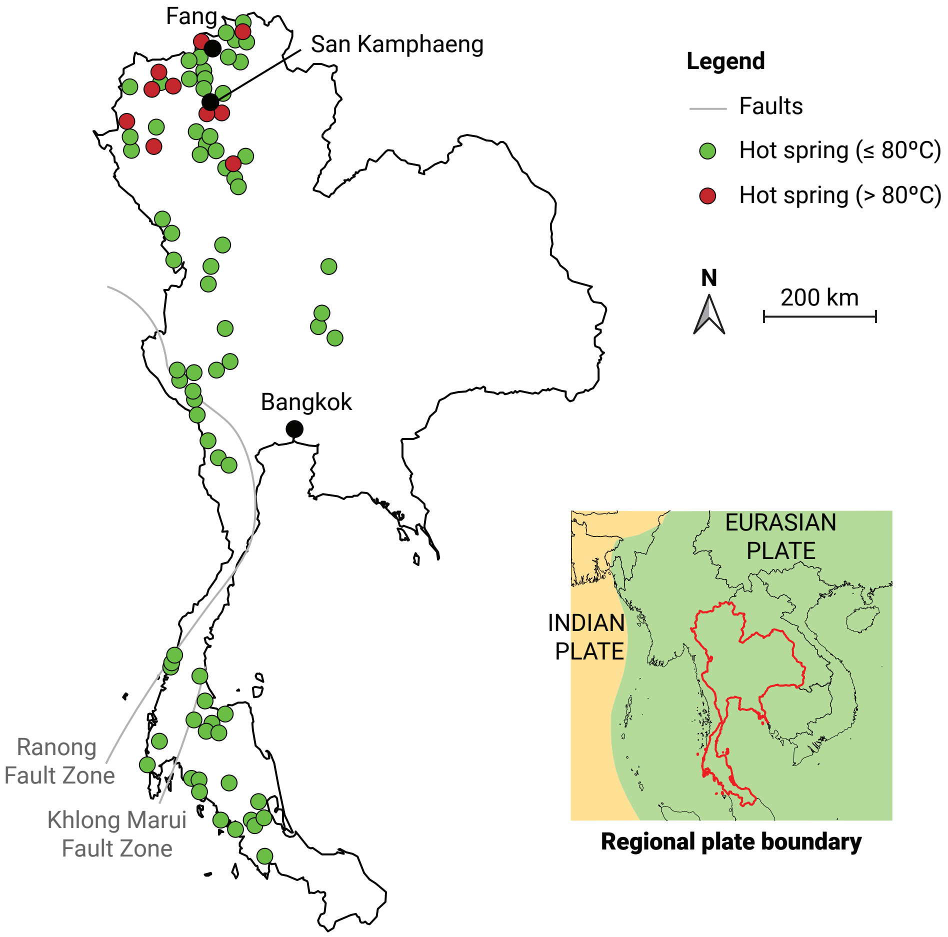


Figure 14: Simplified tectonic setting of Thailand adapted from [222]. Locations of hot springs after [223]. The territory of Thailand in the Southeast Asia region is indicated with red lines in the regional plate boundary inset (modified after [55]).

The Fang geothermal plant was constructed by collaborating with the French Energy Agency, Japan International Cooperation Agency (JICA) and Chiang Mai University [226]. This plant utilises waters from shallow wells with temperatures of 116 °C at flow rates of about 8.3 kg/s [228, 232]. Power output varies from 150 kW_e to 250 kW_e throughout the year and its yearly production amounts to 1.2 GWh/yr [233]. The exhaust hot water (80 °C) from the binary plant is then used to run additional downstream applications such as a 480 kW_t demonstrator for crop drying, cold storage and air conditioning [226]. The cost of production and maintenance of the Fang geothermal power plant is found to be significantly lower as compared to producing fossil fuels [121].

Thailand has conducted several experiments and demonstrations of GSHPs to provide space cooling in various locations [224]. The most notable demonstrations were conducted at the Kasetart University [234] and at the Chulalongkorn University Bangkok [235]. These demonstrations resulted in promising results where electrical power usage is reduced, with COP values ranging from 3 to 4. The results show that the GSHPs at Chulalongkorn University reduce electricity consumption for cooling by 30% as compared to conventional air conditioning. Additionally, some hot springs in Thailand have been developed by the local community and provincial government sector as recreation and spa-related areas [231]. Geothermal exploration studies are being conducted on whether similar Fang geothermal plant cases can be utilised with the hot springs

[223, 236]. If all hot springs were fully utilised as presented, the estimated potential for power generation and direct-use would be 3.9 MW_e and 2.4 MW_t, respectively.

Under the current policy, the Alternative Energy Development Plan, the Thai government has set a target of 30% of its total energy consumption to be from renewable energy sources by 2036, and another target to achieve carbon neutrality by 2050 [25]. These targets are also in line with Thailand's National Energy Plan 2022, which involves increasing the proportion of power generation from renewable energy sources, including geothermal, to 50% in 2040. Although a FIT has not been implemented for geothermal power, the policy seeks to gather more information on Thailand's geothermal potential and feasibility studies to determine suitable technologies for low-heat geothermal power [28]. An update on renewable energy development policy is expected to be released within 2024 after many delays owing to the pandemic [237].

Despite not being near tectonic boundaries or having active volcanoes, Thailand has successfully operated a geothermal power plant for several decades. The power plant represents the combined effort of engaging with other countries with more geothermal experience. The value of similar collaborations is also repeated in the Lahendong (see Section 3.2.2). Thailand also attempted to build their local talent pool for geothermal by conducting several GSHP demonstrations at various universities and public buildings. It is encouraging that Thailand is studying other hot springs to duplicate the Fang geothermal plant project. However, renewable energy scientists perceive that the current support from the Thai government for their work is insufficient to pursue additional energy-related projects. An update to Thailand's renewable energy development is required to provide the direction and support needed for renewable energy scientists.

4. Discussion

4.1. Limitations of the study

Information on the latest geothermal development is only available through newspaper articles and press releases. In the Philippines, the launch of two binary power plants was reported in press releases. In Taiwan, information on the relaunching of the Qingshui geothermal power plant and the establishment of geothermal partnerships were reported from news articles and the industry's press release websites, respectively. The abandoning of the Tawau geothermal plant in Malaysia was reported by the New Straits Times. These webpages are included and cited accordingly.

The study was conducted during a period of global events such as the COVID-19 pandemic and the ongoing Russia-Ukraine war. Such events may have caused positive and negative changes to the country's renewable energy policies, and are reported first in newspapers and press releases. In Thailand, the government has implemented policies to revive tourism in Thailand post-pandemic and prioritised the well-being of its citizens [238]. Such measures have delayed updates to the renewable energy policy [237]. The Russian-Ukraine war is an ongoing atrocity that has caused significant devastation to Ukraine and caused a high volatility of global energy prices [up to 70% in 239]. However, there is renewed interest in countries to improve their energy security through increased renewable energy development as seen in Germany that saw an increase in investments to fund geothermal projects [240].

Data such as geothermal gradient, reservoir pressure, and groundwater flow in most countries are mostly unavailable or not publicly accessible. Furthermore, this data may be presented in the local language, requiring authors to rely on online translations and third-party summary reports.

4.2. Main findings

Among countries considered in this review, seven (China, Indonesia, Japan, Malaysia, the Philippines, Taiwan and Vietnam) have measured temperatures corresponding to high-temperature GRC, and four (India, Republic of Korea, Singapore and Thailand) fall into the low-GRC category, as indicated in Table 2. Countries like Indonesia, Japan and the Philippines are expected to be in the high-GRC group as they reside in tectonically active regions. High-GRC countries are already harnessing geothermal energy for electricity generation, except for Malaysia (due to permit issues) and Vietnam. In contrast, low-GRC countries primarily utilise geothermal resources for heating and cooling. Thailand is the only low-GRC country currently generating electricity, albeit at demonstration scale.

Table 2: Summary of countries' GRC based on their measured temperatures and the final energy carriers when using their geothermal resources. The measured temperature refers to either the measured reservoir temperature or the highest down-hole temperature, whichever is available or the highest. A country is categorised as 'high' if $T > 150\,°C$ and 'low' if $T \leq 150\,°C$. #Heating includes space heating and swimming pool heating applications.

Country	T [°C]	Reference	Application			
			Electricity	Heating#	H_2	Cooling
High-GRC countries						
China	>150	Fu et al. [63]	✓	✓		
Indonesia	>150	Darma et al. [36]	✓	✓		
Japan	>150	Kaieda [101]	✓	✓	✓	
Malaysia	200	Lawless et al. [114]				
Philippines	>150	Halcon et al. [125]	✓	✓		✓
Taiwan (China)	225	Fan et al. [149]	✓	✓		✓
Vietnam	180	Cuong et al. [241]		✓		✓
Low-GRC countries						
India	130	Craig et al. [174]		✓		✓
Republic of Korea	83	Song et al. [185]		✓		✓
Singapore	70	Zhao et al. [211]				
Thailand	130	Ramingwong et al. [228]	✓	✓		✓

Geothermal power projects are often associated with high upfront costs, mainly for exploration and drilling, and long project lead times from exploration to power plant construction. These factors contribute to high financial risk [242–244]. There are two examples of measures adopted by the reviewed countries to mitigate financial risk. The first example is government intervention with policies that provide financial support for geothermal energy projects, as seen in Japan, Malaysia, Indonesia and Taiwan. The second example is through regional organisations such as the Asian Development Bank that helps to maintain project financial viability for developing countries to explore and utilise geothermal energy, of which Lao PDR, Cambodia and Myanmar are recipients [245, 246].

Countries with limited access to conventional geothermal resources and/or oil and gas resources tend to lack expertise in geothermal exploration and utilisation. However, knowledge transfer is possible through international collaborations, such as the Germany-Indonesia collaboration in Lahendong (Indonesia) and the France-Japan-Thailand collaboration in Chiang Mai (Thailand), which have led to the development of demonstration geothermal binary power plants. Additionally, countries can establish geothermal research centres, such as India's Centre of Excellence for Geothermal Energy (CEGE), which serve as centralised entities to nurture local talents and incubate geothermal-related technologies. Building local expertise can also position countries to leverage emerging technologies, such as AGS when they become commercially viable.

Geothermal project development can sometimes encounter challenges due to stakeholder mismanagement issues. Concerns raised by these stakeholders span a wide range, including environmental impacts, property values, health and safety, livelihood, and insufficient public participation in the project [247]. For example, geothermal development in Japan often faces opposition from local *onsen* owners, mainly due to concerns that it may disrupt their livelihoods. In Indonesia, a geothermal power project in Gunung Talang, West Sumatera, experienced delays due to violent clashes stemming from societal movements, largely caused by the lack of local community involvement in the project. Managing stakeholders is not straightforward, as each project requires a unique approach.

EGS, AGS and the reuse of abandoned oil and gas wells are identified as emerging research trends that can promote geothermal uptake in Asian countries. China, India, and Japan have been researching technologies related to heat extraction from deep hot rocks using the EGS/HDR methods. While the EGS potential is promising, commercial exploitation faces technological challenges in controlling rock fracturing and addressing concerns about induced micro-seismicity, especially in urban areas. For countries with established oil and gas industries, such as Malaysia, China and India, ongoing research explores the viability of repurposing abandoned wells for geothermal energy utilisation. Countries committed to developing their geothermal potential are encouraged to persist in exploration efforts and establish local knowledge pools, positioning themselves to adopt emerging technologies effectively.

5. Conclusion

An upward trend from 1995 to 2020 for geothermal applications in Asia indicates that there is a growing demand for geothermal utilisation. In this work, a comprehensive review has been conducted on geothermal development with an extension of low-temperature resources in South, Southeast, and East Asia. China, Indonesia, Japan, Malaysia, the Philippines, Taiwan (China) and Vietnam are identified as high-GRC countries. India, Republic of Korea, Singapore and Thailand are identified as low-GRC countries. Products from high-GRC countries are mainly electricity and space heating. Products from low-GRC countries are mainly space heating and cooling. EGS, AGS and the reusing of abandoned oil and gas wells are identified as emerging research trends that can promote geothermal uptake in Asian countries.

Declaration of competing interest

The authors report no declaration of interest.

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