Geothermal Energy Use and Its Related Technology Development in Japan

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Japan has national targets to intensify the geothermal power generation. The government gives several fiscal incentives for geothermal development and R&D through the Ministry of Economy, Trade and Industry (METI). Beside short-termed target by 2030, Japan has a long-term target by 2050. Therefore, the R&D also has a short-term target to develop the conventional hydrothermal systems effectively with improved technologies and a long-term target to develop supercritical geothermal resources at a depth of volcanic region. The latter covers from basic scientific investigation to highly technological innovation. In contrast, ground source heat pump (GSHP) has been promoted by the private sectors supported mainly by the Ministry of Environment (MOE). A topical research work on the ground source heat pump in Japan is suitability mapping for both closed-loop and open-loop systems based on studies of groundwater flows. The detailed situation and research activities for both geothermal power generation and ground source heat pump will be discussed in this paper. [DOI: 10.1115/1.4050384]

Keywords: geothermal energy, renewable energy

1 Introduction

Located along the Circum-Pacific Volcanic Belt "Ring of Fire," Japan is blessed with an abundance of geothermal energy. According to the potential survey, theoretical potential of geothermal energy to a depth of 3 km is over 20 GW_e [1]. The total capacity of geothermal power plants reached over 500 MW_e already in 1995. Then, however, mainly due to socioeconomic factors, the installation of new capacity stagnated for almost two decades.

Following the accident of a nuclear power plant in Fukushima in 2011, measures to intensify deployment of renewable energy by the Ministry of Economy, Trade and Industry (METI) have renewed interest in geothermal development. For geothermal power generation, the supporting policy covers the full stage of geothermal development and use: exploration risk mitigation, low interest loan for construction, Feed-in Tariff (FiT) for electricity sales, and R&D. Aiming at high FiT price, dozens of small binary power plants of under 1 MW, for which no intensive exploration is needed, have quickly commissioned in recent years [2]. Explorations for larger power generation have also been conducted in dozens of prospects, but the development progress is slow due to technical difficulties and environmental cautions, etc. Two larger steam-flash power plants; Matsuo-Hachimantai (7.499 MW_e) in Iwate and Wasabizawa (46.199 MW_e) in Akita were commissioned in 2019, resulting in the total installed capacity of geothermal power of 554 MW_e [3]. It is still far below the government's target to triple the capacity to be 1500_e MW by 2030. Therefore, METI continues technology development and fiscal support to reduce the resource risks of geothermal development.

There is another long-term target of geothermal technology development to drastically increase the capacity of geothermal power generation to provide baseload. In April 2016, the cabinet of Japan formulated National Energy and Environment Strategy for Technological Innovation toward 2050 (NESTI 2050) in which utilization of supercritical geothermal resources is qualified as one of the most essential technologies to reduce greenhouse gases in 2050 [4]. An R&D project "Development of subduction-origin supercritical geothermal resources" was launched in 2017 to utilize 400–500 °C supercritical fluid at a depth of 5 km or less. Earlier surveys suggested existence of such resources in/around volcanic zones in Japan with a nationwide potential of several tens of GW_e. The project has a target year of around 2040 for the operation of a pilot plant.

In Japan, promotion of ground source heat pump (GSHP) started at the beginning of 21st century led by the private sector. Then with the government's promotional support, the number of installations has been increasing rapidly in recent years. The total installation number in the end of 2015 is 2230 with total capacity of 134 MW_t. Annual heat use (geothermal contribution) is estimated to be 162.2 GW_t-h. Note that the cooling function of GSHP is even more important than heating in terms of energy saving, which is estimated to be 305.9 GW_t-h a year [5].

On the contrary conventional direct heat use in Japan is rather stable. Its dominant part has been bathing [6], but the number of visitors and total flow rate of these geothermal baths are both gradually decreasing with peaks in 2002 and 2007, respectively. The number of other direct use facilities may be slightly increasing due to subsidies from the federal government to promote geothermal energy use. However, since no survey has been conducted in recent years, the data for direct use shown in Table 1 is based on old data [7].

Table 1 summarizes the current geothermal use in Japan [3]. Detailed trends of geothermal energy use and technology development for geothermal power generation and GSHP will be discussed in this paper.

Table 1 Status of geothermal energy use in Japan in 2020 [3]

	Electricity [2]	Direct use [6,7]	GSHP [5]
Total installed capacity	550[a] (MW_e)	2407 (MW_t)	163 (MW_t)
Total generation	2409[b] (GWh)	29,491 (TJ/yr)	765 (TJ/yr)

[a]At December 2019.
[b]Based on the data of FY 2017 (April 2017 to March 2018).

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2 Geothermal Power Generation

2.1 Trend of Geothermal Power Development in Japan. Figure 1 shows the long-term trend of geothermal power generation in Japan. A significant increase from 1970s to 1990 was supported by R&D and exploration subsidies funded by New Energy and industrial technology Development Organization (NEDO). However, as described in Sec. 1, power capacity has been stagnated since 1996. Another issue is that the average capacity factor of the geothermal power plants has been decreasing since the 1970's and the annual power generation has been decreasing since 1997. The major reason is that in the twentieth century with immature knowledge of geothermal reservoir management, developers built larger capacity power plants that were beyond the ability of the reservoirs to support the facilities long-term, resulting in declining steam production with time. Due to this reason, several older power plants have been replaced with new units of smaller capacity since 2010. Therefore, although the total number of the units has increased in recent years because of quite small plants, the total capacity decreased between 2012 and 2017. The increase in capacity in 2019 is due to the commissioning of Wasabizawa and Matsuo-Hachimantai geothermal power plants.

2.2 Ongoing Geothermal Development Projects. A geothermal development project generally takes a long time from exploration to power generation. In addition, there are resource risks, which make geothermal power projects more difficult. To assist in managing these risks, Japan Oil, Gas and Metals National Corporation (JOGMEC) supports the development of geothermal resources using three financial support mechanisms; grant subsidies, equity capital investment, and loan liability guarantees for geothermal development.

In FY2019, 24 projects were accepted for grant subsidies, as shown with red text in Fig. 2. Construction of geothermal power plants has been announced in several other areas such as Minami-kayabe in Hokkaido (6.5 MW, 2022), Oyasu in Akita (15 MW, 2024) and Appi in Iwate (15 MW, 2024), which projects have been also supported by subsidies in previous years.

Matsuo-Hachimantai geothermal power plant, commissioned in January 2019, is a model case in which JOGMEC's support mechanisms have worked effectively, from grant subsidies, equity capital investment, through to the liability guarantees. Liability guarantee system was also applied for Wasabizawa geothermal plant, commissioned in May 2019.

2.3 National Research Highlights. Currently, two METI funded agencies JOGMEC and NEDO are supporting R&D for geothermal developments. JOGMEC has been conducting potential surveys and technology development which would accelerate current geothermal developments. NEDO has been funding research on subduction-origin supercritical geothermal resources with a target year of 2040 for a pilot plant to be operational as a NESTI2050 project.

2.3.1 JOGMEC's Contribution. Aiming at rapid increase of geothermal power capacity, JOGMEC has been conducting rather short-term projects which may contribute to the target capacity increase by 2030, consist of series of a-year-long surveys and a-few-year-long technology developments. It has undertaken airborne helicopter geophysical surveys since 2013 acquiring basic data for the evaluation of some geothermal prospects. Because most geothermal prospects in Japan are located within national parks in mountainous areas where access for surface surveying is quite limited, airborne geophysical surveying is an effective method to cover a wide area with a complex topography, identifying lineaments and hydrothermal alteration zones. By the end of FY2019 it had been conducted in nineteen regions. JOGMEC then has begun heat flow drilling since 2017 to investigate subsurface temperature and geological structure to a depth of about 1000–1500 m in selected prospects found by airborne geophysical surveys. By the end of FY2019, heat flow drilling has been conducted at 11 sites in five regions shown as the green boxes in Fig. 3 [8].

Beside resource surveys, JOGMEC has been conducting geothermal technology development under three themes as follows.

(i) Geothermal Reservoir Evaluation and Management

Technologies of artificial reservoir recharge and permeability improvement are under development. Recharging reservoir by water injection has been studied at a test site in Yanaizu-Nishiyama geothermal field, Fukushima. Increase of steam production has been observed. Permeability improvement has been studied at Yakumo region, Hokkaido. By nonbrine water injection, a permeability increase of 250% has been observed [8]. Manuals of these technologies will be published in the end of the projects.

(ii) Improvement of Exploration Accuracy

Two seismic methods, Distributed Acoustic Sensing—Vertical Seismic Profiling (DAS-VSP) and micro-seismic methods have been studied under this theme.

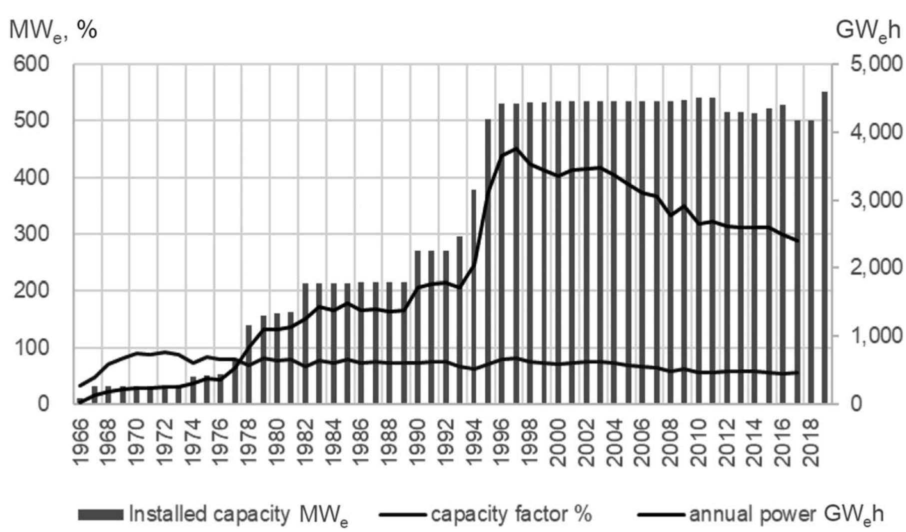

Fig. 1 Geothermal power in Japan: total installed capacity (columns), power generated (darker line), and capacity factor (lighter line) [2]

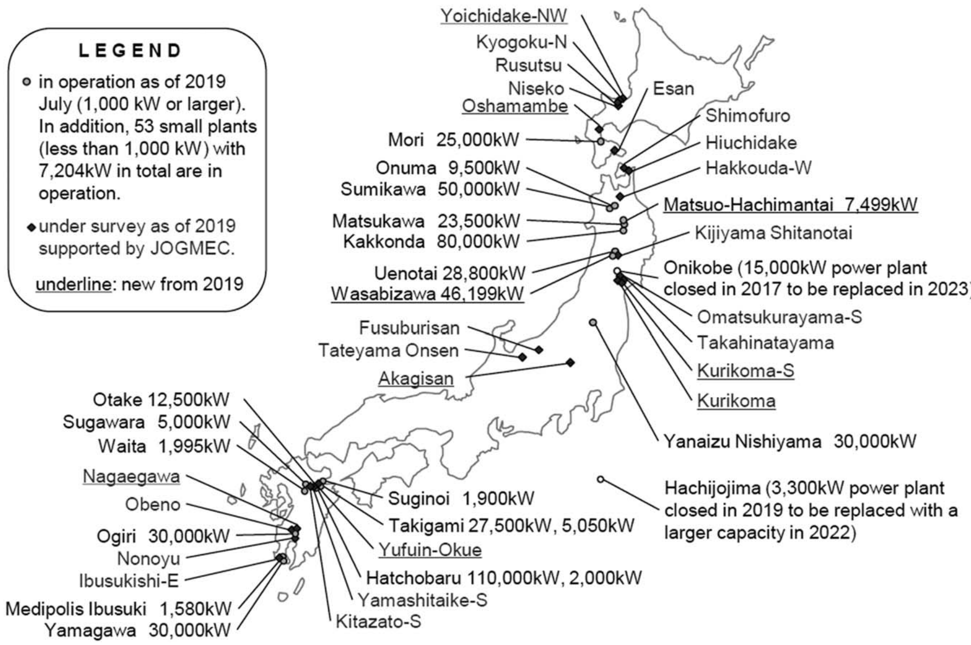

Fig. 2 Geothermal power plants and ongoing projects in Japan

DAS-VSP technology, developed by the oil industry, was improved for application to high temperature geothermal fields by using optical fiber receivers. Results of the field test at Ogiri, Kagoshima show that DAS-VIP gives higher resolution than conventional reflection methods (surface seismic profiling, SSP) especially on the fractures penetrating a wellbore as shown in Fig. 4 [8].

For micro-seismic methods, improvement of vertical resolution has been done by using a tri-axial receiver inserted into a vertical well. A field observation has been conducted using an observation

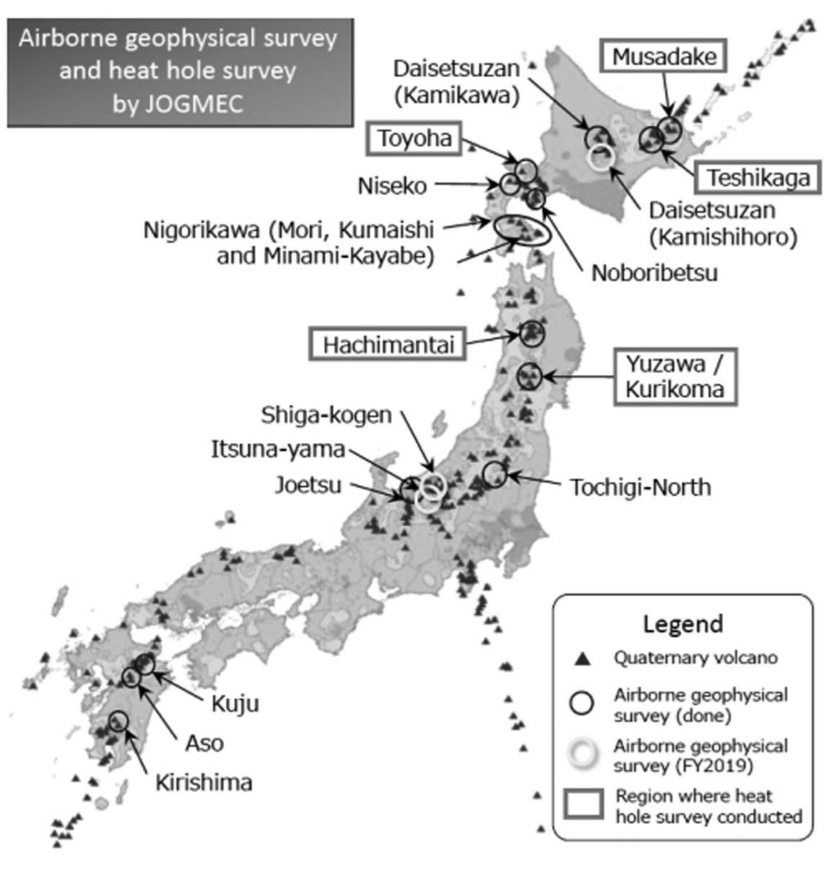

Fig. 3 Regions for airborne geophysical survey and heat flow drilling surveys conducted by JOGMEC [8]

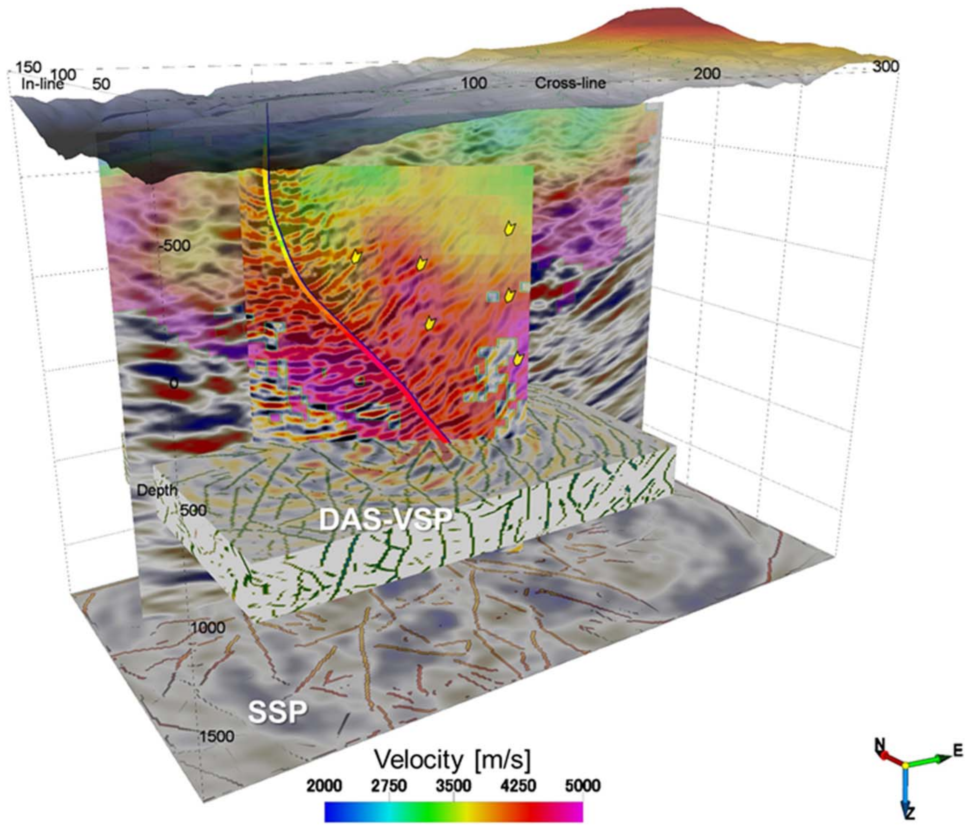

Fig. 4 Comparison of DAS-VSP and SSP survey results for data obtained at Ogiri geothermal field, Kagoshima [8]

well at Kijiyama, Akita. The seismic data will be analyzed with those from sensors set on the ground surface. A thermally resistant tri-axial Fiber Bragg Grating sensor will be developed also in this project.

(iii) Drilling Technology Development

Improvements in polycrystalline diamond compact (PDC) bits for geothermal wells have been achieved. PDC bits have been widely used in oil industry but not in geothermal business because of its limit in applicability to hard volcanic rocks and high temperature condition. Therefore, several improvements on the diamond cutter of PDC bits, such as size and distribution, have been conducted and know-how of its application, such as optimal rotation speed for each rock type, have been investigated. Figure 5 shows the fabricated PDC bit. As a result of field test at a geothermal site, the improved PDC bit showed higher performances in both drilling rate and strength than a conventional tri-cone bit. A better cost performance of the PDC bit may be the next challenge for real application.

Currently under this theme, technologies have been developed on (a) mitigation of well troubles by lost circulation and (b) small rig with high-power. Since most of the geothermal systems in Japan underlies in deep steep mountains, a small rig enables us to enlarge accessible geothermal prospects and to reduce total cost of the drilling.

2.3.2 NEDO's Contribution. NEDO has been conducting geothermal technology development since 1970s. It was closed once in early 2000s, but then restarted in 2012 focusing on technologies for surface facilities. Then NEDO's research direction was shifted to long-term projects to contribute to the target capacity increase by 2050, including subsurface parts to launch an R&D project "Development of subduction-origin supercritical geothermal resources" in 2017 to utilize supercritical fluid of 400 to 500 °C existing at a depth of shallower than 5 km (Fig. 6). Earlier studies suggested existence of supercritical geothermal resources in and around plural volcanic zones from geochemical [9] and geophysical aspects [10]. Then, its high possibility of existence is discussed based on estimated permeability at a depth [11]. The expected total potential reaches several tens of GW of electricity in the nation [12]. A pilot plant is planned to be in operation around 2040.

The hardest technical challenge in this project would be to overcome problems with acid fluid in supercritical conditions. Therefore the project covers various fundamental scientific studies in rock mechanics, material science, and geo-science, as well as technology development in numerical simulation and drilling. Currently the related projects are being led by the National Institute of Advanced Industrial Science and Technology (AIST) and Kyoto University, funded by NEDO.

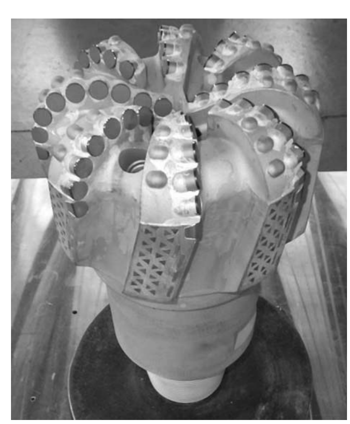

Fig. 5 Fabricated PDC bit [8]

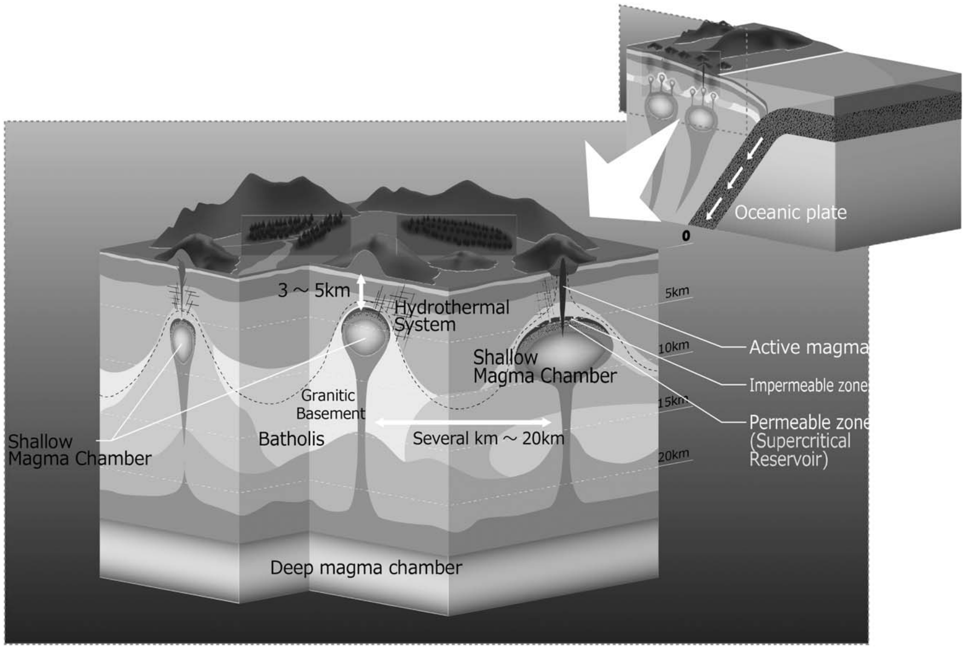

Fig. 6 Conceptual model of supercritical geothermal system in northeast Japan [12]

There are several ongoing research projects on supercritical geothermal system in the world. In Iceland, Italy, Japan, Kenya, Mexico, New Zealand, and the USA, where supercritical condition may be achieved in an accessible depth, drillholes have encountered temperature higher than 374 °C [13], the supercritical point of water. Among them, a drilling in Iceland encountered 427 °C at a depth of 4659 m in 2017 with successful production of fluid. A past drilling at Kakkonda, Japan encountered 500 °C at a depth of 3729 m in 1995 but rocks around the bottom-hole was dry. Although no fluid was found, the temperature record in Kakkonda has risen interest of overseas researchers in supercritical systems. Taking advantage of the natural condition, high temperature in comparatively shallow depth, NEDO's project will begin a test drilling in the next few years after finishing various laboratory studies and site selection.

3 Ground Source Heat Pump

3.1 Trend and Current Status. The installation of GSHP in Japan has been increasing rapidly in recent years, although the total number is rather small (Fig. 7). The Ministry of Environment (MOE) has been conducting census on GSHP installation in the nation every other year. According to this census, the total number of facilities using GSHPs is 2662 (2314 closed-loop, 327 open-loop, and 21 combined) with installed capacity of 163 MW_t and annual energy use of 765 TJ/yr [5]. In essence, a more than doubling in uptake in 5 years.

A large number of GSHP systems have been installed in northern Japan where heating needs are intensive, indicating the economic predominance of GSHP when they replace an old oil boiler (Fig. 8). Nonetheless, GSHPs are widely used in other parts of the nation as well. Since cooling needs are quite high in central to southern Japan, GSHP systems with high COP (coefficient of performance, which is obtained heat energy per used electricity) for cooling [14] are contributing to electricity savings. The MOE's census also shows the cumulative number of GSHP systems by different facility categories. The largest share is individual houses (44%), followed by offices (12%) and public buildings (7.5%) [5].

3.2 Related Studies—Suitability Mapping. Unique studies on closed-loop GSHP systems have been conducted in Japan taking advection effect of groundwater flow into consideration. Since shallow unconfined aquifer in basins and plains in Monsoon Asia has considerable flowrate, the effective heat conductivity of the rock on site depends on flowrate of groundwater due to advection effect. Therefore, the system design of borehole heat exchanger should be done based on the effective heat conductivity of the site affected by the groundwater flow. This approach is quite different from other regions where advection effect is neglectable and system design has been done based only on the heat conductivity of rock or saturated rock. Another topical thing is that, since cooling and heating demands are equivalently high in most part of the nation, a system should be designed to maximize the performance for both heating and cooling. It is also different from other regions where GSHP has been used mainly for heating so that higher geothermal heat flow is preferred. On the contrary in Japan high subsurface temperature is not an important element but higher heat exchange rate caused by groundwater flow is preferred.

A study on suitability mapping of GSHP systems has been done in Japan based on groundwater flow modeling in basins and plains. The study funded by NEDO, was initiated by AIST, Hokkaido

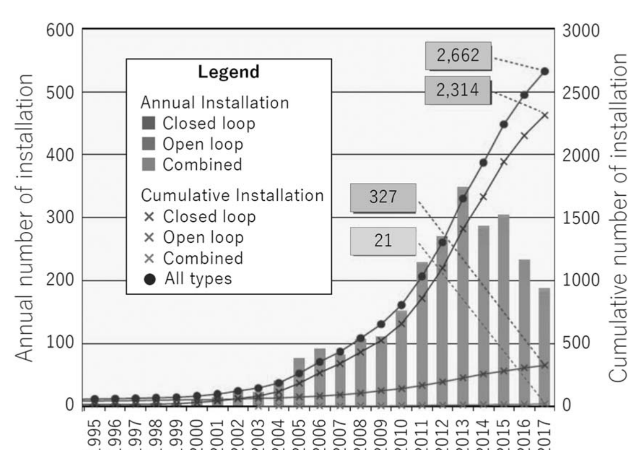

Fig. 7 Cumulative and annual installation number of GSHP in Japan [5]

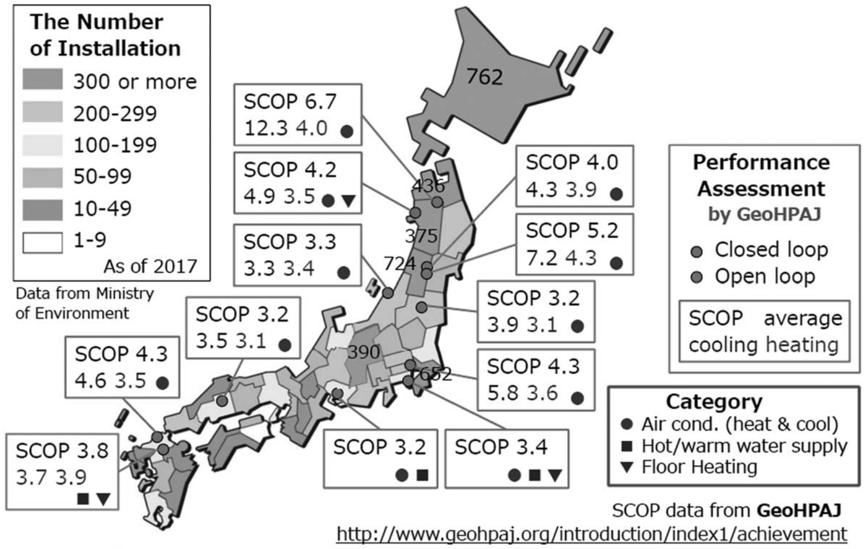

Fig. 8 The number of GSHP installation in each prefecture in Japan [5] and measured system-COP at several systems [13]

University and Akita University to cover all major basins and plains, and companies have subsequently become involved.

Groundwater information is essential to roughly evaluate the suitability of GSHP systems at a site for both open-loop and closed-loop systems. For open-loop systems, information on aquifer depth and flowrate is indispensable to design the well depth and pumping rate of the system. Chemistry of groundwater is also important to avoid scaling of the heat exchanger.

For closed-loop systems, information on effective heat conductivity of the geological formation is essential. In Quaternary basins and plains consisting of unconsolidated sediments in monsoon Asia, effective heat conductivity of shallow underground largely differs from one place to another due to both the existence of aquifers and the advection effect of groundwater flow. Since saturated rock has a higher heat conductivity, existence of shallow aquifer raises heat exchange rate so that information on the water table becomes important. Also since higher water velocity gives higher heat exchange rates, information on 3D groundwater flow is useful for designing subsurface heat exchangers. For a suitability map, sustainable heat exchange rate at several sites (red triangles in

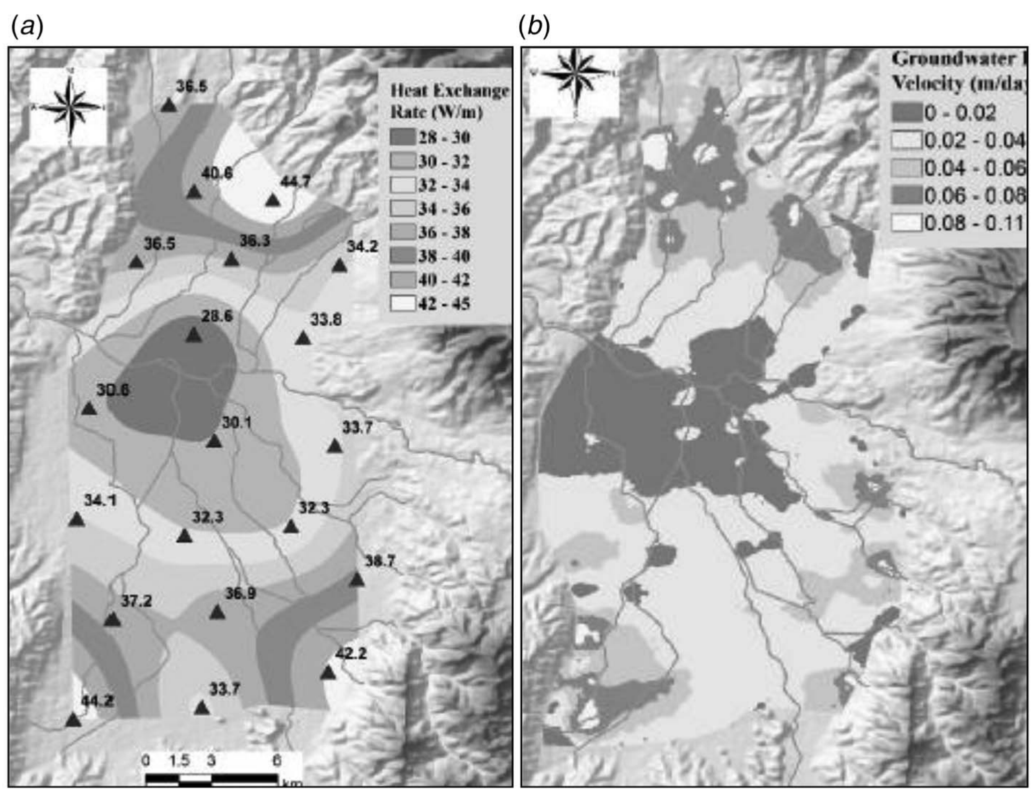

Fig. 9 An example of suitability map: (*a*) distribution of sustainable heat exchange rate and (*b*) distribution of flowing velocity of groundwater [14]

Fig. 9) is calculated by heat exchange simulation using a regional ground water flow model.

Groundwater studies based on field surveying and numerical simulation have been used to prepare separate suitability maps for open-loop and closed-loop systems. Separate maps for heating-only demand, and heating and cooling demand have been developed for based on subsurface temperature data. Figure 9 shows an example of a suitability map for a closed-loop system for heating-only demand [15]. The left map is the suitability map, showing the sustainable heat exchange rate per length of borehole heat exchanger, calculated based on the groundwater flowrate and subsurface temperature. The right map shows the flowing velocity of groundwater, the base data of the left map, obtained as a result of regional groundwater flow simulation. A suitability map of open-loop system is based on the aquifer depth, ability of reinjection into the aquifer, and chemistry of the groundwater. Comparison of suitability maps for closed-loop and open-loop systems for an identical region enables us to select more suitable system at a site.

Study area of such a suitability map normally covers a whole plain or a basin. Therefore, for more administrative purpose, 11 municipalities in Japan have compiled GSHP suitability maps for their own administrative district based on the study results. They opened the information to promote the use of GSHP in their district for energy saving purpose.

4 Conclusion

Japan has national targets to intensify the geothermal energy use for a short term and a long term. Research activities for the short term are to reduce the exploration risk by higher resolution geophysics and to improve reservoir management. Research activities for the long-term target development of subduction-origin supercritical geothermal resources which include basic geoscientific research on subsurface supercritical conditions in volcanic regions and technological innovations for drilling and power generation with supercritical fluid. For promotion of ground source heat pumps, suitability mapping for both closed-loop and open-loop systems, which is quite unique study in Japan, are conducted separately for heating-only mode and heating and cooling modes, based on groundwater information. Such suitability maps are used by local municipalities promoting GSHP systems for saving energy purpose. Thus, geothermal energy use for both power generation and direct use is promoted by federal and local government sustained by research activities.

Acknowledgment

The description on the national projects is based on the open information by JOGMEC, NEDO, and AIST. The related figures are also from the open sources of these organizations as shown in the figure caption and references. The author appreciates the information disclosure of these organizations.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. Data provided by a third party listed in Acknowledgment. No data, models, or code were generated or used for this paper.

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