Exploring Sustainable Geothermal Energy Potential in Beppu, Japan

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Introduction

The transition toward sustainable energy systems has become an urgent global challenge as concerns over climate change, resource depletion and energy security continue to intensify. For countries with limited domestic fossil fuel resources like Japan, the development of renewable energy sources is important in achieving long-term energy stability while reducing environmental impacts.

Among various renewable energy sources, geothermal energy sources offer a promising option due to Japan's unique geological setting along the Circum-Pacific Volcanic Belt (Geological Survey of Japan, AIST). This tectonic environment provides abundant geothermal resources, positioning Japan among the world's most geothermally resource-rich nations.

Despite this advantage, the development of geothermal resources has remained limited compared to its potential. While geothermal power generation began in Japan in the mid-twentieth century, progress slowed for several decades due to high development costs, regulatory constraints, and social opposition in regions closely associated with hot spring tourism.

Many geothermal resource areas overlap with traditional onsen regions, where hot springs play a central role in local culture, tourism, and economic activity. Concerns regarding potential impacts on hot spring water quality and quantity have led to resistance from local stakeholders, highlighting the importance of social acceptance and community engagement in renewable energy development. Existing academic studies have largely focused on large-scale geothermal power generation, while fewer studies examine small-scale, culturally embedded uses of geothermal resources and their role in local sustainability.

Beppu City, located in Oita Prefecture on Kyushu Island, offers a unique and valuable case for examining these issues. As Japan's largest hot spring aream Beppu is characterized by an exceptional concentration of geothermal resources that are integrated into daily life. In addition to bathing, geothermal heat and steam are utilized for traditional cooking methods such as *jigoku-mushi*, space heating, agricultural processing, and tourism-related activities. These practices demonstrate an alternative model of geothermal utilization that emphasizes direct use and cultural integration rather than large-scale electricity generation.

Aim of the Study

This study aims to explore how geothermal energy is utilized and managed in Beppu, with a particular focus on the cultural and historical relevance of the city's onsen tradition. In addition, this study seeks to identify challenges associated with geothermal development, and to analyze diverse perspectives to explore potential pathways toward socially acceptable and sustainable geothermal energy development.

Methods

This study was conducted by a combination of literature review with an experience-based learning approach. The literature review consisted of prior studies, government and institutional reports, and relevant press releases related to geothermal energy, renewable energy policy in Japan, and the cultural and social dimensions of hot spring utilization. This review provided the theoretical and fundamental knowledge necessary to interpret field-based observations.

The experience-based learning focuses on knowledge acquisition through direct engagement with the local community. On-site field visits were conducted in Beppu City to observe the practical utilization of geothermal resources and their integration into everyday life. Through observation of geothermal facilities, hot spring environments, and steam-based applications, this study examined how geothermal energy is incorporated into community life and the social and cultural dimensions of sustainable geothermal energy utilization.

Detailed Field Trip Schedule

The itinerary mostly adhered to the approved proposal, with adjustments made based on local conditions and timing.

Date	Time	Location and Activity
Dec 13, 2025	10:00 – 11:00	Beppu Onsen Museum: Observation of the geological, cultural, and historical background of onsen
	11:00 – 11:30	Onsen-Zome Research Laboratory: Study of onsen utilization for dyeing
	12:00 – 13:00	Eat jigoku-mushi (onsen-steamed cuisine): Study geothermal energy use in local food practices
	13:00 – 15:00	Umi Jigoku and Oniishibozu Jigoku: Field observation of tourism management of hot spring resources
Dec 14, 2025	11:00 – 12:00	Eat jigoku-mushi at Okamotoya: Study of onsen-based culinary business model
	12:00 – 15:00	Visit Myoban District and Myoban Yunosato: Survey of traditional alum production and landscape preservation
Dec 15, 2025	10:00 – 11:00	Experience onsen at Hyotan Onsen: Observation of onsen facilities and visitor management practices
	11:00 – 13:00	Walk in the Kannawa Area: Survey of onsen town layout, infrastructure, and community-tourism interaction
	13:00	Return to Kyoto

Literature Review

Geothermal Energy in Japan

Japan is one of the world's most geothermally endowed countries, with an estimated geothermal potential of approximately 23 GW, ranking third globally. Despite this potential, geothermal power generation remains underutilized compared to other renewable energy sources such as solar and wind.

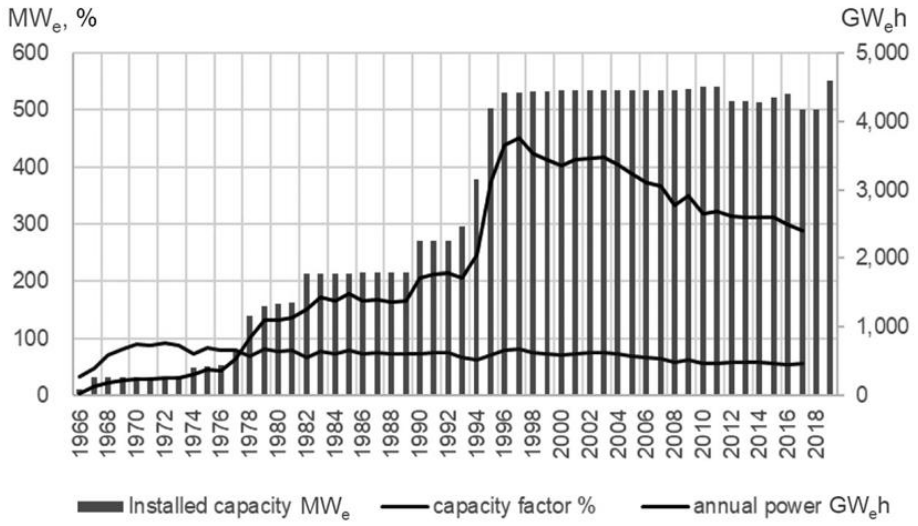

Figure 1. Trend of geothermal power generation in Japan. Reproduced from Yasukawa (2021).

Figure 1 shows the long-term trend of geothermal power generation in Japan. Japan's first geothermal power plant began operation in 1966 and growth from the 1970s to around 1990 was supported by exploration subsidies from the New Energy and Industrial Technology Development Organization. In 1995, the installed capacity had reached approximately 500 MW (Geothermal Research Society of Japan, 2020). However, installed capacity has remained almost unchanged since 1996. The average capacity factor has declined since the 1970s, and annual power generation has decreased since 1997. This decline is mainly due to early development practices, in which power plants were built at capacities larger than what geothermal reservoirs could sustain over the long term, leading to reduced steam production (Yasukawa, 2021).

Following the Fukushima nuclear accident, geothermal energy regained attention as a stable and low-carbon energy source (Taghizadeh et al, 2020). The Ministry of Economy, Trade, and Industry (METI) has since introduced policy reforms to encourage geothermal development, including subsidies for exploration and easing regulations in certain national park areas. Research institutions such as the National Institute of Advanced Industrial Sciences and Technology (AIST) have also launched projects targeting advanced geothermal technologies, including supercritical geothermal systems.

Despite these efforts, large-scale geothermal expansion continues to face social and institutional barriers, underscoring the need to examine alternative models of geothermal utilization that prioritize coexistence with local communities.

Cultural Significance of Onsen and Geothermal Resources

Onsen have long played a central role in Japanese society, serving functions that extend beyond recreation to include health, spirituality, and community life. Historical evidence suggests that the use of hot springs in Japan dates to the Jomon period, when naturally heated waters were valued for their restorative properties. Over time, hot springs became important spaces for physical recovery. During the Nara and Heian periods, the significance of hot springs expanded beyond physical healing to include religious and spiritual dimensions, where Buddhist practitioners incorporated onsen bathing into purification practices. In the Edo period, improvements in transportation and increased domestic travel

led to the growth of hot spring towns, where accommodations, public bathhouses, and leisure facilities emerged around geothermal resources. These developments marked the transformation of onsen into multifunctional spaces combining health, social interaction, and tourism.

With the onset of modernization in the Meiji era, onsen were increasingly promoted as part of national wellness culture. Despite these changes, onsen have continued to function as shared communal spaces grounded in long-standing customs. Onsen bathing is governed by established norms and practices that reflect broader cultural values. Thorough washing prior to entering the bath emphasizes cleanliness and consideration for others. Although communal bathing without clothing may appear unfamiliar to some visitors, these practices are rooted in notions of equality, comfort, and mental calm.

The cultural significance of onsen is closely linked to Japanese concept of wa, or harmony. By utilizing naturally occurring geothermal water without extensive modification, onsen represent an adaptive relationship between humans and the natural environment rather than an attempt to dominate it. Therefore, geothermal development cannot be understood solely as a technical or economic matter. It also carries social and cultural implications.

Social Acceptance and Geothermal Development

Social acceptance has been identified as one of the most critical factors influencing geothermal energy development in Japan (Kubota et al, 2013). Conflicts between geothermal power projects and local communities often arise from insufficient communication, lack of trust, and perceived threats to traditional livelihoods. Projects with strong local involvement and transparent decision-making processes tend to experience fewer conflicts. Conversely, top-down approaches driven solely by national energy goals frequently encounter resistance. These suggest that geothermal sustainability must be evaluated not only in terms of energy output but also in terms of social legitimacy.

To contextualize these social challenges at the national scale, Figure 2 presents the distribution of operating geothermal power plants and ongoing development projects across Japan.

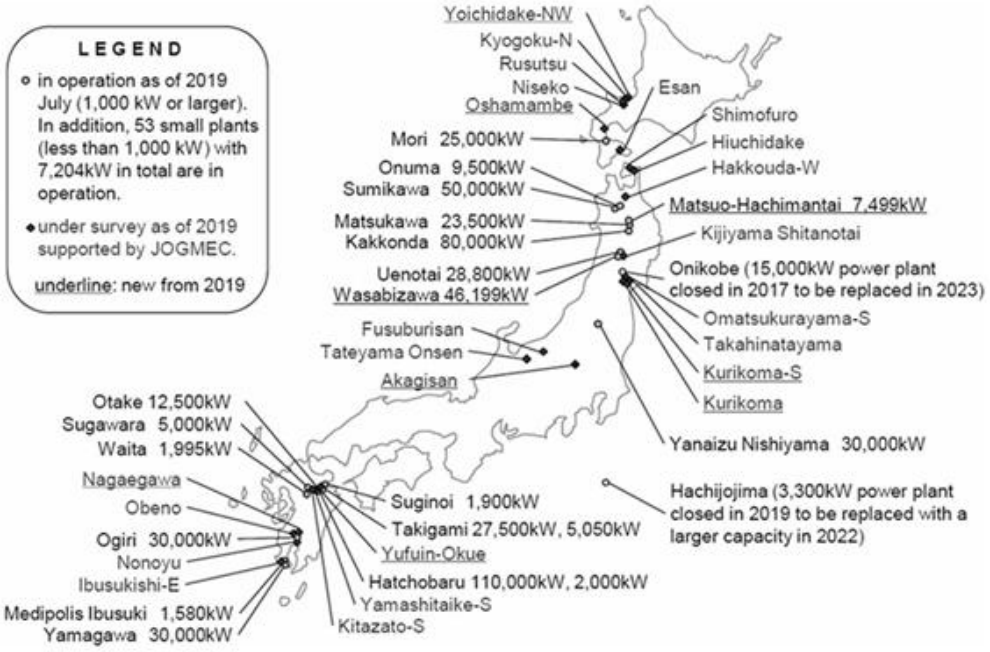

Figure 2. Distribution of geothermal power plants and ongoing geothermal development projects in Japan. Reproduced from Yasukawa (2021).

Figure 2 illustrates the spatial distribution of geothermal power plants and planned projects across Japan, highlighting the concentration of large-scale facilities in volcanic regions such as Kyushu, Tohoku, and Hokkaido. While these projects demonstrate Japan's significant geothermal potential, many have faced delays, downsizing, or cancellation due to opposition from local communities, particularly in areas with established onsen cultures. This pattern underscores the tension between centralized energy development and local resource use. In contrast to these large-scale projects, Beppu's geothermal utilization is characterized by small-scale, diversified, and non-extractive applications that coexist with local livelihoods, illustrating an alternative pathway toward socially sustainable geothermal development.

Results

Field observations conducted in Beppu revealed that geothermal energy is deeply integrated into everyday cultural practices, local industries, and community life.

Geological Formation and Hydrochemical Diversity of Beppu's Hot Springs (Findings from the Kannawa Jigoku Onsen Museum)

Figure 3. Kannawa Jigoku Onsen Museum. (Left) Exterior view of the Onsen Museum. (Right) Steam emission from a natural hot spring source at the museum.

Field-based learning at the Kannawa Jigoku Onsen Museum provided a scientific framework for understanding the geological and hydrochemical processes that underpin Beppu's geothermal system. The exhibits explain that the origin of Beppu's hot springs dates back approximately 50,000 years and is closely linked to volcanic activity associated with Mount Tsurumidake and Mount Garandake. This long-term geological evolution has resulted in a complex subsurface environment in which geothermal heat, water, and geological structures interact to produce diverse hot spring characteristics.

The formation of hot springs in Beppu requires three essential factors: a water source, a heat source, and water passageways. In Beppu, the primary water source is meteoric water, including rain and snow, which infiltrates the ground in the surrounding volcanic highlands. Although the region receives abundant rainfall, only approximately 16% of this water permeates sufficiently deep underground to contribute to hot spring formation, while the majority flows directly into rivers and the sea. This highlights the selective and limited nature of geothermal recharge despite the apparent abundance of surface water.

Once underground, infiltrated water is heated by magma chambers and geothermal heat from the Earth's interior. During this process, the water interacts with volcanic gases, including hydrogen chloride, sulfur dioxide, carbon dioxide, and hydrogen sulfide. These interactions result in the formation

of highly acidic hot fluids capable of dissolving minerals such as sodium and potassium from surrounding rock formations. Therefore, the chemical composition of hot spring water is strongly influenced by both volcanic gas content and rock–water interactions occurring at depth.

Geological structures play a crucial role in transporting geothermal fluids toward the surface. In Beppu, repeated lava eruptions and tectonic activity have created numerous faults and fissures that function as natural conduits for hot water and steam. Under high subsurface pressure, water remains in a liquid state even at temperatures exceeding 100 °C. However, as geothermal fluids ascend through fractures toward the surface, pressure decreases, causing the hot water to boil and separate into liquid and gaseous phases.

This phase separation is a key mechanism underlying the diversity of hot spring water types observed in Beppu. During boiling, volatile components such as hydrogen sulfide and carbon dioxide preferentially migrate into the steam phase. When this steam mixes with shallow underground water, it produces sulfate-type or hydrogen carbonate-type springs. In contrast, residual hot water that has released steam becomes diluted by seepage water and emerges at the surface as sodium chloride–type springs. Furthermore, as geothermal fluids reach the surface, rapid changes in temperature and pressure cause dissolved minerals to crystallize, producing fine particles that scatter light and give some hot springs their characteristic blue or milky-white appearance.

Beppu's geological setting further enhances this diversity. The city is located on an alluvial fan composed of permeable sediments such as sand and gravel, which facilitate groundwater movement. Combined with the presence of magma heat sources and extensive fracture networks, this topography enables hot springs of varying chemical compositions to emerge throughout the city. As a result, Beppu contains seven of the ten internationally recognized hot spring water types within a single urban area, making it exceptional even among volcanically active regions.

These geological and hydrochemical characteristics explain why Beppu possesses the largest number of hot spring sources in Japan, totaling approximately 2,854, and produces the highest volume of hot spring water nationwide. Beyond their scientific significance, these features support diverse cultural, therapeutic, and touristic practices, reinforcing Beppu's identity as a "hot spring city." From a sustainability perspective, the Beppu case illustrates how long-term geological processes, when combined with careful human utilization, can support renewable energy use that is both environmentally grounded and culturally embedded.

Geothermal Tourism in Beppu

Figure 4. The seven hells of Beppu (Left) Umi Jigoku. (Right) Oniishibozu Jigoku.

The Jigoku, commonly referred to as the “Seven Hells of Beppu,”, are a group of geothermal sites characterized by extreme temperatures, vigorous steam emissions, and distinctive mineral composition. These geothermal features are distributed mainly in the Kannawa and Shibaseki areas of Beppu, and each site exhibits different physical characteristics, highlighting the geological diversity of the region.

The Jigoku sites in Beppu function as key tourism resources that contribute to Beppu’s regional economy while showcasing the city’s geothermal characteristics. These sites attract visitors by offering access to stunning geothermal phenomena such as boiling pools, mud eruptions, and geothermal steam, that are unsuitable for direct bathing due to their high temperature and chemical composition. Through careful spatial planning and infrastructure development, potentially hazardous geothermal features are transformed into safe, controlled, and educational environments for public engagement.

This represents a form of non-extractive geothermal utilization, in which economic value is generated without altering subsurface conditions or competing with onsen water use. By directing high-temperature geothermal resources toward tourism, Beppu reduces potential conflicts with local onsen operators and residents. Moreover, the cultural interpretation of these sites reinforces local identity and strengthens the connection between natural phenomena and local community. As such, the hells of Beppu demonstrate how geothermal resources can support regional development in a manner that balances economic benefits, cultural continuity, and social acceptance.

To further understand how geothermal tourism shapes the urban structure of Beppu, the spatial distribution of hotels was examined in relation to major geothermal areas. As shown in figure 5, accommodation facilities are unevenly distributed across the city, with clear clustering near key geothermal tourism zones.

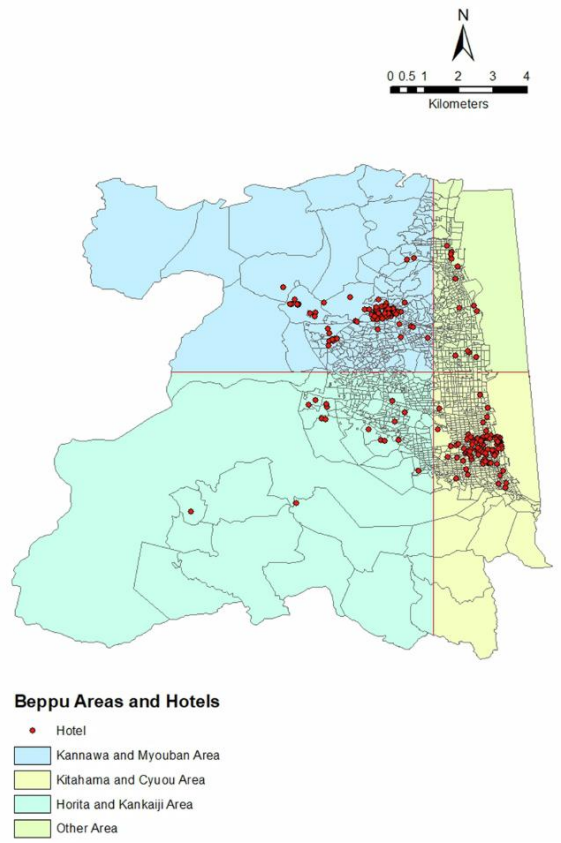

Figure 5. Hotel distribution in four areas in Beppu City. Reproduced from Hu et al. (2024).

Figure 5 illustrates the distribution of hotels across Beppu in relation to major onsen and geothermal areas. A high concentration of hotels is observed in the Kannawa-Myoban and Kitahama-Chuo areas, which correspond closely with major geothermal attractions and well-developed tourism infrastructure. In contrast, fewer hotels are located om peripheral areas, reflecting differences in accessibility, land use, and tourism intensity.

Onsen as Direct-Use Geothermal Applications

Onsen function as a direct-use application of geothermal energy, utilizing naturally heated groundwater for bathing. Hot spring water is continuously supplied from underground sources and managed through controlled distribution systems to maintain stable temperature and flow. In several facilities, excess heat and steam were also used for auxiliary purposes such as space heating and steam cooking, indicating integrated resource use at the facility level.

Figure 6. Hyotan Onsen. (Left) Interior view of the private onsen. (Right) Shower area used to rinse before soaking in the onsen.

The onsen facilities observed varied in water composition, temperature, and bathing style, reflecting the geological diversity of Beppu's geothermal system. Differences in mineral content influenced therapeutic properties, which were communicated to users through on-site information. Bathing spaces were designed to accommodate both residents and visitors, suggesting that onsen serve multiple social functions beyond tourism, including daily wellness and community interaction.

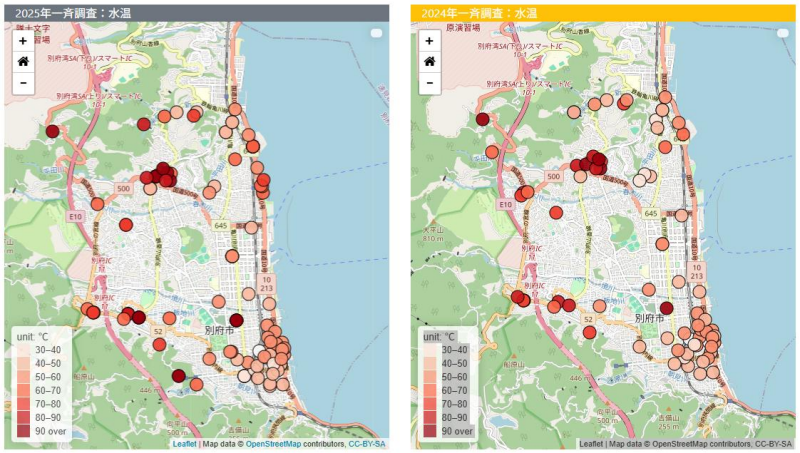

Figure 7. Spatial distribution of onsen water temperatures in Beppu City. (Left) 2025 survey. (Right) 2024 survey. Beppu City-wide Hot Spring Survey (2025); map visualization via WEFN.

As shown in **Figure 7**, hot spring sources in Beppu City exhibit clear spatial variation in water temperature, with higher temperature onsen predominantly concentrated along the coastal zone and Kannawa area. This distribution reflects the underlying geothermal structure of the Beppu geothermal system, where fault-controlled fluid pathways allow high-temperature groundwater to reach the surface. The widespread presence of medium to high temperature sources supports the extensive direct use of geothermal energy for bathing without the need for additional heating. Such special availability enables onsen facilities to operate continuously using naturally heated groundwater.

Onsen-zome: Sustainable Textile Production using Geothermal Resources

Figure 8. Onsen-zome research laboratory. (Left) The laboratory workspace. (Right) Textile dyed using the onsen-zome technique.

Field observation at the onsen-zome research laboratory led by Tomohiko Yukihashi revealed an application of geothermal resources beyond bathing and tourism. Onsen-zome is a natural dyeing technique that utilizes locally sourced plants in combination with hot spring water, where the chemical properties of the geothermal water play an important role in the dyeing process. Rather than serving merely as a heat source, hot spring water functions as a dyeing medium whose mineral composition and pH directly influence the final color outcomes.

A key characteristic of onsen-zome is the variability of dye results generated through interactions between plant pigments and hot spring water. Even when the same plant materials are used, different hot spring water qualities produce a wide range of hues because of the different mineral content and acidity. Furthermore, the chemical composition and pH of hot spring water are not static but fluctuate over time due to changes in subsurface conditions. As a result, even repeated dyeing using the same water source can yield different color tones, making each product unique.

From a sustainability perspective, onsen-zome demonstrates a low-impact use of geothermal resources. The technique does not require artificial additives, relying on naturally occurring geothermal components to induce color. This process aligns with principles of environmentally conscious production by minimizing chemical waste and energy input while maintaining strong ties to local natural conditions.

The practice of onsen-zome also illustrates how geothermal resources support small-scale creative industries and cultural continuity. Such uses can generate cultural, economic, and environmental benefits while maintaining strong social acceptance.

Yunohana Production in Myoban Yunosato

Figure 9. Yunohana Products. (Left) Yunohana bath additive. (Right) Commercial products made with Yunohana.

At Myoban Yunosato, geothermal resources are used primarily to produce yunohana, a mineral bath additive collected from hot spring steam. The Myoban area has a long history of mineral production, dating back to 1725 during the Edo period, when it became known for the extraction of alum (myoban in Japanese). At that time, alum produced in this region accounted for more than 90% of Japan's total supply and was used in medicine, textile dyeing, gunpowder production, and leather processing. This historical context highlights the role of geothermal resources in supporting industrial and everyday needs.

Nowadays, the same production techniques have been preserved and adapted for the manufacture of yunohana, which is widely valued for its therapeutic properties. The production process has remained fundamentally unchanged for over 300 years and has been officially designated as a National Intangible Folk Cultural Asset. In addition, the yunohana goya (the huts used for production) have been recognized as a Nationally Important Cultural Landscape.

Figure 10. Myoban Yunosato. (Left) Yunohana-goya. (Right) Yunohana-goya viewing hut.

The production of yunohana relies on the interaction between geothermal steam and traditional construction techniques. Yunohana is formed inside straw-thatched huts known as yunohana-goya, which are built in locations with abundant geothermal steam. Inside each hut, cobblestones are arranged

to allow hot spring gas to rise evenly from the ground, and a layer of locally sourced blue clay (montmorillonite) is spread across the surface. As geothermal steam passes through the clay, chemical components from both the gas and the clay gradually crystallize, forming a sinter known as yunohana. This yunohana grows at a rate of approximately one milimeter per day and is harvested after 40 to 60 days, dried, and processed into commercial products.

The design of the yunohana-goya reflects environmental adaptation. The straw-thatched triangular roofs stabilize internal temperatures, prevent rainwater infiltration, and allow moisture carried by steam to escape, preventing condensation.

Yunohana production represents a sustainable form of geothermal utilization. It relies on naturally emitted steam and locally available materials, minimizing environmental disturbances. Moreover, the uniqueness of this production method adds cultural and economic value without overusing or depleting the geothermal resources. This demonstrates how geothermal-rich regions can diversify their use of geothermal resources while preserving cultural heritage and supporting local livelihoods.

Jigoku-mushi as a Direct-Use Application of Geothermal Resources

Figure 11. Jigoku-mushi. (Left) Salmon and mushroom cooked using geothermal steam. (Right) Sandwich made from onsen egg and pudding cooked using geothermal steam.

Jigoku-mushi, a traditional cooking method that uses natural geothermal steam, demonstrates an energy-efficient application of geothermal resources in Beppu. In this process, food such as vegetables, eggs, seafood, and desserts is cooked using steam emitted directly from geothermal vents, eliminating the need for gas or electricity. This cooking method enables rapid and uniform cooking because of the stable temperature and high heat capacity of geothermal steam.

Despite the geothermal origin of the steam, food and vegetables prepared by jigoku-mushi method showed no sulfur-related odor or off-flavor. This suggests that the cooking steam consisted primarily of clean water vapor, with minimal transfer of sulfur compounds. Food cooked with geothermal steam does not gain unique nutrients compared to conventional steaming. However, the stable high temperature and rapid cooking characteristic of geothermal steam may enhance nutrient retention and sensory quality by minimizing cooking time.

As a traditional cooking method, jigoku-mushi demonstrates how local culture in Beppu has evolved around geothermal resources, integrating renewable energy use into everyday life while maintaining cultural continuity.

Discussion

Implications of Direct-Use Geothermal Applications for Indirect Energy Development

The findings of this study indicate that geothermal energy in Beppu is predominantly utilized through direct-use applications, including onsen bathing, steam-based cooking, traditional craft production such as onsen-zome, and mineral extraction processes exemplified by yunohana production. These applications rely on geothermal heat and fluids without conversion into electricity.

From the perspective of indirect geothermal utilization, particularly power generation, these observations provide important insights. The extensive and long-standing use of geothermal resources in Beppu demonstrates that local communities possess a high degree of familiarity with geothermal phenomena. This familiarity has contributed to the development of cultural norms that prioritize resource continuity, safety, and environmental balance. However, it also explains why geothermal power development in onsen areas often encounters strong social resistance, as geothermal resources are closely tied to livelihoods, identity, and cultural heritage.

Social Acceptance and Resource Competition

One of the main challenges for geothermal power development identified through this study is the perceived competition between indirect energy extraction and existing direct-use applications. Onsen operators and residents commonly express concern that geothermal power development may lead to reductions in hot spring volume, changes in water quality, or disruptions to geothermal flow systems. These concerns are particularly significant in Beppu, where the economic and cultural value of onsen-based tourism exceeds the perceived benefits of large-scale power generation.

The coexistence of diverse direct-use applications observed in Beppu suggests that social acceptance is strongly influenced by whether geothermal development aligns with local values of harmony (wa) and continuity. In this context, indirect geothermal energy development that prioritizes large-scale extraction without visible local benefits is likely to face opposition. Conversely, development strategies that emphasize transparency, monitoring, and benefit-sharing may be more socially acceptable.

Toward Complementary Geothermal Development Pathways

The Beppu case suggests that indirect geothermal energy development should not be positioned as a replacement for existing direct-use applications, but rather as a complementary pathway. Small- to medium-scale geothermal power generation, waste-heat recovery, and cascading energy systems could potentially coexist with onsen-based use if carefully designed. The tourism-oriented management of high-temperature sites such as the Jigoku further demonstrates that geothermal resources can be zoned according to temperature and cultural significance.

By learning from Beppu’s direct-use practices, geothermal energy developers can better understand the importance of localized management, cultural sensitivity, and stakeholder engagement. These lessons are particularly relevant for other geothermal-rich countries, including Indonesia, where similar tensions exist between geothermal power development and community-based resource use.

Conclusion

This study examined the utilization and management of geothermal resources in Beppu through an experience-based learning approach combined with a review of relevant literature. The findings demonstrate that geothermal energy in Beppu is predominantly applied through direct-use practices. Overall, Beppu provides a valuable case study demonstrating that sustainable geothermal development can take multiple forms beyond electricity generation. Tourism-based utilization, traditional industries, and direct-use applications collectively contribute to regional sustainability while preserving cultural heritage. These insights offer important lessons for other geothermal-rich regions.

Limitations and Future Study

While this study provides qualitative insights into geothermal utilization in Beppu, the findings may not fully capture variations in geothermal management practices across other geothermal areas in Japan.

Future research could build upon this study by incorporating quantitative data, such as geothermal flow measurements, long-term monitoring of water quality, or energy efficiency assessments of direct-use applications. Further interdisciplinary research integrating energy policy and cultural studies would contribute to a more comprehensive understanding of how geothermal energy can be developed sustainably while respecting local traditions.

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