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Review

Establishment of enhanced geothermal energy utilization plans: Barriers and strategies

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A R T I C L E I N F O

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A B S T R A C T

Geothermal energy has received tremendous attention as a largely untapped renewable resource that does not produce significant CO_2 emissions during electricity generation. Worldwide installed capacity of geothermal energy plants has reached 14.3 GWe in 2017. However, widespread adoption of geothermal technologies should consider its potential environmental impacts. In this study, we first review the current state-of-the-art enhanced geothermal systems around the world, especially the United States, Philippines, Indonesia, Turkey and New Zealand. Then, we address the challenges and barriers to its adoption from the institutional, regulatory, technological and financial aspects. We also propose several strategies to implement geothermal energy plans, including (1) establishment of clear national energy utilization policies, (2) consolidation of geothermal laws and regulations, (3) engagement in geothermal potential assessment and periodic maintenance services, and (4) provision of fiscal incentives, financial supports and guarantees. Finally, we illustrate the implementation plans and business model of enhanced geothermal system deployment to conduct a demonstration plan for geothermal energy utilization. A case study of geothermal utilization in Taiwan, i.e., the Chingshui geothermal field, was discussed.

Contents

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1. Introduction

According to the Energy Technology Perspectives [1], five key strategic technologies need to be implemented for CO_2 reduction: renewable energy (32%), improvement in energy efficiency (32%), carbon capture and storage (15%), nuclear (11%) and fuel switching (10%). For a clean energy supply towards a green economy [2], renewables are considered a non-polluting and environmentally friendly technology, with a relatively lower operation and maintenance cost. Geothermal energy has received tremendous attention as a largely untapped renewable resource [3]. According to the Technology Roadmap for Geothermal Heat and Power reported by the International Energy Agency [4], geothermal electricity generation would reach 1400 TWh per year by 2050, which is about 3.5% of global electricity production, avoiding ~800 Mt of CO_2 emissions per year. The advantages of utilizing geothermal as an energy supply system include (1) continuous electricity generation for 24 h per day, (2) a predictable and sometimes flexible resource, in contrast to solar and wind energy, (3) clean and sustainable energy production, (4) increased energy security, (5) reduction of CO_2 emissions and other air and water pollutants, (6) lower consumption of fresh water, and (7) flexibility of operation.

Table 1 presents two different forms of geothermal energy, i.e., shallow geothermal and deep geothermal, with reference to the depths of geothermal well drilling. Due to the geothermal gradient, the underground temperature increases as the depth increases, so high-temperature geothermal systems require deeper well drilling. Most commercial geothermal energy plants use the shallow type, where the heat is extracted by a ground-source heat pump (GSHP) [5]. Some enhanced geothermal power plants are using GSHP and becoming more business-oriented. However, many electric power plants remain in the testing phase for the purpose of improving their technical operation; supercritical geothermal systems are still an immature technology that is being studied and re-verified in the laboratory. Typically, water from high-temperature (greater than 240 °C) reservoirs is partially flashed to steam [6].

Among the various geothermal energy technologies, enhanced geothermal systems (EGS) are more efficient in terms of producing electricity and could supply a significant fraction of the low-temperature thermal energy used [7,8]. As shown in Fig. 1, EGS can extract heat from engineered thermal reservoirs, i.e., tight rock that has not been fractured naturally, through fluid injection and rock stimulation. The concept of EGS was originally proposed and developed at the Los Alamos National Laboratory in the U.S. in 1974 [9]. In 2013, the Geodynamics plant in Habanero (Australia) became the first private commercial EGS plant for large-scale electricity production [10]. An EGS plant consists of complicated above-ground and underground facilities, where the above-ground facilities account for a large proportion of the total cost [9]. Different types of hydraulic-fracturing fluids, such as polyallylamine [11] and

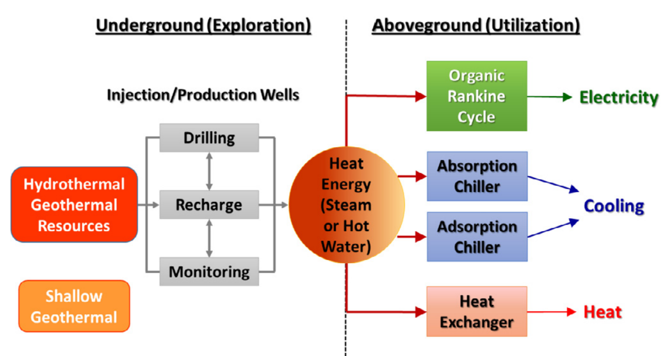

Fig. 1. Outlook on the utilization of hydrothermal geothermal resources.

Table 1
Geothermal resource application, in terms of drilling depth and its associated temperature range.

Types	Geothermal system	Drilling depth (m)	Temperature range (°C)	Current state
Shallow-depth geothermal	Conventional geothermal system (low temperature)	1000–2000	<100	Business-oriented geothermal power plant
	Conventional geothermal system (medium temperature)		100–200	
	Conventional geothermal system (high temperature)		200–300	
Deep-drilling geothermal	Enhanced geothermal system (EGS)	3000–5000	100–300	Partly business oriented geothermal power plant
	Supercritical geothermal system	Close to lava	400–600	In R&D stage

supercritical CO_2 [12–14], have been developed and deployed.

To achieve a higher overall thermal efficiency, the concept of cascade utilization was proposed, where the geothermal heat at different thermal levels is harnessed in sequential processes [15]. As shown in Fig. 2, the system can be designed in a multiple-level cascade with electricity production and other thermal applications such as cooling and direct use. The cascade system can optimize the utilization efficiency of geothermal energy resources for medium-to-low enthalpy, thereby reducing the additional consumption of fossil fuels. Geothermal resources also can be combined with other energy supply systems to increase the overall process efficiency and cycle temperatures [16]. For instance, geothermal-solar or geothermal-biomass hybrid plants provide synergy without compromising their original sustainability and environmental benefits [17]. Over 90% of exploited geothermal sites are operated with liquid-dominated systems, where pressures of the reservoir increase with depth in response to the density of the liquid phase [6]. In contrast, vapor-dominated systems exhibit vertical pressure gradients controlled by the steam density. Although the vapor-dominated geothermal resources are not as abundant, they exhibit fewer problems than liquid-dominated systems. For geothermal power plants, current energy conversion technology can exploit resources having a wide variety of thermodynamic and chemical characteristics [18]. Depending on turbine inlet pressure and efficiency, however, only ~20% of the thermal power of the flowing steam can be efficiently converted into electricity [19].

According to a survey of more than 60 nations worldwide [20], most countries have no legal regulations or guidelines for deploying geothermal power plants. This highlights the urgent need for research on the legal governance and management and environmental impact assessment of geothermal plant installations. In this study, we first review the current information and state-of-the-art technologies for geothermal energy utilization around the world. Then, we illustrate the environmental impacts of noise, air quality (such as CO_2, H_2S, NH_3, H_3BO_3, Hg and As) and water quality (such as composition of fluid discharges and toxicity) on the environment, ecosystem and human health. To effectively lower carbon emissions and ensure energy security, policymakers must acknowledge and address public concerns prior to promulgating and implementing relevant regulations. We also address the challenges and barriers from the regulatory, institutional, financial and technical aspects. Lastly, we propose a comprehensive performance evaluation program, including evaluation methods, key performance indicators and business models in Taiwan (e.g., the Chingshui geothermal field) for geothermal energy utilization plans.

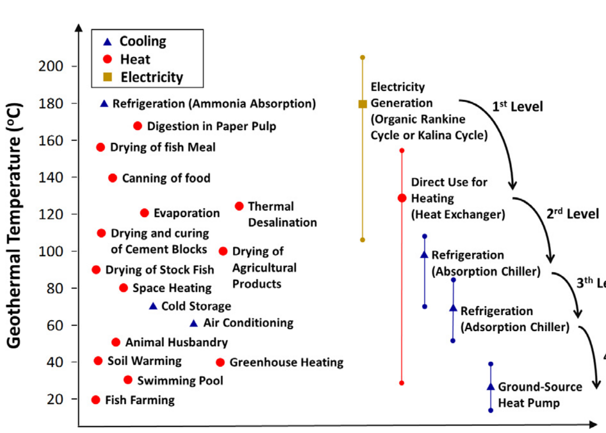

Fig. 2. Polygeneration using geothermal energy sources for multiple benefits.

2. Enhanced geothermal system (EGS) around the world

The worldwide cumulative installed geothermal electricity generating capacity has dramatically increased, from 0.2 GW in 1950 [21] to 12.7 GW in 2015 [22]. In 2010, major applications of geothermal resources were direct use for heating (117,740 GWh_{th}/yr) and electricity production (67,250 GWh_e/yr) [23]. World electricity generation from geothermal resources through kinetic conversion of high- or medium-temperature steam was estimated to be 68 TWh in 2012 [24]. The International Energy Agency [4] estimates that by 2050 geothermal energy for direct heating use and power production should increase to 1600 TWh_{th}/yr and 1400 TWh_e/yr, respectively. Fig. 3 shows the worldwide installed capacity of geothermal energy plants in 2017. Worldwide high-temperature geothermal sites mostly are located along the edges of plates. Only a few sites are located in intraplate rift zones (e.g., East African Rift Valley) or hotspots (e.g., Hawaii) [25]. In 2017, the countries with the largest installed capacity of geothermal power were the United States (~3.72 GW), the Philippines (~1.93 GW), Indonesia (~1.86 GW), Turkey (~1.06 GW), New Zealand (~0.98 GW), Mexico (~0.92 GW), Italy (~0.92 GW), and Iceland (~0.71 GW) [26]. In this part, the top five countries of installed geothermal power capacity are briefly illustrated.

2.1. United States

In the U.S., government-supported research projects have made great progress on EGS technology. Currently, there are five EGS demonstration plants in the U.S.: The Geysers, Newberry Demonstration, Desert Peak, Brady's Hot Springs, and Raft River. The following describes each of these plants:

1 The Geysers

The first well and power plant were completed at this government-supported research project in California in 1921 [27]. By 1990, a total of 26 power plants had been built, for a capacity of more than 2 GW [27]. The system extracts heat from engineered reservoirs through fluid injection and rock stimulation. The EGS stimulation has created a distinct reservoir in the high-temperature zone, which has proven that a distinct reservoir can be created on the margins of an operational hydrothermal field.

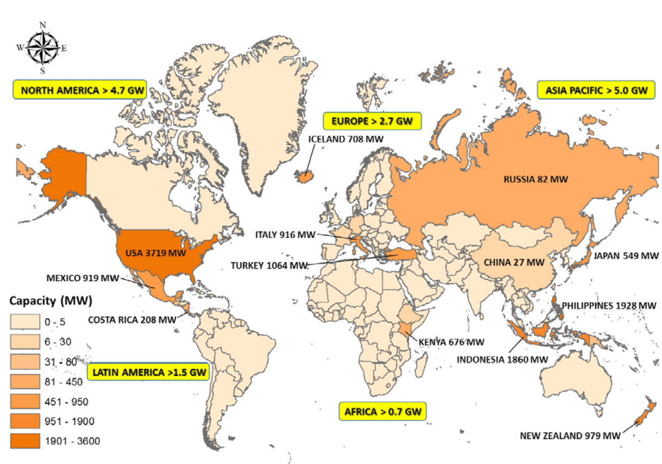

Fig. 3. Installed capacity of geothermal energy plant in 2017 worldwide [14.3 GWe]. Statistical data of cumulative installed geothermal power capacity was gathered from the literature [26].

2 Newberry EGS Demonstration

In 2013, AltaRock Energy announced that it had created multiple stimulation zones for a single wellbore at the Newberry EGS demonstration site by utilizing innovative diverter technology. Diverters comprise non-toxic, biodegradable materials or naturally occurring minerals that can temporarily seal fractures while new fracture sets are created, ultimately facilitating the availability of a larger rock volume for heat extraction [28]. In addition, permanent seismic monitoring sensors were installed to track the evolution of well stimulation and ensure pre-established safe limits on seismicity. With this demonstration project, the potential benefit was a significant reduction in the cost of production from an EGS field, with the successful production of an additional 1.7 MW from an existing field in Nevada using EGS technology. Furthermore, this demonstration was the first EGS system to be grid connected.

3 Desert Peak Demonstration

By hydraulic and chemical stimulation, the Ormat Technologies Company has increased the injection rate and maximum flow rate of the target well from near zero to hundreds of gallons per minute over the past years [29]. The shear stimulation phase was conducted in August 2011 to increase the injection rate by an order of magnitude. In addition, the Ormat Technologies Company developed decision-tree workflows for a rapid operational decision process.

4 Brady's Hot Springs

Located in Nevada, Brady's Hot Springs is currently utilized for geothermal power exploration and development, as well as agricultural processing [30]. Both the Bureau of Land Management (BLM) and the Department of Energy (DOE) are in the process of conducting a focused environmental assessment to evaluate the proposed activities and final stimulation plan [28]. Seven geothermal production wells at depths of 400–1770 m penetrate permeable zones in tertiary volcanic rocks in the hanging wall of the Brady fault [30].

5 Raft River Project

The Raft River geothermal project is conducted in southern Idaho. The DOE plans to demonstrate the technical and economic viability of EGS technology for thermal and hydraulic stimulation of a target well [28]. In 2016, U.S. Geothermal, Inc. plans to drill a new leg on one of the Raft River production wells, which is expected to increase the power plant output by up to 3 MW [31]. This would bring the total output of the plant to the maximum allowance (i.e., 13 MW) under the power purchase agreement.

2.2. Philippines

The Philippines, located along the Pacific Ring of Fire, has a geothermal advantage due to the presence of underground reservoirs of hot fluids found in many parts of the country. The Philippine Department of Energy estimates that there is a total of 4.94 GW of available geothermal resources in the country [32]. As of 2010, the installed capacity is approximately 1.87 GW, which accounts for 12% of the national power mix [32]. Strategies to develop these resources arose from government initiatives to reduce the country's dependence on imported fuel and, recently, to shift from non-renewable to renewable sources of energy, focusing on naturally-abundant and regenerative forms. Technology transfer and manpower development were acquired through bilateral agreements and collaborations with other countries such as the United States, New Zealand, Italy and Japan and organizations offering support mechanisms such as the World Bank, the United Nations Development Program, and the Overseas Economic Cooperation Fund.

In the past, several reservoir management challenges, including injection breakthrough and the influx of cooler, marginal fluids and corrosive reservoir fluids, have had significant economic impacts on operations. They have been dealt with by extensive research, which has led to a large body of theoretical and operational data [33]. To date, the most important technological barriers include maintaining the steam supply for the existing plant capacity, handling acidic wells, and dealing with rapid corrosion rates. Major changes in the geothermal industry in the Philippines have shifted to (1) the ownership (privatization), (2) regulatory landscapes, and (3) the implementation of plant rehabilitation for improving plant efficiency and dependable generation capacities [34]. Current development focuses on high-temperature conventional geothermal energy resources, while unconventional geothermal technologies such as EGS have yet to be applied commercially [35].

2.3. Indonesia

Indonesia has the largest potential for geothermal energy around the world, i.e., 40% of the world's potential geothermal resources, corresponding to a capacity of 29 GW [36]. However, the utilization of geothermal energy is currently only about 4% of total potential capacity. The challenges and barriers to geothermal development in Indonesia include (1) high upfront capital requirements and risk, (2) uncertainty on pricing mechanisms, and (3) regulatory uncertainty for overlapping areas. It is estimated that a total cost of USD 35–50 million would be required for preliminary studies, including exploration wells to prove the reserves without any external financing. However, development and exploration costs are solely borne by the geothermal industry. Since the current tariff agreement is often up for renegotiation, there are no guarantees on energy prices. From the perspective of developers, the current environment of geothermal development projects is potentially high risk, especially for small companies. In addition, approximately 80% of Indonesia's geothermal reserves are located in protected forest and conservation areas [37]. Therefore, geothermal activities could be conducted in these areas only through the revision of geothermal law. Moreover, extra costs are incurred in connecting the electricity produced in remote areas to the main grid [38].

2.4. Turkey

Turkey is the fourth-ranked country worldwide with the largest installed geothermal power capacity in 2018. The potential of geothermal electricity generation in Turkey is estimated at about 4.50 GW [39]. However, more than 55% of installed capacity of power plants was still from the fossil-based sources, and about 35% was from hydropower plants. The share of the total installed capacity from geothermal energy in the end of 2015 was only 0.9%, corresponding to ~620 MW [40]. Therefore, the Turkish government has set a target of a 30% share in national energy sources from renewable energy by 2030 [41]. To promote private sector investment in geothermal exploration, the Development Bank of Turkey and the World Bank have introduced the Turkey Geothermal Risk Sharing Mechanism under the Climate Technology Fund in March, 2018 [42]. By this mechanism, the exploratory drilling costs of developers are substantially reduced in the event of an exploratory drilling failure.

2.5. New Zealand

New Zealand is the fifth largest country of the worldwide installed geothermal power capacity in 2018. Currently, the geothermal energy in New Zealand produces approximately 13% of the country's electricity supply. In New Zealand, geothermal energy for electricity generation is a secure and sustainable alternative with relatively low costs to fulfill the growing demand of electricity. For instance, the Wairakei power plants have operated at a load factor of >90% for more than 40 years. The New Zealand government has set an ambitious target for 90% renewable electricity by 2025 [43]. The Resource Management Act is the principle regulation to maintain the sustainable use of natural resources, including geothermal energy, land, air and water.

3. Strategic environmental assessment for EGS system

Geothermal energy has the potential to preserve the environment, create jobs, and change lives around the world. With the exception of possible effects caused by induced seismicity, EGS is considered to be the most environmentally benign technology for generating base-load electricity. The potential effects of induced seismicity can be mitigated by using modern geo-scientific methods. In addition, continuous monitoring of micro-seismic noise can be implemented for both simulation of the reservoir extent and development of a warning system for possible onset of a significant seismic event. With the environmental impacts and benefits taken into consideration, EGS is considered to be the best available technology (BAT) for generating large amounts of electric power.

The imperative steps to complete an EGS reservoir project are (1) characterizing and selecting an appropriate site, (2) drilling injection/production wells and creating the reservoir, (3) completing and verifying the circulation loop, and (4) operating the EGS system and equipment. Considering the great increase in the geothermal energy industry, concerns about the environmental impacts of this industrial sector have attracted the attention of stakeholders including representative of the policy, industrial and scientific sectors [44]. Strategic environmental assessment (SEA) is a systematic approach to providing the decision-support platform, and then ensuring environmental sustainability with an effective decision-making system for policies, programs and plans [45–47]. With SEA, the environmental impacts of a geothermal energy plan could cascade down through the tiers of decision making, which should reduce the amount of work that needs to be undertaken. Geothermal energy utilization needs to be carefully operated without causing adverse effects on the environment, ecosystem and human health. Therefore, the engineering, environmental and economic perspectives should all be considered in SEA for geothermal energy.

SEA consists of procedural tools for determining the potential environmental impacts from a general policy or a specific project. Such an evaluation should be conducted along with a life-cycle assessment (LCA), in accordance with the ISO 14040 [48] and 14044 [49]. LCA is defined as the quantitative estimation of environmental impacts based on the energy and material flow analyses from the life cycle of a product and/or process [50]. The environmental impacts and benefits of an EGS project largely depend on (1) characteristics of the reservoir, (2) geothermal fluid chemistry, (3) type of power generation, and (4) type of emissions of the life cycle inventory [44]. Moreover, environmental impacts and benefits are subject to a number of uncertainties, which could stem from the initial state of the reservoir, as well as from the geological and operational parameters. Usually, the uncertainty can be evaluated using a discrete parameter analysis [51,52]. Several LCA studies have been conducted to evaluate the environmental performance of geothermal systems such as via ground source heat pump [53] and various applications, such as electricity production [54] and transportation [55].

3.1. Potential environmental impacts

It is impossible to produce and transform geothermal energy into a form that can be utilized by people without having some impact on the environment. As presented in Table 2, potential environmental impacts from geothermal energy development may include air/water pollution, solid waste disposal, noise pollution, thermal pollution, land use, land subsidence, induced seismicity/landslides, water consumption, disturbance of natural hydrothermal manifestations, altering natural vistas, and catastrophic events [56,57]. In particular, groundwater use and contamination, land subsidence and induced seismicity as a result of water re-injection into a fractured reservoir formation are considered the most concerning environmental impacts of geothermal power plant development. The following sections provide detailed consideration of those impacts.

1 Induced seismicity

Induced seismicity can be attributed to deep mining or injection of fluids into deep formations [25,58]. The main mechanisms to explain the occurrence of induced seismicity in geothermal settings include (1) pore-pressure increase, (2) temperature decrease, (3) volume change due to fluid withdrawal/injection, and (4) chemical alteration of fracture surfaces [59]. EGS are typically characterized by higher injection rates (i.e., <100 L/s) than those associated with wastewater disposal wells (i.e., <20 L/s) [60]. According to the experience gained at Wairakei geothermal field, re-injection at a large pressure would induce earthquakes that can be felt in the local area, while re-injection at a saturated water-vapor pressure would not produce any observable earthquake activity. In addition, experts at The Geysers found that geothermal field development and expansion have resulted in seismic activity in the form of "micro-earthquakes." In general, micro-earthquakes occur in converting hydrothermal systems with a very low magnitude, which can be detected only by instrumentation. A majority of the observed data from existing EGS projects suggest that the higher energy radiated from the shearing is caused by a high stress released from relatively small joint lengths [61]. This suggests that if there were some perceived events on the surface, the frequency content would be too high to generate any seismic risk. However, minor events may still raise concerns among local inhabitants.

The risk of induced seismicity is a key factor to be accounted for at the design stage [62]. The potential effects of induced seismicity can be mitigated by using advanced geo-scientific methods, such as 3D thermo-poroelastic analysis [63], to characterize potential reservoir target areas before drilling and stimulation activities. However, quantitative modeling of induced seismicity is still a challenging and complex matter [64]. Continuous monitoring of micro-seismic noise can serve as a vital tool not only for estimation of the reservoir extent, but also as a warning system to alert scientists and engineers of the possible onset of a significant seismic event [56].

2 Water use and footprint

In most EGS applications, surface water is needed for both stimulation and operation of the reservoir to evaluate the circulation patterns of re-injection water. Extracting water from the watershed to meet the needs for geothermal system exploitation,

Table 2
Indicators of potential environmental impacts for deploying EGS.

Category	Impacts	Descriptions
Landscape/ feature	Land and landscape	Land use and land subsidence; altering natural vistas, and catastrophic events
	Heat-tolerant vegetation	High rhizosphere temperatures (e.g., $\geq$40 °C)
Engineering	Subsidence	Carbonates and silicates due to changes of pressure and temperature
	Hydrothermal eruptions	Disturbance of natural hydrothermal manifestations
	Induced seismicity	Injection of fluids into deep formations
	Induced landslides	Due to temperature and water level in rocks, especially in tectonically active areas
	Water usage	Stimulation and operation of reservoir
Environment	Waste heat releases (thermal effects)	Large quantities of geothermal flows and inefficiency electricity conversion, resulting in disturbances of wildlife habitat and vegetation
	Noise	Air drilling (120 dBA); vertical well discharge (up to 120 dBA); heavy machinery (90 dBA)
	Air quality	Toxic and human health effects resulting from CO_2, H_2S, CH_4, Hg and ammonia emissions
	Water quality	Lithium (Li), boron (B), arsenic (As), ammonia (NH_3), mercury (Hg), chloride (Cl), and hydrogen sulfide (H_2S) due to the composition of fluid discharges

construction and operation varies greatly depending on the locality. The source of the water supply can be a nearby high-flow stream, a river, or a temporary surface reservoir. The water requirements for drilling have been reported between 5 and 30 m^3, depending on the geology technology and the depth [65]. The water footprint of geothermal power plants with air or hybrid cooling ranges from 0 to 1.5 m^3/MWh, while that with water cooling consumes up to 17 m^3/MWh [66].

During the development phase, the environmental impacts of the chemical content and suspended sediment level of wastewater should be evaluated. In some cases of EGS operations, water treatment facilities are needed for removing potentially hazardous contaminants dissolved or suspended in the circulating geo-fluid or cooling water to ensure sufficient quality for re-injection and reuse. Therefore, it is necessary to coordinate regional water use during field development with other local water demands for agricultural or other purposes [56].

3 Water quality

EGS operations are subject to subsurface contamination through casing defects and improper well installations. The compositions of fluid discharges might include lithium (Li), boron (B), arsenic (As), ammonia (NH_3), mercury (Hg), chloride (Cl), and hydrogen sulfide (H_2S), which may have toxic environmental effects on aquatic life, stock (as stock watering), crops (as irrigation water), and humans (as drinking water). It was noted that volcano- and fault-hosted hot springs were characterized by relatively large variation in metal concentrations, especially for B, Li and As [67]. In addition, closed-loop systems of GSHP may contain toxic thermal transfer fluids that can pollute groundwater when leaking [68]. On the other hand, surface contamination during plant operation is generally not considered the key challenge because all the produced fluid is re-injected.

4 Air quality

Depending on site characteristics, the emission of air pollutants from geothermal energy plants may comprise CO_2, H_2S, NH_3, NO_x, and volatile organic matters/metals may be emitted from geothermal plants. The presence of non-condensable gases such as H_2S, CO_2, and CH_4 are mainly associated with flash-steam and dry steam power plants [69]. The amounts of sulfur dioxide emissions are in an average range between 0.2 and 1.0 g/kWh [70]. However, the emission of air pollutants from geothermal energy are on average less than that from conventional fossil fuels [71]. In particular, geothermal plants emit very small amounts of NO_x or none at all [57].

5 Land use and requirements

In many countries, potential geothermal sites are located in conservation areas and/or protected forests such as national parks, where the exploration and development of geothermal energy are prohibited. Also, although geothermal energy plants have been recognized as requiring much less land area per MW installed compared to other power plants, additional costs are typically incurred in connecting produced electricity from remote areas to the main grid. Furthermore, revision of geothermal law is generally required for geothermal activities to be conducted in protected areas.

6 Effect of thermal heat to the environment

Geothermal energy plants may result in the release of waste heat into the water environment due to large quantities of geothermal flows and the inefficiency of electricity conversion. This undesirable temperature change in the ground and water environment may impact the water quality or aquatic ecology [68]. A broad survey indicated that flowering plants in geothermally heated environments can tolerate high rhizosphere temperatures (e.g., $\geq$40 °C) [72].

3.2. Environmental benefits

The environmental benefits of utilizing geothermal energy for varies types of applications, such as a dry steam power generation system [73], a combined heat and power generation system [74], organic Rankine cycle (ORC) [62], and heat pump systems [75,76], have been studied. These benefits include zero greenhouse gas (GHG) emission during operations, the modest use of land, the potential for CO_2 sequestration, and low environmental impacts. The details of the above environmental benefits are discussed in the following section.

1 Zero GHG emission

Geothermal power plants built on EGS reservoirs and using "closed-loop" cycles will not generate additional CO_2 emission [56]. According to the results of LCA [44], the global warming potential of this form of energy is mostly associated with fuel consumption in the construction and operation stages. The GHG emissions per unit of energy produced by an EGS plant are commonly estimated in the range of 40–60 g CO_2-eq/kWh [77]. In particular, drilling is the process with the highest impact, essentially because of its use of fossil fuel [62]. If the "carbon tax" mechanism was implemented, the cost for generating electricity from fossil-fueled power plants would increase relative to other less-polluting technologies. Since EGS plants would not be penalized during power generation, they could gain an economic advantage over all plants that use carbon-based fuels. On the other hand, if the "carbon credits" program was established, EGS plants would gain additional revenue by selling carbon credits on the emission trading market, under the clean development mechanism (CDM).

2 Potential in CO_2 sequestration

Brown [78] developed a conceptual model for utilization of CO_2 as the EGS reservoir heat-transfer fluid based on the Fenton Hill hot dry rock reservoir. The concept of using CO_2 instead of water as a working fluid at high pressures introduces an innovative model in the operation of EGS plants. CO_2 holds certain thermodynamic, or heat transfer, advantages over water in EGS applications. The actual heat flow rate when using CO_2 as working fluid for EGS can be up to five times greater than that using the formation brine as a working fluid [12]. Moreover, if water is used as the working fluid in EGS plants, water is lost during operation. However, the lost CO_2 fluid could result in geological sequestration of CO_2. Therefore, CO_2 may achieve high rates of heat extraction and can offer geologic storage of carbon via mineral carbonation reaction as an ancillary benefit [79].

It was estimated that a single EGS reservoir having a pore space of 0.5 km^3 could hold in circulation 28.3 tons of CO_2, corresponding to 70 years of CO_2 emissions from a 500 MW coal-fired power plant with a capacity factor of 85% [78]. Therefore, the EGS plants could play a valuable symbiotic role in controlling CO_2 emissions, allowing exploitation of the abundant supply of coal without contributing CO_2 to the atmosphere. For symbiotic integration of CO_2 sequestration with geothermal heat utilization, Mohan et al. [80] have also developed a CO_2-based EGS model paired with the integrated gasification combined cycle (IGCC). The results indicate that a Rankine cycle could maximize the conversion of geothermal heat to electricity while reducing the pressure of supercritical CO_2 to the injection pressure for subsequent recirculation [80].

3 Modest use of land

EGS plants have been recognized as requiring much less land area per MW installed or per MWh delivered than fossil-fueled, nuclear, and solar power plants. For a typical geothermal project, the required land areas excluding wells are in the range between 160 and 290 m^2/GWhe/yr, and up to 900 m^2/GWh/yr if including wells [81]. Among all renewable energy sources, geothermal sources have lower surface area per unit, e.g., 20 $MW_{th} = 10\ m \times 10\ m$ well size [69]. Geothermal energy demand can be matched from the smallest to the largest energy-consuming utilities. Since the land required for EGS plants is actually not completely occupied by the plant and the wells, it can be used for farming and cattle raising [56]. Also, the EGS plants are not necessarily tied to hydrothermal areas, so it is possible to locate them within populated or industrial districts. With good engineering practice, the directional drilling of multiple wells from a few well pads could minimize the land use requirement.

4. Barriers and challenges for establishing geothermal energy plans

Development of geothermal energy would likely take 5–6 years for a preliminary survey, exploration, test drilling, field development, power plant construction, and operation and maintenance. The executive barriers for establishing geothermal energy plans can be categorized into institutional, regulatory, technological, and financial categories. Table 3 presents the potential barriers and strategies to overcome them for establishing EGS plants. The details of each barrier are illustrated in later sections.

4.1. Institutional barriers

Land suitability and availability can be the greatest institutional barriers and challenges. In addition, there is a general lack of direction within the government in terms of national energy policy with regard to geothermal resources. In many countries, geothermal energy is not well recognized by the general public as an alternate energy source. In some cases, local authorities are not aware of the benefits of geothermal energy systems. Also, there are insufficient human resources in government institutions dedicated to the relevant regulation and promotion of geothermal energy utilization. This would lead to delays in obtaining approval for granting concessions [82]. Furthermore, inconsistent definitions among water, groundwater and geothermal resources at the central and local levels can cause a major information gap [83].

4.2. Regulatory barriers

Most geothermal resources are located in restricted and conserved areas such as national parks, where the exploration and development of geothermal energy are prohibited. Therefore, an environmental impact assessment (EIA) needs to be conducted. A possible land use change in policy and/or regulation needs to be initiated by the land managing agency; however, review and approval of such changes can take a long time. In some cases, various regulations and/or acts may be incompatible and in conflict with each other. Aside from the land issue, in the case of EGS, the EIA may not be needed, since it would not really result in a serious water pollution or land subsidence, for example, in Germany. In addition, al Irsyad, Halog and Nepal [84] found that renewable energy projections, aside from those for biomass, largely overestimated the capacity factor. The uncertainties and errors in renewable energy projections should be critically assessed to develop anticipatory measures for policymakers.

4.3. Technological barriers

Since EGS power facilities can operate essentially emissions free with a small footprint, the environmental impacts of the entire EGS plant might be positive, e.g., reducing the growth of GHG emissions while providing a reliable and sustainable source of electricity [56]. However, the common operational problems of EGS include (1) corrosion, (2) scale formation in production and reinjection wells due to deposition of calcite, silica and metal sulfides, (3) shortage of water supply, and (4) induced micro-earthquakes (i.e., magnitude less than 4.5). Depending on the reservoir mineralogy and reinjection conditions (such as characteristics of a fluid), minerals can be precipitated within the reservoir and/or on the inner surface of the pipelines. Calcite deposition is commonly found in relatively alkaline reservoirs, particularly those with high bicarbonate (HCO_3) and carbonate (CO_3) ions or relatively low temperatures (<220 °C) [85]. The kinetics of silica precipitation and dissolution exhibit a greater influence on permeability alteration than temperature-dependent solubility [86].

For EGS systems, the biggest technological barriers are the knowledge gaps and technology uncertainties that surround the artificially created underground geothermal reservoir [87]. Other barriers may include (1) lack of expertise within community/city government, (2) lack of key technology and industry, (3) complexity of project and technology, (4) high risk undertaking, (5) lack of research centers, and (6) limited access to information.

Table 3
Potential barriers and possible overcome approach for establishing EGS.

Categories	Barriers	Approach to overcoming the barriers
Institutional	• Local authorities' unawareness of geothermal energy system benefits • Land suitability and availability • Cumbersome tender process	• Geothermal leasing • Continuity of geothermal energy awareness efforts by initiating an education program • Establishment of an effective tender committee
Regulatory	• Policy and legal issues • Complicated legal and regulatory bureaucracy • Unclear regulation in environmental impact assessment • Incompatibility and conflict between regulations or acts	• Statutory authority and utility regulations • Support on EGS industry development • Provision of legal consulting services to EGS developers as part of geothermal incentive programs • Implementation of strategic environmental assessment (SEA)
Technological	• Lack of expertise within community/city government • Lack of exploration data • Lack of own technologies for drilling, as well as production and O&M of reservoir • Complexity of project and technology/high risk undertaking	• Geothermal survey • Support of research in geothermal resource exploration techniques • Development of new and cost-reducing drilling technologies • Deployment of process integration technologies for system optimization • Integration of geothermal heating in the urban infrastructure
Financial	• Low electricity purchasing price • No economic feasibility • High price for water use	• Power purchase agreement (PPA) • Reconstruction of feed-in tariff (FIT) model • Loan guarantee programs • Cost shares and/or direct grant programs • Incentive for new users
Others	• Low social acceptance and public awareness • Lack of partnership with stakeholders/private investors • Tender arrangement • Resistance to change	• Centralized licensor/tender committee • Need for education program

Significant system designs, such as capacity, steam fraction and water chemistry, would have impacts on the likelihood of EGS success and tariff system. However, the correlation between problematic design and the odds of failure highlight the importance of good engineering practices, where the relevant regulations should be adhered along with an adequate market assessment [88].

4.4. Financial barriers

Economic feasibility is an important barrier to EGS development by local leaders in communities or renewable energy power facility installers. Both the growth rate and installed capacity of geothermal power are behind those of wind and solar energy, which may be attributed to the high initial investment, long payback time and construction time, difficulty of resource assessment, and challenges in modularizing geothermal energy systems [89]. In general, geothermal power projects take 5–7 years to develop from resource discovery to commercial operation. As with oil and mining projects, the size of the geothermal resource cannot be confirmed until drilling takes place. Moreover, the scarcity of drilling rigs and crews cause high drilling costs, thereby hindering geothermal exploration [82]. On the other hand, in some countries, if the generated renewable electricity capacity exceeds the capacity of the existing electricity grid, the installer will install and maintain the circuits connecting renewable energy power facilities and power grids, which would cause a great burden on power generation cost for the renewable energy installers. Therefore, economic incentives to new users can serve as an important enabler for an EGS project.

5. Strategies to overcome barriers for establishing geothermal energy plans

Concrete actions by policy-makers could include tax reductions to promote the growth of local installation and maintenance companies or advanced energy-efficient technologies (such as heat pumps [90] and geo-exchanger firms [91]). Fig. 4 shows the strategies needed to overcome the institutional, regulatory, technical and financial barriers to establishment of geothermal energy plans. These include (1) establishing policy and government responsibility, (2) providing economic incentives and price supports, (3) internalizing externalities, social acceptance and investor mobilization, (4) developing and localizing key technologies and industries, and (5) geothermal leasing.

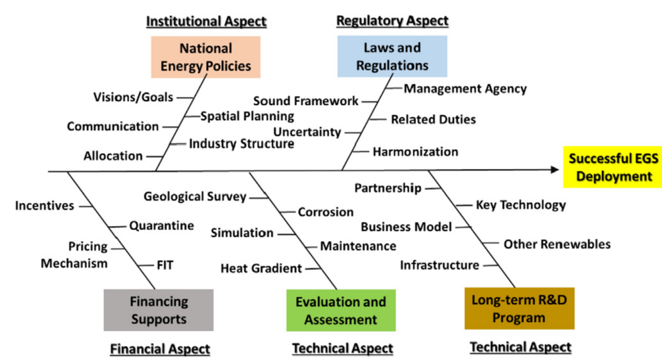

Fig. 4. Overcome strategies on establishing geothermal energy plans.

The details of each strategy are described in the following sections.

5.1. Establishment of clear national energy utilization policies

Policy makers should provide a clear vision and policies for national geothermal energy utilization. It is essential to support this vision and these policies via active communication with developers and by employing more geothermal experts in government institutions [82]. Specific spatial planning should be provided to meet the pattern of distribution within a region. In addition, the value of geothermal resource development should be maximized to reconstruct the industry structure toward greener and cleaner energy technologies.

5.2. Consolidation of geothermal laws and regulations

Changes in law are necessary to advance geothermal development. Typically, geothermal governance, regulation and management should be consolidated by a single government office, sufficiently staffed with knowledgeable professionals on geothermal [82]. A sound regulatory framework is desirable to establish policy and government responsibility and prevent uncertainty in procedures, which can cause unnecessary delays and improper use of water resources [91]. In other words, an integrated, centralized and authorized management agency should be established to execute the integration of all energy and natural resources. To effectively lower carbon emissions and ensure energy security, policymakers should critically address public concerns prior to promulgating and implementing relevant regulations. It is also necessary to coordinate land-use regulations, e.g., forestry accessibility for geothermal energy. Both top-down and bottom-up approaches to government standard operational procedures should be considered simultaneously in executing policies. Related duties and responsibilities should be governed by an independent government body that considers issues from a cross-sector perspective. Furthermore, development of the Geothermal Sustainability Assessment Protocol is a promising instrument to ensure policies that will support the sustainable use of geothermal resources [92].

5.3. Engagement in EGS potential assessment and periodic maintenance services

To establish a geothermal power plant, production should be carefully estimated based on the best available knowledge [92]. Therefore, a comprehensive geological survey and evaluation is essential to making efficient and large-scale use of geothermal energy resources while mitigating earthquake risks and well drilling costs. It is important to identify the typical thermal gradient for EGS plants [93]. Fig. 5 shows the EGS spectrum in terms of temperature gradient and formation permeability. It suggests that the mean thermal gradient typically stands at an increment of 25–30 °C per kilometer of depth [94], due to the flow of heat from within the earth. However, the thermal gradient of several areas is sometimes greater, e.g., over 40 °C per km of depth in the western United States [95]. According to the Geothermal Electric Evaluation Model developed by the MIT group [96], a geothermal gradient greater than 80 °C per km of depth is economical at the current level of EGS technology. From the perspective of geological design, the thermal conductivity of the ground material plays an important role in the performance of continuous operation using a GSHP [97].

Current technology can be used to characterize potential EGS sites for power generation, as presented in Table 4. Various site properties of the reservoir include (1) temperature gradient and heat flow, (2) stress field, (3) geological characteristics and history

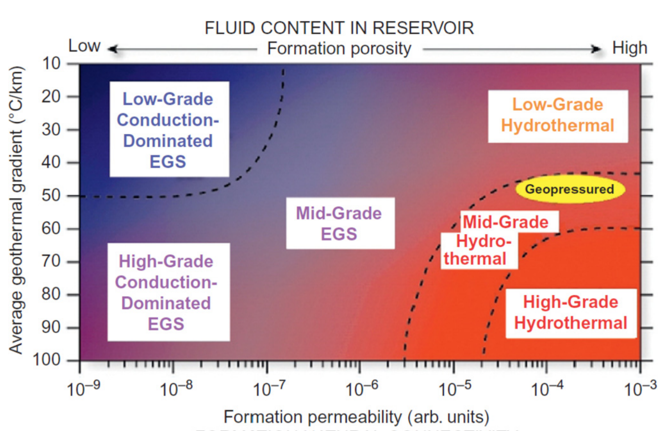

Fig. 5. EGS spectrum in terms of temperature gradient and formation permeability. Reprinted from the literature [98,99].

such as lithology, stratigraphy, structure and faulting, (4) in-situ fluids and geochemistry, (5) permeability and (6) seismic activity [87,100,101]. To determine the technical feasibility of significantly increasing EGS capacity, a sufficient amount of the natural resource should be available and established to supply the increase in energy production. Therefore, a geothermal survey should be performed at potential sites to ensure resource availability and the feasibility of large-scale deployment.

Integrated numerical simulation models, such as thermal–hydraulic–mechanical and chemical behavior of injection and production wells [102], TOUGH2 nonisothermal flow simulator [103,104] and three-dimensional hydrogeological and geomechanical model [105], are valuable in enhancing productivity. Moreover, the location of the reinjection zone and/or target is important to achieve successful design and management of a reinjection strategy, as well as ensuring the sustainability of geothermal fields [106]. On the other hand, corrosion can be managed through pipeline material selection, such as the use of corrosion-resistant coatings or corrosion-resistant alloys during plant design [65]. Moreover, periodic shutdowns and maintenance services of wells and surface facilities should be required for scale removal and corrosion control [107].

5.4. Provision of fiscal incentives, financing supports and guarantees

To effectively promote geothermal utilization technology in different areas, public administration organizations should be aware of the need for efficient electric energy generation and provide financial supports and incentives accordingly [91,108]. Pricing mechanisms, such as power purchase agreements (PPAs) and feed-in tariffs (FITs), should be designed to ensure the commercial viability of geothermal technology. According to the survey, subsidizing failed wells in the exploration stage and providing FITs (or price guarantees) for geothermal energy and increased tax benefits for geothermal developers would be strong incentives [82]. Usually, the investment loads in financing the preliminary survey and exploration activities would be performed, and the pricing system would be adjusted following exploration and a feasibility study. To properly fund geothermal exploration that provides proven capacity (financially viable and bankable), exploration data verified by a reputable international institutes should be provided.

6. Establishment of implementation plans and business model for EGS

6.1. Long-term R&D programs for key technologies and applications in industries

Incorporating design lessons learned from prior EGDS development into current EGS project construction is important. R&D programs should be focused on key components, such as exploration data, own drilling technologies, production and O&M of the reservoir, especially on their application in local industries. Several critical EGS technologies should be thoroughly evaluated and tested before the economic viability of EGS is considered. These technologies include (1) temperature-hardened submersible pumps, (2) zonal isolation tools, (3) monitoring and logging tools, and (4) coupled models to predict reservoir development and performance [109]. Significant improvements on EGS drilling technologies are especially necessary to access deeper resources, thereby reducing the cost of both the drilling and converting the energy into electricity.

Process design and integration technologies should be combined with LCA for multi-objective optimization [110]. In general,

Table 4
Important site properties of the reservoir.

Properties	Available technologies
Temperature gradient and heat flow	• Temperature measurement tools in shallow boreholes • Geothermometry (chemical/isotopic)
Stress field	• Interferometric Synthetic Aperture Radar (InSAR) • Global Positioning System (GPS)
Geological characteristics and history	• Geophysical surveys (magnetotelluric, electrical resistivity, magnetic surveys, etc.) • Lithologic analysis • Geologic mapping
In situ fluids and geochemistry	• Self-potential; streaming potential • Geologic models from the oil and gas industry (potential for stimulation)
Permeability	• Interpreting the drill-stem tests (DSTs) from several hydrocarbon exploration wells • Tested average interval by applying Monte Carlo procedures
Seismic activity	• Seismometers located in shallow surface holes
Others	• Proximity to transmission • Land availability • Demographics

deployment of process integration could minimize the total exergy destruction throughout the system [111]. Table 5 presents the technical information and performance evaluation of geothermal power plant in the literature. An integrated energy conversion system, such as solar-geothermal hybrid [112,113], could be designed not only to improve the quality of geothermal energy but also to augment the efficiency and capacity of the energy system. Cascade technology and versatile utilization for geothermal resources should be promoted to ensure the sustainable exploitation and utilization of geothermal resources [114]. A centralized energy/recycle center for collecting renewable energy should be installed. Other innovation schemes of geothermal utilization include a geothermal source for water desalination [115], geothermal plants with carbon capture and storage [116–118], geothermal water utilization for spas and health tourism [119], synergy of geothermal energy exploitation with deep oil and gas systems [120,121], and coupled with district heating networks [122,123]. The international manufacturing cooperation mechanism, technical platform and basic structure should be considered prior to establishing the business/commercialized models.

6.2. Cost benefit analysis for optimal configurations

The criteria to optimize the performance of EGS system design should be the economic profitability, the thermodynamic efficiency in the usage of the resource, and the life-cycle environmental impacts [110]. These criteria also are the key concerns for public acceptance of geothermal energy. Rising energy production costs have significantly affected communities and businesses. The fact that geothermal energy can be domestically generated would ensure the security of the energy supply and help offset foreign interference in energy affairs. Unlike coal and natural gas, geothermal energy is not associated with any hidden costs such as land degradation, high air emissions, forced extinction and destruction of animals and plants, and health impacts to humans [127]. Moreover, geothermal energy can bring significant economic advantages such as much-needed jobs and tax revenues to rural areas, where many of the geothermal resources that can be produced for energy consumption are located [127]. In addition, many geothermal companies provide additional voluntary contributions to neighboring communities.

Deep wells typically exhibit high uncertainty on well costs, which are controlled by the probability distributions of key variables. Yost et al. [128] proposed a Decision Aids for Tunneling (DAT) program to determine the uncertainty of well costs as a function of a fixed material cost, an hourly cost, and the time required for an EGS project. Similarly, Lukawski et al. [129] have developed correlations to determine the economic feasibility and risk of an EGS project with 2400–4600 m geothermal wells.

6.3. Implementation plans of EGS deployment: a case study in Taiwan

Taiwan has very limited land-based energy resources, and

Table 5
Technical information and performance evaluation of geothermal power plant in the literature.

Country	Year	Capacity (kW)	Core technology	Operating conditions	Q_B (kg/s)	T_{in} (°C)	η_{th} (%)	η_{ex} (%)	η_{us} (%)	Evaluation tool	Reference
China (Huabei)	2011	400	Organic Rankine cycle (R-123)	Geothermal water; P_e: 0.38 MPa.	50	108	1.8–8.1	–	–	On-site demonstration	[124]
United State	2013	–	Brayton cycle with SF_6 mixture (15%) in CO_2	Geothermal water; Recuperator of 40 m^2	20	160	13.0	–	–	Newton–Raphson method	[125]
Australia	2013	2200	Hybrid solar-geothermal power plant (binary ORC)	Solar energy fraction of 27%; Geothermal water	50	90–180	–	–	19–23	Aspen HYSYS	[126]
Australia	2013	–	Hybrid solar-geothermal power plant	Solar energy fraction of 68% (solar areas: 8000 m^2)	50	150	–	12.4	27.2	Aspen HYSYS	[113]
United State	2015	37,000	CO_2–based EGS with IGCC (ORC)	Neopentane as working fluid; P_e: 0.5–0.8 MPa;	1200	200	9.7–11.8	–	–	Aspen	[80]
China (Tianjin)	2016	500	Organic Rankine cycle (R245fa); double flash	Geothermal water	–	110	5.7	39.8	60.0	Grey relational analysis	[114]
Indonesia (Wayang Windu)	2017	1660	Kalina cycle system	Ammonia–water mixture; P_e: 1.02 MPa	48	180	13.2	–	–	Aspen HYSYS	[111]

*Q_B: brine mass flow rate; P_e: pressure of evaporator; η_{th}: thermal energy efficiency (%); η_{ex}: exergy efficiency (%); η_{us}: utilization efficiency (%).

therefore the country depends heavily on imported energy. By 2012, Taiwan's imported energy accounted for 97.5% of its total energy consumption. The cost of Taiwanese imported energy was as high as 61.7 billion USD, and the rate of growth is approximately 9.1%, thereby bringing a significant burden to Taiwan's economy. Taiwan is located at the junction of the Eurasian Plate and the Philippine Plate Orogen; the stratum folds and a large number of faults with rock uplift cause breaking of the central mountain range with higher geothermal gradient. Abundant rainfall allows lava to flow along the cracks of the stratum into underground rock formations; the geothermal gradient or magma sweltering heat thus produces abundant geothermal resources. Although shallow geothermal or EGS technologies are quite developed overseas, research teams need to make adjustments for local use due to the complexity of Taiwan's geology and topography.

The Energy Planning Report by National Science and Technology Program in 2008 points out that geothermal energy is an important category of renewable energy. This report estimates that geothermal energy may have a 7.14 GW power generation unit in the future. During the first phase of the energy project, this team estimated the geothermal energy potential of four areas in Taiwan: Datun Volcano Group, Yilan, Lushan East region and Hualian. Areas with an altitude below 1000 m and a depth within 4000 m have geothermal power potential for about 260 MWe, and the applicable geothermal power would be 33.6 MWe. It was found that the northeastern region of Yilan, the Nantou Lushan Mountain region, and the east side of the eastern Central Mountains have high surface heat flow. In addition, the silicon dioxide geological thermometer is not applicable in estimating the surface heat flow of acidic fluid, so there is no record of the surface heat flow of Datun Volcano Groups. Among all the data collections, Yilan had the greatest estimated reserves of geothermal power with a potential of up to 6704 MWe. Although there are many geothermal power areas (hot springs) in Taiwan, there is currently no geothermal generating facility under construction.

Currently, Taiwan focuses primarily on developing deep-drilling geothermal energy, where the key is to focus on obtaining geothermal strata with temperatures above 300 °C. When the temperature of the geothermal source is below 200 °C, it is more suitable for developing low power systems along with a small R&D investment. If the survey finds that the temperature of the heat source of the geothermal reservoir is between 200 and 300 °C, then this resource can be combined with the use of biomass energy. In this case, the heat from combustion of biomass energy can be used to produce water vapor and generate electricity. The National Energy Program in accordance with INITATIVE 5 Planning for geothermal power generator related equipment for R&D purposes focuses on investigation and assessment of the EGS in Taiwan on reserves that can be developed. To plan for future geothermal power plant construction and equipment research and development, the following three steps are required: (1) plan of power scale; (2) determination of power generation technology and equipment; and (3) design and construction of power plants. The experience of geothermal utilization in the Chingshui project reveals several good engineering practices [130], such as (1) the well valves used were left fully open to maximize productivity, but minerals in the hot water crystallized and blocked the passages whenever the pressure dropped; and (2) the amount of hot water extracted was excessive, and there was not enough natural rainwater to make up for it; this caused a loss of groundwater, resulting in a gradual drop in power produced.

6.4. Business model in Chingshui geothermal exploration

Chingshui geothermal field is one of the most promising geothermal energy sites in Taiwan due to its relatively higher resource temperature and available geological and reservoir studies. Geothermal reservoir temperatures are approximately 200–300 °C; geothermal fluid is produced from a jet temperature of about 120–150 °C; the fluid enthalpy unit weight is approximately 800–950 kJ/kg; and the steam quality is about 8–14% [131]. The shallow geothermal utilization in the Chingshui site is using the Kalina cycle. From 1973 to 1975, a reconnaissance survey of this site was performed by the Industrial Technology Research Institute (ITRI). Further exploration was conducted by the Chinese Petroleum Corporation from 1976 to 1980, and a geothermal power plant was built in this field by the National Science Council in 1981. However, the plant was decommissioned in 1993 due to technical problems including crystalline deposits obstructing the wells, resulting in the steam output gradually being diminished. In 2008, the government of Taiwan initiated a pilot study for geothermal exploration in the Chingshui area. So far, 19 deep production wells have been drilled in a 6-km-long band along the Chingshui stream with commercially successful wells confined to a 2-km^2 area at the southeast end of this zone [130].

In 2010, Jieyuan Technology Corporation joined the geothermal power generation project conducted by the ITRI, introducing Rkualianna circulatory system generators [132]. The generators installed have a capacity of 50 kWe, and the limit of the maximum generating capacity was designated to be 35 kWe. The total test power lasted 373 h with a total generating capacity of 9336 kWe, which is, to date, the only successful independent geothermal test generation project in Taiwan. To overcome the technical barriers, ITRI has been working on methods for encrustation controlling and post-encrustation well flushing, and technologies for water injecting back into the subterranean strata after use, which would help maintain underground water levels and prevent environmental pollution caused by dumping hot water into rivers.

The unit cost of electricity for fixed investment is approximately 0.085 USD/kWh, the unit cost power generation operation is 0.064 USD/kWh, and the total unit cost of power generation is 0.149 USD/kWh. These estimates are based on the geothermal potential of the land area data review and analysis of power systems installed capacity planning and cost analysis collected by the Yilan County Government, assuming that the operating lifespan of a power plant is about 30 years and that 3 MWs of installed capacity plant annual net power generates about 18.2 GWh. According to the current market rate, wholesale geothermal power is 0.16 USD/kWh. The annual after-tax net profit would be approximately 0.196 million USD, with a rate of return on investment of 7.3% [133]. This estimation could help promote the build-operation-transfer (BOT) model for the Chingshui project, and pave the way for the reconstruct-operation-transfer (ROT) geothermal power project. The operating experience gained through the development of a geothermal demonstration project in Taiwan could provide a solid foundation for moving the geothermal resource forward as an economically viable technology for the country in the future.

7. Conclusions and recommendations

7.1. Conclusions

In this study, we provide the insightful and useful information for establishing the enhanced geothermal energy utilization plans, in terms of challenges, opportunities and strategies. A sustainable energy supply system should be affordable (cost-effective), reliable, and environmentally friendly, and it should efficiently utilize local resources and networks. Both the environmental and economic benefits of geothermal energy technologies can be realized by (1) promotion of an overall energy utilization efficiency, (2) increase of energy security, (3) reduction of CO_2 emissions and other air and water pollutants, (4) reduced consumption of fresh water, and (5) flexibility of operation scheme. In fact, since no two project sites are identical, each EGS plant must be designed to project-specific conditions. The experiences and lessons learned are the key to developing a successful EGS project. The government should help reduce the risk of EGS development, by assuming some of the exploration risk and/or improving the prices of electricity and steam. Due to the long development times and the upfront risk and exploration, economic incentives to new users should be provided as an important enabler for EGS. On the other hand, environmental performance can change considerably depending on both the reservoir conditions and the design of the plant. Therefore, it is necessary at the design stage to find a suitable compromise to limit the risk of induced seismicity and other environmental impacts. Also, an integrated system with cascade technology and versatile utilization, such as (1) solar-geothermal hybrid, geothermal coupled with (2) district heating networks, (3) water desalination, (4) carbon capture and storage, (5) deep oil and gas systems, and/or (5) tourism and entertainment, such as spas and health tourism, should be promoted to ensure the sustainable exploitation and utilization of geothermal resources.

7.2. Recommendations

With the consideration of environmental impacts and benefits, an enhanced geothermal system should be regarded as the best available technology for generating large amounts of electric power. Avoiding the adverse impacts of geothermal exploration and operation on the environment and human health requires careful site selection, effective regulatory oversight, and an appropriate monitoring program. Strategic environmental assessment should broadly present the preferred environmental, ecological, social and economic outcomes to minimize the detrimental effects of a project or activity. Incorporation of design lessons learned from prior development into current project construction is highly recommended. As a result, to optimize the performance of a geothermal energy plant, system design should take into account economic profitability, thermodynamic efficiency in the usage of the resource, and life-cycle environmental impacts.

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