Applied Thermal Engineering 258 (2025) 124575

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Current status and advancement from high yield and oilfield geothermal energy production: A systematic review

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ARTICLE INFO

Keywords:
Geothermal energy
Geothermal system
Oilfields
Enhanced geothermal systems
Sustainability
Renewable energy

ABSTRACT

This review provides a comprehensive assessment of the current state and advancements in geothermal energy production from enhanced geothermal systems, and the oilfields. As the emphasis on developing a sustainable environment intensifies, it is crucial to use energy sources judiciously. The adoption of renewable energy technologies is essential to establishing energy systems that are significantly more sustainable than the current reliance on fossil fuels. Over the past few decades, research has demonstrated that harnessing geothermal energy and improving the efficiency of existing geothermal systems are both effective strategies for addressing energy challenges. Although geothermal energy, particularly from enhanced geothermal systems, and oilfields has certain limitations relative to other renewable sources, it offers significant advantages by reducing environmental impacts and lowering emissions of harmful gases. The current study, reveals at least 18 enhanced geothermal systems sites have been in operation, with approximately 40 years of development experience with several case studies and pilot projects related to oilfield geothermal energy are in existence. As of 2023, the total installed capacity of geothermal energy worldwide stands at 14,846 megawatts. The past decade has seen significant improvements in geothermal energy extraction techniques. Looking forward, geothermal energy is poised to play a pivotal role in the global energy transition, offering a reliable and low-emission energy source that is essential for achieving long-term sustainability goals.

1. Introduction

The primary source of geothermal energy is the heat produced and stored naturally beneath the earth for millions of years during its formation [1,2]. It is less site-dependent than wind or solar energy and potentially more accessible than many hydrocarbon resources, making it a safe and sustainable long-term energy source [3,4]. Geothermal systems have a high load factor, which is one of their key advantages since each megawatt offers more power throughout a year than wind or solar [5]. Conventionally, wells are drilled near volcanoes or subterranean magma sources to extract geothermal energy. This approach allows energy extraction from high-heat sources by employing a system where injection occurs through one well while production occurs through another. Fig. 1 illustrates the numerous ways geothermal systems can be utilized.

Geothermal energy, especially high-yield geothermal energy, is strongly linked to oilfields due to the geological and thermal features of their subterranean settings. Hot rocks at lesser depths are economically viable in oilfields due to larger geothermal gradients. Existing wells and pipelines can be used for geothermal energy extraction, reducing start-up costs. Hydrothermal resources in some oilfields can be used to generate geothermal energy. Enhance geothermal system (EGS) can use oil extraction methods like hydraulic fracturing to increase geothermal potential. Transitioning from oil extraction to geothermal energy can mitigate environmental impacts, as geothermal energy is renewable and low-emission. Successful conversions, such as the Puna geothermal venture in Hawaii and the Copa hue geothermal field in Argentina, demonstrate the feasibility and benefits of this synergy.

The potential for heat recovery in numerous large oil and gas fields

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https://doi.org/10.1016/j.applthermaleng.2024.124575
Received 31 March 2024; Received in revised form 7 October 2024; Accepted 7 October 2024
Available online 12 October 2024
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Nomenclature

AGS	Advanced Geothermal System
AI	Artificial intelligence
BHE	Borehole Heat exchanger
CFD	Computational fluid dynamics
COP	Cost of production
CLGS	Close loop geothermal system
DCHE	Deep close heat exchanger
DFM	Discrete fracture model
DFN	Discrete fracture network
DHX	Down Hole Heat Exchanger
ECM	Equivalent continuous model
EDFM	Embedded discrete fracture model
EGS	Enhanced Geothermal System
GAI	Geological Agency of Indonesia
GSHP	Ground Source Heat Pumps
HDR	Hot Dry Rock
IEA	International energy agency
IGM	Improve grey prediction model
IRENA	International organization for renewable energy
ITRT	Improved thermal response test
ITRT	Improved thermal response test
KGD	Khristianovic-Geertsma-De Klerk
LCOE	Levelized cost of electricity
MWHF	Multi-Well Horizontal Fracture
NCG	Non-condensable gases
NPR	Naval Petroleum Reserve
ORC	Organic Rankine Cycle
P &A	Plucking and abandonment
PKN	Perkin, Kerns, and Nordgren
RSS	Rotary steerable systems
SAR	Signal averaging system
SAGD	Steam assisted gravity drainage
SBT	Slender body theory
SRV	Stimulated reservoir volume
STA/LTA	Short time average/ long time average
SWOT	Strength, Weakness, opportunity, and Threats
THM	Thermos hydro coupling model
USD	United States Dollar
USDOE	United States department of energy
UK	United Kingdom
US	United State

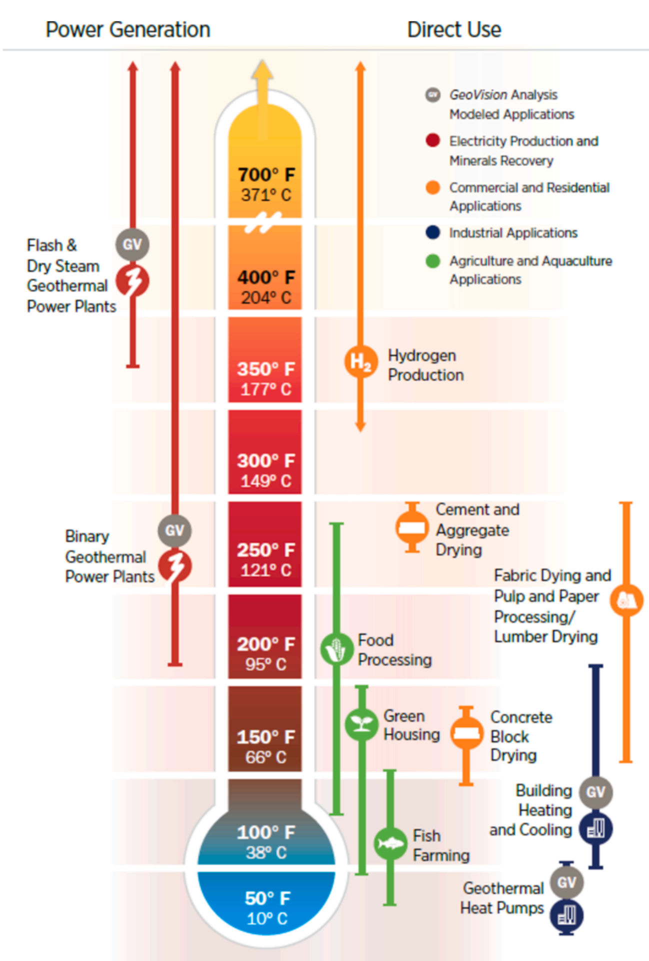

Fig. 1. Geothermal energy technology applications and uses [12].

around the world has been thoroughly examined. According to McKenna et al. [6], more than 1000 MW of electricity could be produced from fluids co-extracted in oilfields along the Gulf Coast. Limpasurat et al. [7] explored the possibility of capturing the significant heat stored in heavy oilfields subjected to steam flooding, they estimated that a single injector-producer system could generate approximately 14 kW of net power. Ennett et al. [8] projected that oilfields in the Los Angeles basin could produce a net geothermal power output of approximately 7,430 kW, with a Net Present Value (NPV) of $41 million over 30 years. Sanyal et al. [9] indicated that an abandoned gas well on the US Gulf Coast could generate around 350 kW of net geothermal power from co-produced water.

Some researchers like Kumar et al. [10] focused on the global perspective of geothermal energy development but neglected to bring out the various research gaps regarding its developments. Moska et al. [11] focused on the recent stage and advancement of geothermal energy from the Baltic states (Lithuania, Latvia, Estonia, and Poland), which cannot reflect the world. Sharmin et al. [1] reviewed geothermal extraction, advancement, and improvement, but their research only focuses on enhance geothermal systems. Energy generation from EGS and oilfield is not well documented in geothermal technology study. To respond to these deficits, our review selected 240 most recent publications from high-impact journals according to the following keywords: Hot dry rock, enhanced geothermal system, oilfield geothermal energy, geothermal energy production advancement, application of AI in geothermal energy, etc., then lastly 12 publications were selected for macro characterization. Fig. 2 summarizes the method employed in conducting the systematic review within the scope.

Findings from this systematic review reveal, reveals at least 18 enhanced geothermal systems sites have been in operation, with approximately 40 years of development experience with several case studies and pilot projects related to oilfield geothermal energy are in existence. As of 2023, the total installed capacity of geothermal energy worldwide stands at 14,846 megawatts, which can further help geothermal energy policymakers to re-explore geothermal energy from the oilfield and EGS by using the most recent methods or technologies to achieve net zero carbon emission.

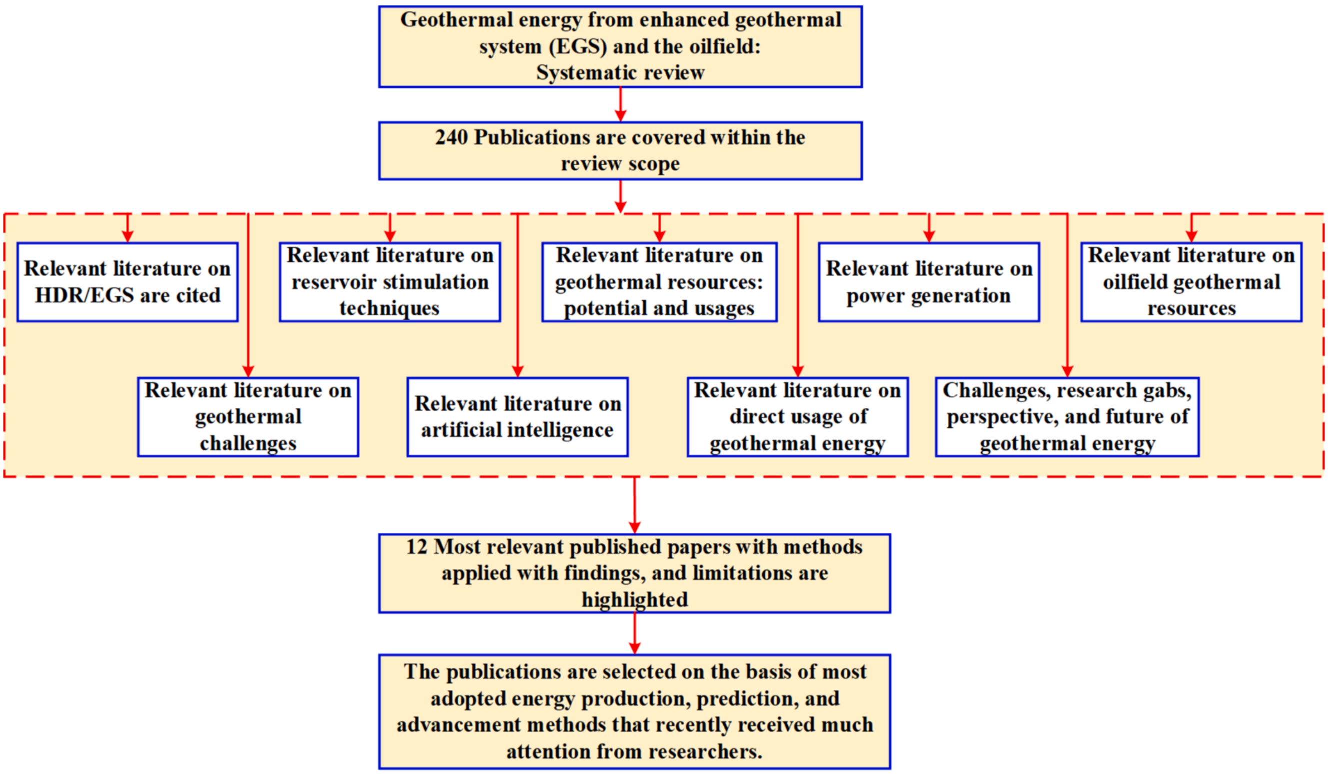

Fig. 2. Method in conducting the systematic review.

Table 1
Conventional fracture theory model's assumption, strength, and weakness.

Ref.	Models	Assumption	Strength	Weakness
[13]	PKN	Length is expected to be substantially more significant compared to the fracture's height	– The PKN approach accounts for the turbulence effect, particle velocity system, and fluid flux method	– The model cannot solve for vertical fracture extension.
[16]	KGD	The fracture height is assumed to be the same as the reservoir height in the model.	– The model applies to fracture lengths that exceed fracture heights.	– The model cannot solve vertical fracture extension. – Leak-off damages are not taken into consideration by the model.
[18 21]	P3D	Overall layers, the model treats height as a constant.	– The fracture height is not constrained by the thickness of the reservoir in this updated PKN model.	– The model only considers horizontal fracture propagation within the dense media. – The model cannot describe specific types of fractures.
[20 19]	PL3D	The model considers the complete 3D elasticity equation to explain fracture width.	– The model considers all 3D elasticity equations to define fracture extent.	– The model rarely considers the heat transfer in the reservoir.

2. Conventional method of fracturing

The standard fracturing method originated during WWII, two fracture hypotheses explain the major fracture based on fracture extension, direction and height assumptions. Researchers Perkin, Kerns, and Nordgren created the PKN model [13]. PKN's initial model incorporates the impact of turbulence and the flow of fluids [14].

In 1955, Khristianovich and Zheltov established KGD, which stands for Khristianovic-Geertsma-De Klerk [15,16], another well-accepted hypothesis, which assumes the fracture height is the reservoir height. Two standard fracture theory models are based on elastic mechanics and cannot explain the vertical fracture extension [17]. For reservoir fracture height development, numerically oriented PL3D, P3D, and complete 3D examples were constructed. Using the PKN model, P3D was created in the 1980 s to study vertically hydraulic fractures in horizontally stratified reservoirs [18]. Unlike the PKN model, the P3D fracture's height is not constrained by the reservoir's thickness [16,19,20]. When describing a fracture network, this model has currently taken the position of the PKN or KGD model. Table 1 summarises the conventional fracture theory assumption, strengths, and weaknesses.

2.1. Stimulated reservoir volume

Due to rapid mining equipment advancements, standard fracture theory technologies cannot capture fracture complexity. As a result, the technology known as stimulated reservoir volume was created to boost production within the petroleum industries [22]. This method employs hydraulic fracturing (HF), to create a shear slip along the initial fracture, the geothermal industry, specifically enhanced geothermal, adopted this method [18].

The most crucial measure to represent the hydraulically fractured volume following stimulation is the stimulated reservoir volume SRV. Existing models based on micro seismic events frequently lack a consistent geometric definition, resulting in considerable SRV calculation and interpretation discrepancies. Only one fracture extension in a reservoir may be explained by conventional fracture theory [23]; some scholars provide a solution by using the theory of probability to

Table 2
Stimulated reservoir volume model assumption, strength, and weakness [26,27,30,31].

Model	Assumption	Strength	Weakness
DFN	The fracture's properties are modeled using statistical techniques.	Only one fracture extension in a reservoir can be resolved using conventional fracture theory, while the DFN can solve more complex fractures.	Due to the complexity of actual natural fractures, challenges, and ambiguity occur when integrated hydrological, tectonic, chemical, and thermal processes are considered.

characterize using the equivalence principle model, which is referred to as DFN, which stands as "discrete fracture network" [24]. The model can explicitly characterize every fracture within the domain and several methods of heat extraction from cracked rocks using the discrete technique [25,26]. The Monte-Carlo stochastic approach is used to determine the distribution of fractures; this model thus compensates for the drawback in the conventional method of fracturing theory. The technique enables research into the mechanics of geothermal reservoirs [18], but the DFN approach cannot guarantee consistency; for example, based on the evolution of natural fracture systems in the field is explained by geological history and the mechanism [27–29], a linearly elastic mechanic in fractures are used to mimic the geomechanically produced networks of fracture [30]. However, no suitable heat transport model characterizes the discrete fracture network in geothermal reservoirs. Based on current research, the fracture can be described by studying heat transmission between the network as a rectangular conduit of fractures in the rock [31]. Table 2 summarizes the DFN assumption, strengths,andweaknesses.

2.2. Techniques for modelling fracture networks for better performance

Geothermal energy presents an inherently attractive option as a green and sustainable energy source, derived from natural processes. As a result, several initiatives are being taken to improve the performance of geothermal systems; some of the techniques for enhancing the performance are as follows:

- Expandable tubular casings, higher penetration rates, low clearance well casing designs, casing while drilling, and other advancements have increased deep EGS well economics. These technologies are detailed in [32,33].
- Micro seismic imaging defines reservoir subsurface fracture geometry while forecasting induced seismicity microearthquakes [34,35]. Conventional seismic monitoring and tracking systems may detect microearthquakes in real short time average/ long time average detectors (STA/LTA). In complex signal processing settings, template-based detection methods detect small seismic events using array-based waveform correlations [36]. To prevent geothermal-induced seismicity, physics-based, hybrid, and statistical forecasting methods are being used [37].
- Permeability can be improved by stimulating hydraulically subsurface circulation channels with dense working fluids [38,39]. Addition of sodium chloride (NaCl) in mineral solvent or change in geothermal reservoir temperature, pressure, and chemical composition can change fluid's density [40,41]. The significant advantage in utilizing carbon dioxide as a circulating fluid in enhanced geothermal systems plants over brine is higher heat flow due to its chemical, thermal, and physical properties [42].
- Integrated and hybrid geothermal systems, which use other energy sources to boost output efficiency, have garnered interest recently. Some studies recommend combining geothermal systems with wind, hydropower, biomass, etc. Hybrid geothermal systems use 44 % for heating, 12 % for power, and 44 % for cooling [43].
- Numerous simplified fracture models have been developed to enhance geothermal energy performance, with four standard models included in Table 3 [44].

Table 3
Techniques for modelling fracture networks for better efficiency [44].

Fracture models Discrete fracture network model (DFN)	Equivalent continuous model (ECM)	Discrete fracture model (DFM)	Embedded discrete fracture model (EDFM)
– Fracture distribution is a comprehensive model – The matrix and fracture flow are ignored	– Faults structure and distribution are neglected – Particular porosity and permeability are simplified	– More accurate than ECM – Accounts for rock matrix seepage flow – Requires several unstructured grids	– Minimizes computational complexity – Discretizing the matrix and fracture system

Table 4
Presents the attributes of geothermal systems.

Geothermal systems	Range in depth	Attributes	Comparative characteristics
EGS	2000–10000 *m*	Extracting thermal energy from low-permeability Hot dry rock formations without groundwater.	Harvesting a substantial quantity of heat within artificial fractures facilitates the extraction of substantial energy from rock formations devoid of significant water content employing hydraulic fracturing techniques.
Hydrothermal Systems	500–4500 *m*	Harvests thermal energy from rocks characterized by high permeability in the presence of groundwater	Conventional applications are less commonplace, as the preponderance of geothermal energy is primarily harbored within hot dry rocks, notably concentrated in regions characterized by active volcanic activity.

3. Enhanced geothermal systems or hot dry rock (HDR)

Hot dry rock is a 150–650 ^{0}C rock mass found at depths of 3–10 km [54]; it contains about 90 % of the geothermal energy that is now available. HDR was first discovered in 1974 at the Los Alamos National Laboratory research, and research has been ongoing at Soultz-sous-Forêts, France, since 1987 [45–47]. With the exception of hydrothermal systems, this method extracts energy from arid rock formations even without water [18,48]. Table 4 lists geothermal system characteristics that can be created by increasing a reservoir's hydraulic capacity.

Extraction of geothermal energy begins with reservoir investigation. As shown in Fig. 3, an optimal conventional geothermal system requires heat, permeability, and water.

There are three main methods for stimulating HDR reservoirs: hydraulic, chemical, and thermal stimulation [47]; the most significant reservoir stimulation method now in use is hydraulic fracturing [49].

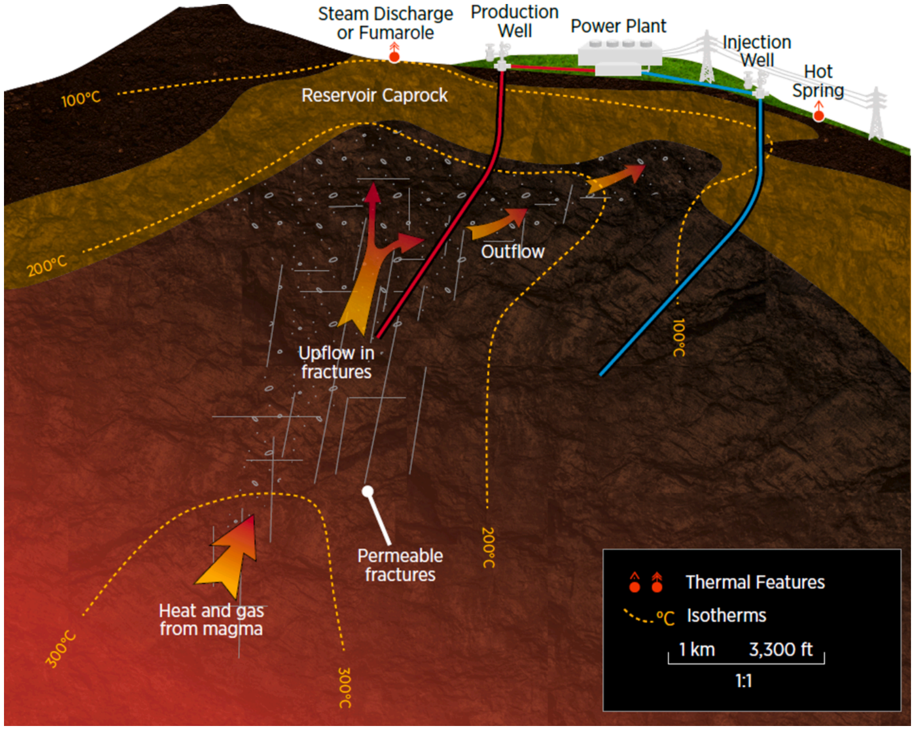

Fig. 3. Schematic representation of an exemplary geothermal system hot rock and a heated sedimentary aquifer [12].

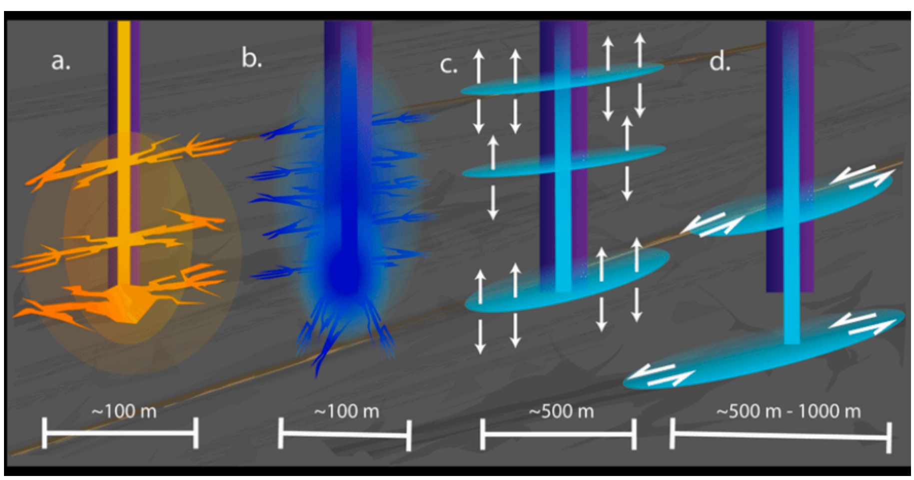

Fig. 4. Schematic representation of stimulation techniques used in EGS reservoirs [56].

This approach was first applied in the oil and gas sector to improve the permeability of tight formations [50]. Alkaline/acidic liquid injected into the well dissolves reservoir minerals in chemical stimulation methods [51]. Thermal stimulation is used alongside hydraulic fracturing and chemical stimulation to stimulate reservoirs but has garnered little research and application [52]. Thermal stimulation involves introducing cool fluid into hot formations below rock-fracture pressure [53]. Cold flow and contracting formation rocks create open fractures, while geothermal reservoir cooling promotes fracture propagation [54]. Fig. 4 depicts the stimulation techniques used in EGS [55]. a) Chemical stimulation, where the yellow colour represents acid concentration as the chemical reacts with the minerals in the pre-existing space; b) Thermal stimulation, where the dark blue colour represents cold fluid that creates fractures around the hole; c) Hydro shear stimulation, where high-pressure fluid is injected into rock openings to fracture it; d) lower-pressure hydro shear stimulation.

3.1. Engineering classification of EGS

Based on the artificial stimulation method, the engineering systems for thermal extraction are categorized into three types: Fracturing-enhanced geothermal system (F-EGS), pipe-enhanced geothermal system (P-EGS), and excavation-enhanced geothermal system (E-EGS) [57]. The most common geothermal energy extraction technology is F-EGS, which uses injection wells, production wells, and reservoirs stimulated by hydraulic, thermal, and chemical stimulation [58].

P-EGS constructs fluid flow channels by embedding pipes in subsurface rock, allowing fluid to flow inside the pipes and exchange heat with the rock through the pipe walls [59]. F-EGS requires large-scale reservoir fracturing, but P-EGS is a closed-loop system that conserves water and reduces induced seismicity. Additionally, since the fluid does not directly contact the hot dry rock, issues such as corrosion, scaling, and environmental pollution are avoided [60]. However, pipe exterior

Table 5
Specifications of some EGS plants across the world.

Project location	Capacity	Project types	Project duration	Temp. (K)	Fluid type
Japan, Hijiori	130000 W	Granodiorite	From 1985 to 2002	463.15	Water
France, Soultz-sous-Forets	1000 W	Granite	From 1984-present	473.15	Brine
USA, Fenton Hill	60000 W	Granite	From 1974 to 1995	465.15	Water
Switzerland, Basel	3000000 W	Granite	From 2002 to 2009	473.15	Water
Australia, Habanero EGS Project	1700000 W	Granite	From 2003 to 2013	536.15	Brine
Germany, Groß Schönebeck	1000000 W	Rotliegend formation, (Sandstone, andesite)	From 2000-present	418.15	Water

surface area severely limits P-EGS heat transfer efficiency. Despite optimizing the piping arrangement (many pipes, annular pipes, vertical heat pipes) to enhance heat transfer area, its heat extraction efficiency is uncertain and lower than other geothermal systems.

E-EGS is a mining technology concept that uses local hydraulic fracturing or blasting to improve rock cave ability and fragmentation sizes. Split rock is carried to a heat exchange zone to form a regulated geothermal reservoir [57]. By eliminating uncontrollable large-scale reservoir fracturing, E-EGS can significantly reduce fluid filtration loss and induced seismicity, showcasing significant potential for geothermal extraction. However, the heat extraction performance and optimal operating conditions for these three geothermal systems remain unclear.

3.2. Current status of enhanced geothermal systems

Enhanced geothermal systems represent a transformative approach in geothermal energy, enabling power generation in areas without naturally occurring hydrothermal resources. EGS technology and deployment have advanced. The Frontier Observatory for Research in Geothermal Energy (FORGE) in Utah shows effective drilling and artificial reservoir creation, making EGS a geothermal innovation hub. EGS projects like Austria's GeoTief and the UK's Eden Project demonstrate global momentum [61,62].

Tech advances are key to EGS's success. Directional drilling and hydraulic fracturing improve hot rock formation permeability, reservoir efficiency, and heat extraction. Canopus Drilling Solutions' Directional Steel Shot Drilling (DSSD) hybrid drilling technology is fast and cost-effective, overcoming difficult geological conditions [63]. Additionally, Halliburton's GeoESP Intake system reduces power consumption and operational issues in high-flow geothermal applications, further boosting plant efficiency and sustainability [63].

Superhot rock energy is another ground-breaking area within EGS. By accessing geothermal reservoirs at supercritical temperatures (exceeding 400 °C), this technology offers higher energy output and efficiency. The US department of energy (DOE) and various research institutions are actively exploring this potential through pilot projects and feasibility studies, recognizing that even tapping into a small fraction of these resources could dramatically increase clean energy generation [61,62].

Despite these advancements, EGS faces challenges, particularly in terms of high up-front costs and risks associated with drilling and reservoir creation. The DOE estimates that $225–$250 billion is needed to scale next-generation geothermal technologies commercially. EGS projects need simplified regulatory processes and community interaction to handle environmental and social issues and gain public acceptance [61,62]. To prove performance and economic viability, large-scale commercialization requires continual research, pilot initiatives, and supportive policy. [62].

Table 5 shows key parameters for worldwide enhanced geothermal systems plants [64–66]. While constituting a minority compared to more prevalent and widely dispersed geothermal systems globally, they exhibit more significant potential [45].

Many technical concerns affect a geothermal plant's operation, like other renewable energy sources. Many projects have failed because of capital costs, and safety anomalies. Hot dry rock drilling is difficult because it needs deep drilling, which can weaken rock walls. Fluid short-circuiting in one or more key channels between the production and injection wells prevents effective heat transfer between the rock formation and the fluid [67]. They also present technical concerns like locating and verifying geothermal resources, which are harder than other renewable technologies. Historical and ongoing concerns about geothermal energy causing earthquakes [68]. A recent 5.5 magnitude earthquake in

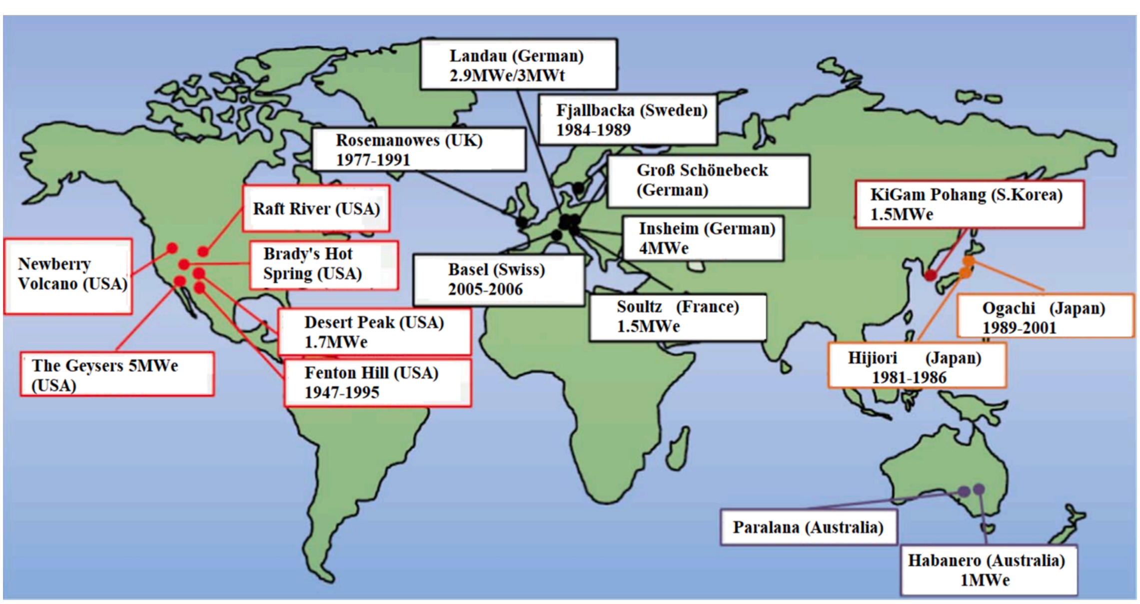

Fig. 5. Diagram shows the global distribution of EGS locations [58].

Pohang, South Korea, near a geothermal plant site was connected to poor reservoir stimulation risk management [69,70]. One major environmental effect is seismicity. Geothermal fluid extraction over 50 years has caused 15 m of soil subsidence in the Wairakei field [71]. The wells' operations have the worst environmental effects, including noise from drilling and testing, groundwater pollution frombrokencasts, and other things [72]. However, recent Caltech research suggests that geothermal energy could reduce strain and aftershocks and protect the region against larger earthquakes [73,74]. Despite these hurdles, at least 18 EGS sites have been constructed since the first at Fenton Hill, offering EGS 40 years of development experience Fig. 5 [58].

3.2.1. Emergence of new technologies in EGS

New technologies are constantly being developed for enhanced geothermal systems, and the industry is actively exploring advances from other fields that could improve efficiency and reduce initial risks. As these technologies mature, EGS should gain credibility as a reliable baseload power source [75]:

3.2.2. Drilling

Drilling deep wells traditionally uses rotary drilling. New drilling technology has transformed the energy industry, making natural resource extraction more efficient and cost-effective. Operators can dig non-vertical wells via directional drilling, reaching previously inaccessible sites [76]. This strategy maximizes resource recovery and reduces surface disturbance and environmental effect. Rotary steerable systems (RSS) have revolutionized drilling. RSS technology allows real-time wellbore trajectory modifications, speeding up and improving drilling accuracy. Furthermore, advancements in automation and robotics have led to the development of autonomous drilling rigs capable of performing complex drilling tasks with minimal human intervention. These rigs utilize advanced sensors and algorithms to optimize drilling parameters, enhance safety, and reduce operational costs [77].

3.2.3. Stimulation

Predominantly, enhanced geothermal systems implementations thus far have relied upon the stimulation of pre-existing fractures through water injection. Subsequently, a seismic mapping procedure is conducted to delineate the regions where these stimulated fractures occur, following which production wells are established within these designated zones. On the other hand, in unconventional oil applications, Multi-Well Horizontal Fracture (MWHF) technologies have evolved to stimulate and maintain multiple fracture networks simultaneously. These technological advancements, coupled with the utilization of deviated well trajectories, hold the potential to facilitate the creation of more productive geothermal reservoirs within rock formations. This focal area of research is underscored within initiatives such as the initiatives led by the United States Department of Energy (USDOE), including the FORGE and COLLAB projects.

3.2.4. Production management

Enhanced geothermal systems implementations commonly employ 'open-hole' completions for both injection and production wells, wherein production casing and cement are omitted. This methodology lacks the precision to regulate designated injection and production points along the wellbore, resulting in fluid flow dictated by zones of highest permeability. Consequently, this may lead to the establishment of dominant flow channels, extracting heat predominantly from localized areas while neglecting other reservoir sections with lower flow rates. In thermal oil production scenarios, particularly those employing steam assisted gravity drainage (SAGD) techniques for bitumen recovery, advanced technologies have been devised to control fluid injection and production points within elongated horizontal wells. Those advancements encompass the deployment of high-temperature isolation packers, alongside inflow and outflow control devices, commonly denoted as ICDs and OCDs. Empirical evidence suggests that these technologies effectively enhance reservoir connectivity and mitigate 'short-circuiting' phenomena between injector and producer wells in such operations. The applicability of these technologies to EGS holds promise for similar improvements in reservoir management and thermal efficiency.

3.3. Emergence of the discrete fracture network in EGS

The discrete fracture network (DFN) is now being used more frequently to address issues in mining and geothermal engineering [78]. The performance of the DFN has improved with the accessibility of advanced computer techniques, making it the most flexible technique to investigate complex fracture networks and the present conditions of the rock mass [22]. DFN models successfully characterize rock masses when the fracture network is represented statistically [82], and the fracture sets are used in computational modelling to show the network structure. There has been a lot of interest in practical numerically oriented approaches for investigating the geothermal extraction, thermo hydro coupling problem from a fracture rock mass DFN model [23], for forecasting the coupled behaviour of fluid flow and heat exchange, DFN models have been widely developed [79]. The numerical simulation of such models has demonstrated that discontinuities are flexible since they explicitly represent the discontinuity attributes and fracture geometries [80].

3.3.1. Challenges of using DFN in enhance geothermal system.

In recent years, DFNs have proven reliable for borehole mapping, geomechanically evaluation, geothermal technology, and various oil and gas sectors [30]. Despite their adaptability, integrating the complexity of rock masses into DFN models still has some restrictions and difficulties. Because of the intricate geological structure of naturally occurring or purposefully induced fractures inside the fractured reservoir, identifying the distribution of a large-scale fracture network system included in the HDR through a small number of boreholes is a considerable difficulty [54]. The decision to include a comprehensive geometrical description of the fracture and their accompanying fracture connections posed the main challenge in using the DFNs for subsurface flow simulation [81], intrinsic geological faults, bedding planes, schistosity planes, shear zones, joints, and faults are also in place [82]. As a result of technological advancements, digital photogrammetry enables mining operations and geotechnical mapping of outcrops. The technique can offer joint roughness characteristics, joint wall strength, and joint infill material properties [83], as well as other necessary data sets; regrettably, the method cannot give the main geological discontinuities, fracture density, fracture direction, aperture breadth, and rock matrix characteristics are the main determinants of fluid flow based on Bordas [22].

4. Geothermal resources in oilfields

The geothermal energy market has been expanding at 10.9 % annually due to laws encouraging renewable energy sources [84]. Many countries have pledged to reduce carbon emissions or achieved net zero by 2050 [85]. As a result, more research is being done to convert oil and gas wells to geothermal wells; the concept has faced difficulties for a while. Still, only a few experimental projects, primarily those involving co-produced fluids for small-scale power generation, have been successful so far [86]. The geothermal resources found in hydrocarbon fields are classified as unconventional geothermal resources since the reservoir has a low temperature and is typically located in sedimentary strata [87].

The relatively new geothermal industry can significantly benefit from the extensive expertise and skill set developed within the oil and gas sector; geothermal energy extracted from oilfields is recorded in several nations in various world regions. According to [89], China's first geothermal power plant, was created by utilizing water from

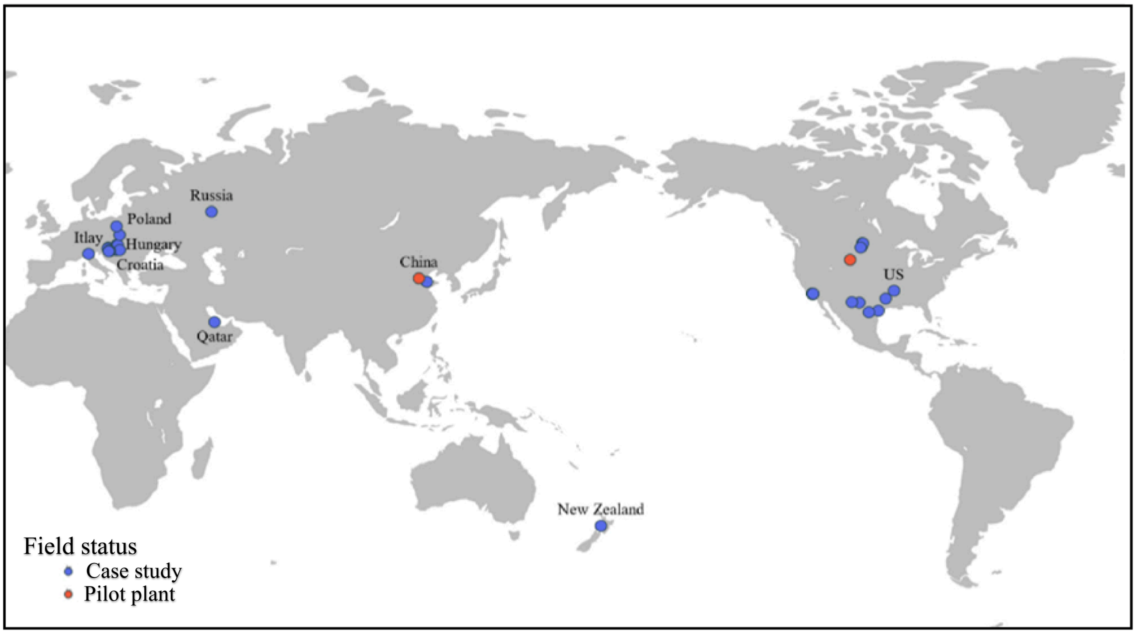

Fig. 6. Geothermal operations in global hydrocarbon fields [88].

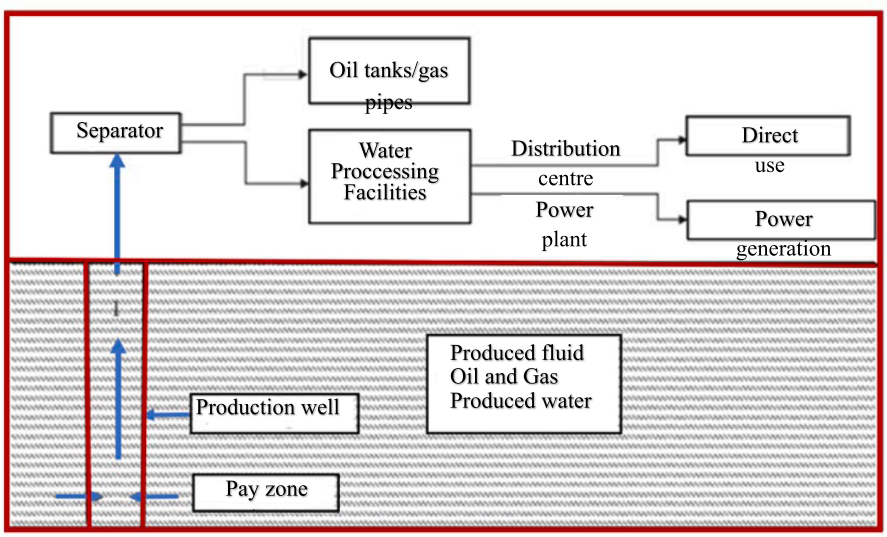

Fig. 7. Diagrams illustrate the modified flow of fluid created during geothermal extraction via production wells [91].

waterflooding wells, was another well-known project for developing geothermal energy in oilfields. Fig.6 depicts the locations of such petroleum fields; most projects are carried out in the United States, Europe, and China.

4.1. *Methods of extracting geothermal energy from oilfield*

There are two main ways to extract geothermal energy from the oilfield: Mature wells in operation that yield significant quantities of high-temperature water, and abandoned wells [90]. In mature active wells geothermal resources are extracted from active oil wells [91]. Geothermal extraction from matured wells uses formation water that has been geothermally heated [92]. Based on technology readiness and supported by successful field testing [86], co-production may not have the same potential contribution level as conventional hydrothermal reservoirs or EGS. Still, it can recover more energy from a currently used source; Fig. 7 illustrates co-production processes [12]. Nevertheless, the

Table 6
Projects related to geothermal power generation utilizing co-produced fluids.

Year	Operated	Location	Power Output (kW)	Ref.
2021	Parex Resources and Universidad Nacional de Colombia-Medellin	Las Maracas – Colombia	100	[94]
2016	University of North Dakota	Williston Basin- USA	124	[95]
2011	PetroChina	Huabei Oilfield – China	310	[96]
2008	US Department of Energy	RMOTC Wyoming – USA	180	[97]

Table 7
Summary of worldwide projects involving directly utilizing geothermal resources in oilfields.

Location of oilfield	Geothermal resource	Utilizations type	Comments	Ref.
Albania	Abandoned wells	Heating greenhouse	Water derived from geothermal sources, reaching temperatures of Water with temperatures 65.5 °C was utilized for the purpose of heating greenhouses.	[9191]
Austria, Styria	Abandoned wells	Spa resorts	Water derived from geothermal sources are utilized at the spa resorts Loipersdorf and Walterdor.	
Hungary, Algyo,	Hot water production	Geothermal water EOR	Since 1969, water from geothermal sources has been utilized in thermal water flooding operations.	
Hungary, Savoly	Hot water production	Gathering heat-trace oil	Water derived from geothermal sources was employed to heat the gathering pipe in Savoly. reference	
China, Shengli	Abandoned wells	Space heating	From 2002 to 2015, the implementation of heating the space in the area of Furong resulted in conserving $3*10^4$ tons of standard coal and $2*10^4$ tons of oil.	[102]
China, Daqing	Hot water production	Transporting crude oil	Five projects collectively replaced 7,000 tons of standard coal annually.	[102103103103]
China, Liaohe	Hot water production	Space heating	Twelve projects contributed to the replacement of 24,400 tons of standard coal annually.	
China, Huabei	Abandoned wells	Gathering heat-tracing Oil	Geothermal oil recovery from two abandoned wells results in the daily conservation of approximately 5 tons of oil and 3,500 cubic meters of gas.	
China, Zhongyuan	Hot water production	Space heating	A singular project resulted in the annual conservation of 2,537 tons of standard coal.	

efficacy of this geothermal method use is strongly associated with oil and gas extraction processes and largely relies on production rate and water temperature [93].

Pilot initiatives have effectively generated power by harnessing coproduced fluids during oil and gas extraction in the United States, China, and Colombia. The inaugural pilot demonstration initiated by the United States Department of Energy commenced in 2008 at the Rocky mountain oilfield testing centre in Wyoming, USA. The strategic advantage of this location lies in its numerous operational oil wells interconnected to a central facility for fluid separation. Table 6 presents some of these projects.

Geothermal extraction from abandoned wells: Wells are inevitably abandoned upon depletion of hydrocarbon reservoirs to an economically viable level. The information gathered during the hydrocarbon extraction determines the well's geothermal production potential [88]. Before usage, refurbishment of certain wellbores may be necessary to facilitate the recovery of heat from abandoned wells. Numerous studies have evaluated the viability of geothermal energy production from abandoned wells [98–101]. These investigations conducted case studies entailed the development of several mathematical models for calculating heat extraction, and attested to the geothermal potential of defunct wells. Though each scenario was unique, significant determining factors include fluid injection temperature, injection rate, insulation type, bottom hole temperature, fluid choice, and geothermal gradient, according to numerous studies.

4.2. Notable geothermal energy production from the oilfields for direct usage

Although the idea of using an abandoned oil well as a geothermal well is still relatively new, a few pilot projects have been started and reported with success [86] a 250 kW organic rankine cycle (ORC) power plant at the Natrona County, Wyoming-based Naval Petroleum Reserve No. 3 (NPR3)'s Teapot Dome field is one of these projects, with the advance of recent technology, more project will be possible. Table 7 provides a comprehensive summary of global geothermal direct utilization projects within oilfields. These projects were executed in both operational producing wells and decommissioned wells. The broad and successful deployment of direct utilization for oilfield geothermal resources is attributed to advanced practices and well-developed technology in geothermal direct utilization.

4.3. Technology for thermoelectric generation

Thermoelectric generating is one of the cutting-edge technologies

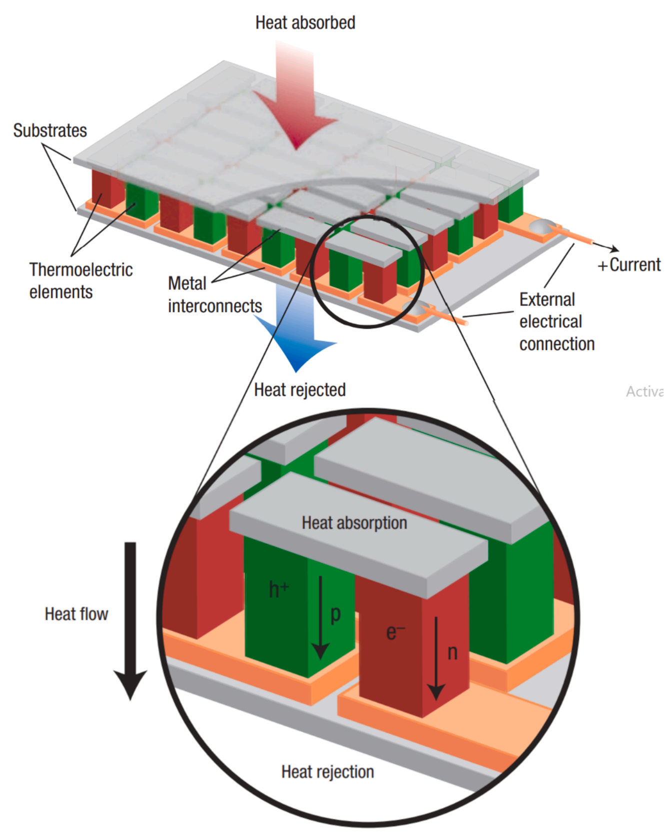

Fig. 8. Schematic of thermoelectric generator [110].

thought to hasten geothermal power growth [104]. A few oil and gas sector researchers have recently looked into using thermoelectric technology. Wang et al. [105] identified the critical parameters affecting the performance of thermoelectric generating, while Li et al. [104] illustrated the viability of surface and subsurface power generation in the oilfield. In a geothermal application, thermoelectric generation technology has been explored and tested experimentally by Xue et al. [106]. Wang et al. [107] provided a theoretical framework for optimizing thermoelectric generator setup and design, allowing for the more effective utilization of geothermal resources. The methods of oilfield geothermal extraction are improved by thermoelectric technology [108]. Some wells that don't produce enough heated water in binary

Table 8
Summary of selected performance evaluations of geothermal-drive organic rankine cycle systems.

Ref.	Brief title	Highlights
[125]	A system utilizing geothermal energy for hydrogen production.	The hydrogen production experienced a 150 % increase as the temperature of geothermal water increased from 130 °C to 200 °C.“
[126]	A geothermal-driven facility incorporating liquefied natural gas.	The numerical analysis illustrated the capability to harness energy from low-temperature heat sources, exemplified by geothermal hot water.
[127]	A poly-generation system propelled by geothermal water for oilfield applications.	The output power of the Organic rankine cycle exhibited an approximately 300 % increase as the heat source temperature rose from 110 to 115 °C.
[128]	Geothermal Utilization of Decommissioned Oil and Gas Wells.	Organic Rankine Cycle systems were recognized as a promising method for harnessing geothermal energy from high-temperature oil and gas wells.
[129]	Power Generation in Oilfields Utilizing Low-Temperature Geothermal Water.	Through the optimization of the plant and the utilization of R601a as the organic rankine cycle with the utilization of an optimized working fluid, a 40 % increase in power output was achieved.

energy production may be investigated as potential wells for thermoelectric power generation. This technology exhibits a broad temperature range applicable for power generation extends as low as 30 °C [104]. Such characteristics facilitate the utilization of additional geothermal resources and the development of more wells for power generation. Fig. 8 shows the see-beck effect provides the foundation for producing thermoelectric electricity; thermoelectric modules could convert thermal energy directly into electricity under certain temperature differentials without using mechanical labour to operate the turbines [109].

4.4. *The advanced geothermal system (AGS)*

The advanced geothermal system, or closed-loop geothermal (CLG) energy production technology, has recently attracted significant interest for its use in deep, high, and low enthalpy systems for producing electric power and direct use [111]. Fluid constantly flows in a closed loop through a well in a closed-loop system. Borehole heat exchangers (BHEs) are widely employed as reliable heat sources, with good depths ranging from 50 to 350 m, while the deep borehole heat exchanger has a depth that ranges from 1 to 4 km. The Pacific International Centre for High Technology Research and the Engineering Advancement Association collaborated to create deep BHEs, which were first demonstrated to be practical in Japan in 1991 [112]. Because it is a standard technology for lower-capacity applications, it is frequently chosen for geothermal, solar, or waste heat recovery [113]. The organic fluid to be used must possess the following qualities: to be earth-friendly and high evaporation; it should not rust, not be poisonous, and not be corrosive; it should be less costly maintenance-wise; it should be affordable and readily available; it should have temperature and pressure stability [114]. Two deep BHE plants were tested in Switzerland: one in Weissbad, with a drill 1600 m deep, which began operating in 1996 [115], and one at Weggis, with a 2300-meter-deep borehole, which began operating in 1994 [116]. However, neither of these initiatives was designed to be closed-loop systems in the beginning.

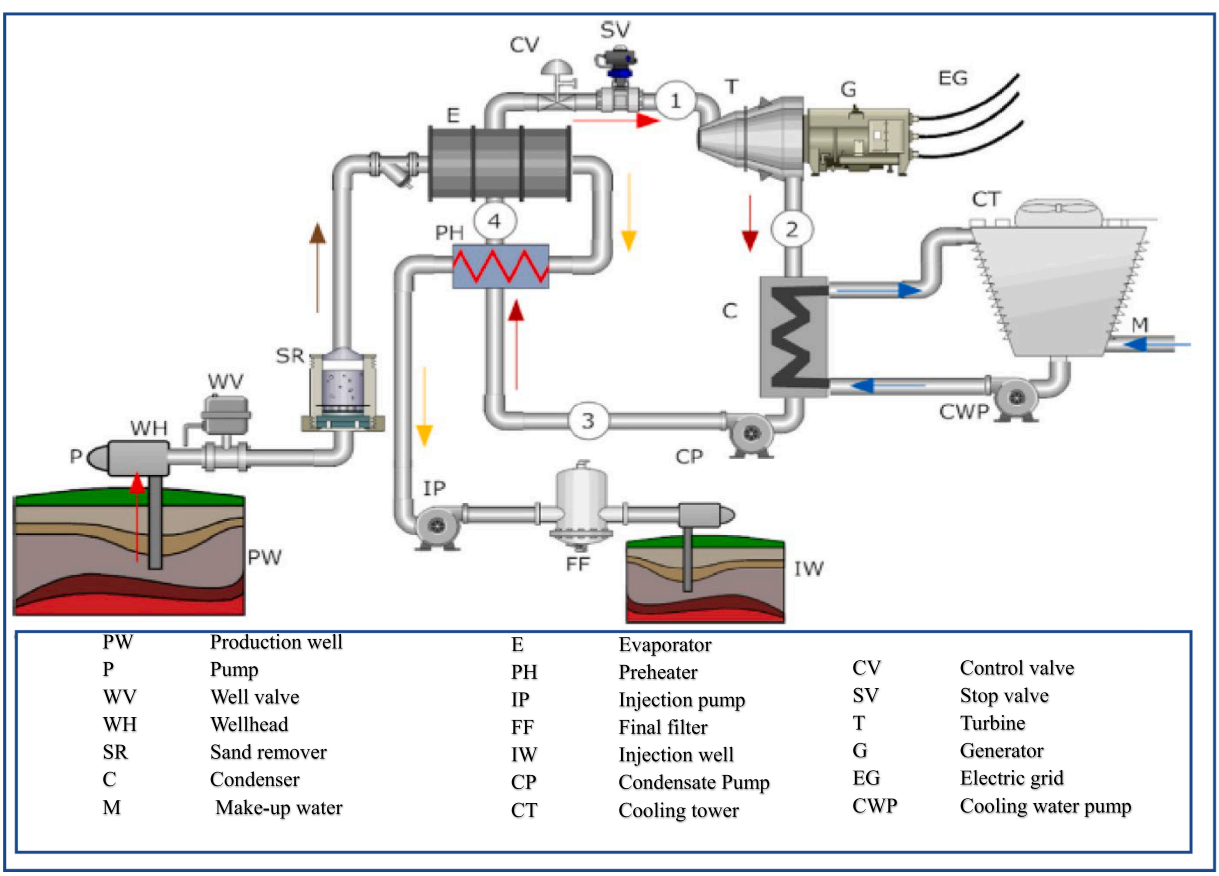

Fig. 9. Binary geothermal power station layout [132].

Table 9
Successful implementation of notable oilfield geothermal power generation projects employing a binary system has been achieved.

Country/ site	Rate of flow bbl./d	Temperature of water °C	Power generated kW	Comments	Ref.
USA, North Dakota	30,000	98	250	The first commercially implemented geothermal electricity generation project within an oil and gas well in the United States.	[134]
Wyoming, USA	40,000	90.6–98.9	132	Generated more than 2,210 MWh of power within the initial 3.5 years.	[135]
Hubei, China	18,114	110	310	By the end of 2011, the generated power amounted to approximately 31×10^4 kWh.	[89]

4.5. Organic rankine cycle in the oilfield (ORC)

Power cycles that operate optimally with low- or moderate temperatures include the organic Rankine cycle [96]. The ORC system has received much attention and has been frequently used to produce power at lower temperatures. The selection of working fluid is crucial in designing geothermally driven organic rankine cycle systems to ensure high efficiency. The conventional classification of organic working fluids is based on the slope of the saturation vapor curve, thereby categorizing the fluids into wet, dry, and isentropic states [117]. The working fluids are subcritical, R245fa, R600, R600a, and R236ea. Then superheated R600, R152a, R236ea, R142b, and R600a. While R134a, R600a, R22, and R32 are supercritical working fluids. One of the challenging tasks of using the system is choosing the right working fluid [118]; there are about 57 different kinds of organic working fluids [119]. Numerous advanced researchonthe choice of system working fluids, operation control strategies [120], analyses of the economy [121], the system forms [122], and theoretical models [123] to increase the efficiency of geothermal energy generation or its total utilization have been conducted. A recent area of research in geothermal energy is the efficient utilization of low-temperature, medium thermal energy using organic rankine cycle-based power generation [124]**.** Table 8 presents an investigation into the performance of organic rankine cycle systems driven by geothermal energy.

4.6. Electricity from binary plant

Due to its classification as an intermediate to low-temperature geothermal energy source, the oilfield geothermal resource lower-temperature systems would naturally be the next step in the evolution of geothermal power generation [130]. As its name implies, the binary cycle consists of two cycles employing geothermal fluids with low to moderate temperatures to heat or generate power to supply heat to greenhouses, farms, hospitals, and other buildings [131]. The process involves transferring heat from a high-temperature fluid to a secondary fluid, causing vaporization at a lower temperature but higher pressure which facilitates the secondary fluid's utilizing vapor to drive a turbine, as seen in Fig. 9.

The inaugural geothermal binary power plant, with a 670 kW rating, operated in 1967 at Paratunka, close to Petropavlovsk in Russia [133]; it supplied a small village and a few farms with electricity and heat for use in greenhouses. It functioned effectively for a long time, supporting the idea of binary plants as we know them today. Table 9 presents a comprehensive summary of executed projects in geothermal power generation within oilfields, incorporating binary power plants employing produced water. It is worth mentioning that most of the ongoing projects in oilfield geothermal power generation exclusively employ produced water. While extracting geothermal resources from abandoned wells is feasible, operators consistently opt to utilize producing wells to initiate projects.

5. Emergence of artificial intelligence (AI) into geothermal exploration

Artificial intelligence, or AI for short, is the study and application of scientific methods to develop intelligent programs, particularly computer-based intelligent programs. It makes sense to expect that artificial intelligence will help geothermal energy technologies advance and speed up development timetables [136]. Artificial intelligence has been employed in the oil and gas industry to reduce costs and risks in various technical activities. Many studies are also being done on remote sensing's use for geothermal exploration. For instance, research by Miyazaki mapped possible geothermal resources using thermal infrared, aerial signal averaging system (SAR), and satellite data [137]. Investigating the potential utility of artificial intelligence within the

Table 10
Present summaries of deep learning machine learning methodologies application.

Area of research	Methods	Issues tackle	Ref.
Injection/Production Wells Engineering	LSTM, DNN, decision trees, Shallow NN	Advancements have been made in developing Proxy models that are utilized to predict volumes of production and injection, along with associated decline rates and to extrapolate absent production data. Additionally, efforts have been directed toward forecasting production flow rates and predicting temperature profiles within geothermal wells.	[147,148]
Reservoir Characterization	PCA, SVM, k-means clustering, MLP, ACE, NN, ANN, deep learning classifier.	Research endeavors encompass the investigation of inter-well connectivity and fracture characterization, reservoir temperature prediction through the analysis of gas-phase fluid compositions, discrete characterization of Assessment of small-scale fractures, categorization of reservoir temperatures, and forecasting permeability distribution alongside fault detection.	[144,149]
Drilling	Multiple Linear Regression, Shallow NN,	Anticipating the rate of penetration. (ROP)	[150–152]
Exploration	NMFk, SNN, Deep Neural Networks.	Invert geophysical data, interpret gravity data, conduct Play Fairway analysis, and perform prospective analysis.	[153,154]
Reservoir Engineering	SVM, PCA, deep NN, random forest, decision trees, ANN, GMDH-ANN, MLP, LSTM.	The professional pursuits involve optimizing activities, including determining optimal good placement, estimating pressure and thermal Evaluating drawdown, forecasting temperature and pressure profiles in geothermal wells, predicting production enthalpy, developing predictive models for tracer returns, and mapping vertical permeability.	[149,155,156]

Table 11
Total exploration cost of geothermal power plant.

Category	Power plant size (MWs)	Cost	Unit	Ref.
Total cost	NA	1.8 x 106	€	[162]
	50	(5–10) x 106	$	[163]
	5	1 x 106	€	[164]
	50	9 x 106	$	[164]
Specific capacity cost	NA	150	$ per KWe	[165]
	50	150	$ per KWe	[166]
	50	183	$ per KWe	[167]
	NA	127.1	$/KWe	[168]

Note: NA signify not available.

geothermal energy sector is crucial, particularly in identifying areas where substantial opportunities for impact are present. Sircar et al. [138] illustrated how artificial intelligence has reduced exploration risks while increasing exploratory well efficiency. However, Heghedus et al. [155] Examine the role of artificial intelligence in advancing the development and implementation of automated drilling technology, leading to notable enhancements in tripping speed, penetration rate, and drilling costs. Xu et al. [139] demonstrated how rock physics inversion may be accelerated and made more effective using artificial intelligence. Zhou et al. [140] demonstrated how fuzzy-genetic inversion model can accurately detects fractured geothermal reservoirs' dominant flow area, especially with long EGS operation times. Increasing the permeability assumption improves accuracy. Research by Zhou et al [141] provides a genetic algorithm (GA) inversion model that finds dominant flow routes in fractured geothermal reservoirs with over 82 % accuracy for smooth channels. This method guides hydraulic fracturing to improve geothermal systems.

Geothermal resource exploration necessitates the analysis and management of several uncertainties. Artificial intelligence has been widely employed in the late stages of geothermal exploration, particularly in geophysical interpretation [142,143] and geochemical production [144]. Still, there is little study on the early stages of prospecting [145,146]. Table 10 Systematically presents summaries of utilized deep learning and machine learning methodologies across diverse geothermal energy production research domains.

Despite the remarkable advancements and growing availability of algorithms driven by artificial intelligence and applications, the integration of this technology into the geothermal industry is accompanied by various logistical, technical, and financial hurdles. Algorithms based on machine learning rely heavily on data; thus, their ability to model physical phenomena is contingent upon the availability of suitable datasets. While within geothermal operations, substantial volumes of raw data are generated, which must be characterized by attributes such as accessibility, accuracy, structural integrity, relevance, and security, among others [157].

6. Geothermal energy economic impact

Geothermal energy (GE) projects provide energy security, create direct, indirect, and induced jobs, and help economy sectors. Unlike oil and gas, GE costs are stable, boosting energy security. GE is also more reliable than wind and solar because it does not fluctuate. Reliability boosts its economy and energy security. However, GE initiatives may harm local hunting grounds or pastures and tourism in historical monuments or national parks.

Investors prioritize economic feasibility and financial profitability when investing in resource development. Geothermal energy (GE) power plants have longer payback periods (5–7 years) and greater initial investment costs than other renewable energy power plants, making the situation more complicated [158]. Geothermal resource size and quality are unknown until well drilling. Therefore, geothermal technology investment risk is significant [159].

Evaluating geothermal energy system economic feasibility is the first critical stage. Low-temperature geothermal power plants may not be profitable due to the high cost of drilling geothermal wells [160]. A geothermal power plant's economic assessment can be done in several ways. The levelized cost of energy (LCOE) the project's lifetime per-unit energy cost is an established metric. To recover capital investment and cover power plant maintenance and operating costs over its lifetime [161]. The main components in LCOE analysis are investment costs,

Table 12
Notable geothermal plant and their capacities in the United States.

State	Geothermal Plant	Capacity (MW)	Operator	Ref.
California	Geysers geothermal complex	~725	Calpine corporation	[171]
California	Salton Sea geothermal field	~340	Cal energy, Ormat technologies	[172]
California	Coso geothermal field	~270	Coso operating company	[173]
California	Mammonth geothermal complex	~40	Ormat technologies	[172]
Nevada	Steamboat spring geothermal complex	~65	Ormat technologies	[172]
Nevada	Beowawe geothermal facility	~18	Terra technologies	[174]
Nevada	Stillwater geothermal complex	~47	Enel green power	[175]
Nevada	Mcginness hill geothermal complex	~100	Ormat technologies	[172]
Utah	Blundell geothermal plant	~38	Pacificorp	[175]
Utah	Cove fort geothermal plant	~25	Enel green power	[175]
Hawaii	Puna geothermal venture	~38	Ormat technologies	[172]
Oregon	Neal hot springs geothermal plant	~22	US geothermal	[176]
Idaho	Raft river geothermal plant	~13	US geothermal	[176]

Table 13
Notable geothermal plant and their capacities in Philippines.

State	Geothermal Plant	Capacity (MW)	Operator	Ref.
Luzon	Tiwi Geothermal Power Plant	~234	AP Renewables, Inc.	[177]
Luzon	Mak-Ban Geothermal Power Plant	~458	AP Renewables, Inc.	[177]
Luzon	BacMan Geothermal Power Plant	~140	Energy Development Corp	[178]
Visayas	Leyte Geothermal Power Plant Complex	~701	Energy Development Corp	[178]
Visayas	Palinpinon Geothermal Power Plant	~192	Energy Development Corp	[178]
Mindanao	Mindanao Geothermal Production Field	~108	Energy Development Corp	[178]
Visayas	Northern Negros Geothermal Power Plant	~49	Energy Development Corp	[178]
Luzon	Bacon-Manito Geothermal Power Plant	~150	Energy Development Corp	[178]

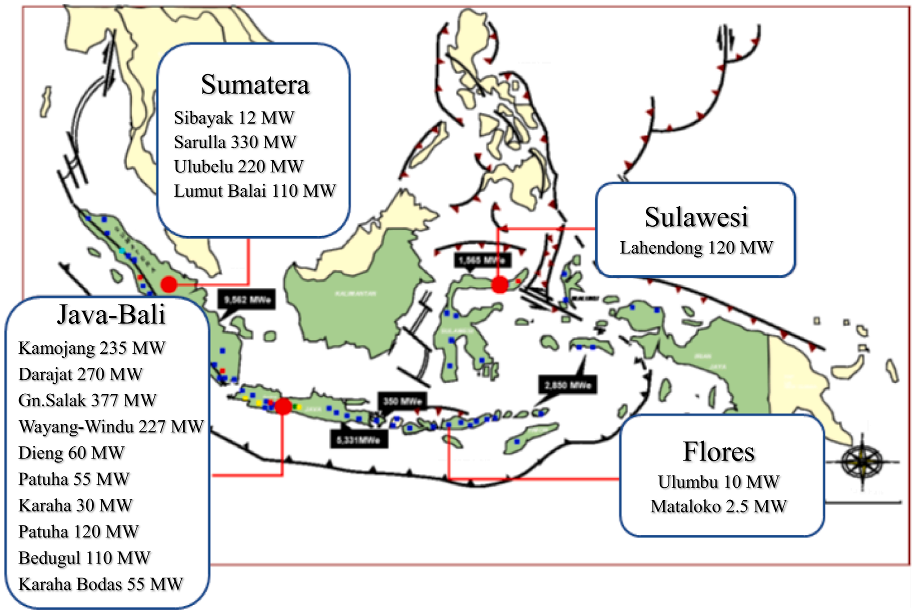

Fig. 10. Indonesian geothermal re
Source location map and installed capacity [180].

facility lifetime, average power production, facility availability, and discount rate [161]. Table 11 shows resource exploration cost estimates from several sources. Exploration can cost $1–10 million.

6.1. Distribution of geothermal energy

Geothermal energy reduces a nation's fossil fuel use and CO_2 emissions by providing inexpensive, low-carbon base-load power and heat [169]. Active volcanoes and tectonic plate boundaries are common locations for geothermal fields. Nearly 40 nations can meet their electricity needs with geothermal energy [172] technically. However, only 24 nations generate electricity from geothermal energy. The US and Philippines have the mostgeothermalelectricity installed. Tables 12 and 13 show US and Philippine geothermal plants and their capacity. It is expected that the amount of geothermal electricity produced from hydrothermal resources will rise from 11 GW in 2010 to 17.5 GW by 2020 and to roughly 25 GW by 2030, the East African Rift Valley, Central and South America, the United States, Japan, New Zealand, and Iceland are predicted to experience the most of this increase [170].

Indonesia should lead in renewable energy development and use. Its 29 GW geothermal potential is the world's largest [179], as seen in Fig. 10. The resources and reserves of Indonesia are spread among 312 different regions, the Directorate General of New Renewable Energy, and Energy Conservation of Indonesia and the Geological Agency of Indonesia (GAI – Badan Geology Kementerian ESDM). The present geothermal fields operate from 13 locations as opposed to 10 in 2015.

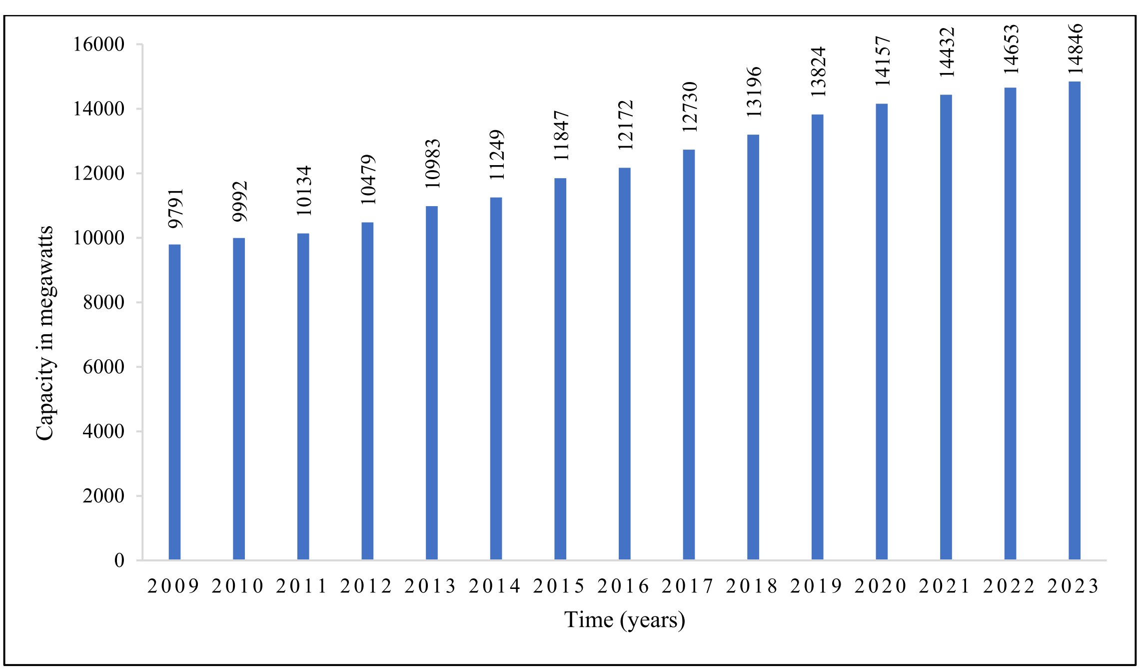

Fig. 11. The global installed geothermal energy capacity from 2009 to 2023 [183].

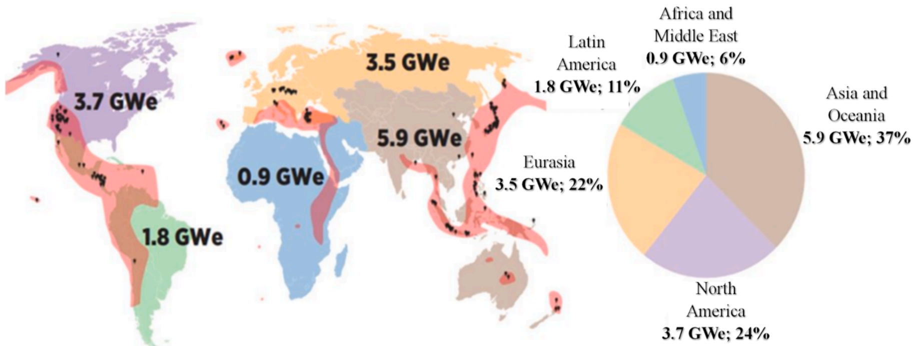

Fig. 12. Globally install geothermal electricity plants by region [184].

The overall installed capacity stands at 1948.5 MW, with additional capacities of 510 MW, marking an increase from the initial installed capacity of 1438.5 MW in 2015 presented in Melbourne. The fastest growth in geothermal energy development over the past few years can be seen in this added capacity. Geothermal power stations, such as Sibayak (12 MW), provide the currently installed capabilities. Kamojang (235 MW), Wayang Windu (227 MW), Ulu Belu Patuha – West Java (55 MW), Ulumbu – Flores (10 MW), Mataloko – East Nusa Tenggara (2,5 MW), Lahendong and Tompaso (120 MW), Karaha – West Java (30 MW), Darajat (270 MW), (Lampung, 220 MW), Dieng (60 MW), Gunung Salak (377 MW), Sarulla – North Sumatra (330 MW), are the power plants that make up this list. A minimum of an additional 190 MW will be put into service in 2019, including the 55 MW Lumut Balai plant in South Sumatra, the 20 MW and 30 MW Sorik Marapi Modular Units 1 and 2, the 5 MW Sokoria Unit 1, and the 80 MW Muara Laboh Unit 1 plant in West Sumatra. By the end of 2019, the overall capacity will be around 2,138.5 MW.

6.2. Geothermal energy installations and usage

Despite high capital expenditures, geothermal use has gained global recognition, especially in energy generation and direct-use applications like cooling and heating. Geothermal energy has generated several hundred megawatts of electricity since 1913, increasing production throughout the years. Over the preceding decades (2009–2023), geothermal energy capacity increased to 14,846 megawatts in 2023. Ten countries contribute 94.52 % of the installed capacity. Fig. 11 shows the global geothermal energy installed capacity in megawatts from 2009 to 2023 [181].

Geothermal energy demand is rising as geothermal unit installations increase annually. The US, Indonesia, and the Philippines have the most cumulative geothermal power capacity in 2023. These three countries have some of the world's largest geothermal facilities and many geothermal projects under development.

Research conducted by Salhein et al. [182] using improve grey model (IGM) prediction model, shows that by 2030, the anticipated ranking of geothermal energy installed capacity is as follows: Mexico, Italy, Japan, Iceland, United States, Kenya, Turkey, New Zealand, Indonesia, and Philippines, with capacities of 1.0778 GW, 0.9425 GW, 0.481 GW, 0.7589 GW, 3.925 GW, 1.6694 GW, 2.3714 GW, 1.0695 GW, 2.8617 GW, and 1.9281 GW, respectively.

6.3. Geothermal power generation

In 2023, 1 GW of additional geothermal power generation capacity comes online, increasing the total installed capacity to approximately 15.8 GW [184]. Surprisingly, only around 10–12 % of the global potential for geothermal electricity has been utilized based on existing geology understanding and technology [185]. This was below the five-year average of 0.5 GW since 2016 but more than double the increases in 2020. Capacity was expanded in Chile, China, Taipei, Iceland, Indonesia, New Zealand, Turkey, and the United States [186]. The International Energy Agency estimates that by the middle of this century, geothermal energy will provide 3.5 % of the world's power and 3.9 % of its heat [187]. As of 2021, the global installation of the geothermal electric plant by all the region is 15.8 GWe, as observed in Fig. 12, which

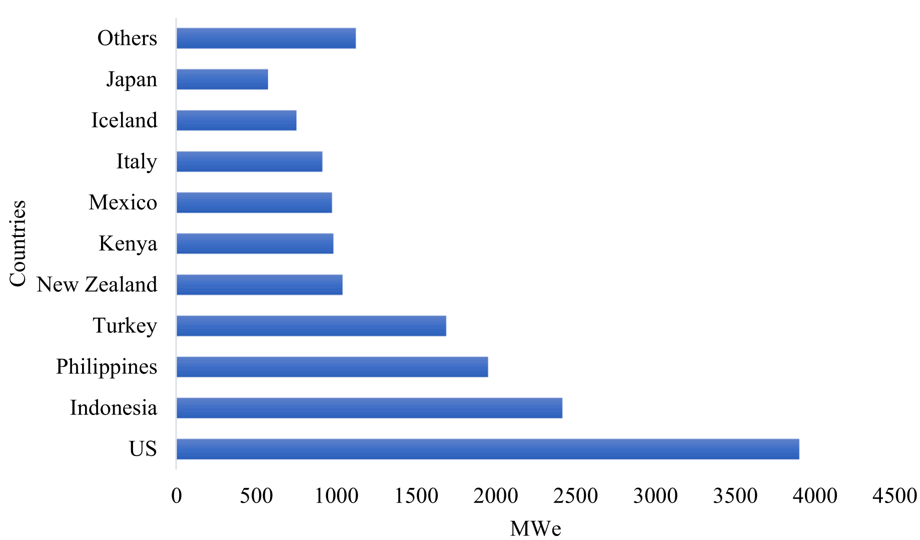

Fig. 13. Top 10 countries with geothermal power generation capacity in 2023 [192].

Table 14
Countries with the highest population density (per 1,000) in direct usage of geothermal energy [194].

Countries1000 /megawatt		Population/TJ	
Iceland	(7)	Iceland	(99.1)
Sweden	(0.67)	Sweden	(6.22)
Finland	(0.42)	Finland	(4.23)
Switzerland	(0.26)	Norway	(2.34)
Norway	(0.21)	New Zealand	(2.12)

Table 15
Geothermal energy usage by land-area per 100 km2 [195].

MW		TJ per year	
Switzerland	(5.32)	Iceland	(32.62)
Netherlands	(4.14)	Switzerland	(32.18)
Iceland	(1.93)	Sweden	(13.86)
Sweden	(1.48)	Hungary	(11.94)
Austria	(1.31)	Austria	(10.30)

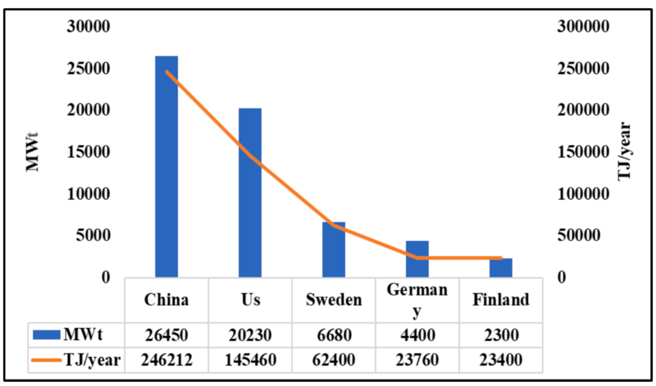

Fig. 14. Global Front-Runners in the deployment and utilization of geothermal heat pump systems [193].

shows regions characterized by elevated temperatures through the representation of red zones, while black symbols denote the presence of geothermal electric plants, a significant proportion of the plants are situated within areas characterized by high temperatures.

By the end of 2023, the total installed capacity for geothermal power generation reached 16,335 MW, reflecting an increase of 208 MW shown in Fig. 13. According to the international energy agency, the US produces 0.4 % of utility-scale geothermal electricity from facilities in seven states, more than any other country [188]. Indonesia has 40 % of the world's geothermal energy, yet only 5 % is used to generate electricity [189], government wanted 7 GW by 2025. Mexico generates 2 % of its electricity from geothermal facilities [190]. Turkey aims to create 600 MW of geothermal power by 2023, with 4.5 GW potential [187]. High temperatures (over 180 ^{0}C) are the geothermal resources that are more frequently used [191].

6.4. *Geothermal energy for direct usage*

Direct geothermal use is the oldest and most adaptable, used for decades in over 82 countries. There are two types of direct geothermal use [132]; Heating buildings, growing crops in greenhouses, drying them, and many industrial processes are direct-use methods. Oilfield uses include flooding geothermal water, conveying crude oil, and heat tracing [91]. However, geographical area and population figures show that smaller countries, particularly Nordic ones, dominate. Finland, Switzerland, Iceland, Norway, and Sweden have the highest installed capacity per capita (MW/population) and yearly energy consumption per capita (TJ/yr/population) (see Table 14) [193].

Netherlands, Austria, Iceland, Sweden, and Switzerland are the "top five" countries in terms of installed capacity per unit of land area (MWt/area). In contrast, Switzerland, Iceland, Sweden, Hungary, and Austria are the top five countries in annual energy use per unit of land area (TJ/yr./area) (see Table 15).

Turkey, Japan, China, Hungary, and Iceland have the biggest installed direct-use capacity (MW), accounting for 76.0 % of global capacity. Iceland, China, Turkey, Japan, New Zealand, and Turkey have the highest annual energy use (TJ/yr.), the foremost countries in geothermal heat pump technology include Germany, the USA, Finland, China, and Sweden, as detailed in Fig. 14. Similarly, with yearly energy consumption (TJ/yr), the leading nations are China, Sweden, the USA, Germany, and Finland. These prominent countries collectively represent 77.4 % of the total installed units [193].

The use of geothermal heat pumps for room heating, bathing, swimming, etc. increased the global capacity factor from 0.265 to 0.300 from 2015 to WGC 2020 [193]. As of 2023, Fig. 15 shows continent-wise geothermal capacity (GW), generation (TWh), and cumulative capacity. Geothermal resources in China account for 7.9 % of the global total, equivalent to 462.65 billion tons of conventional coal. There are high-temperature convective, medium-and-low-temperature convective, and medium-and-low-temperature conductive geothermal resources in different sections of the country, reflecting its geological and tectonic diversity.

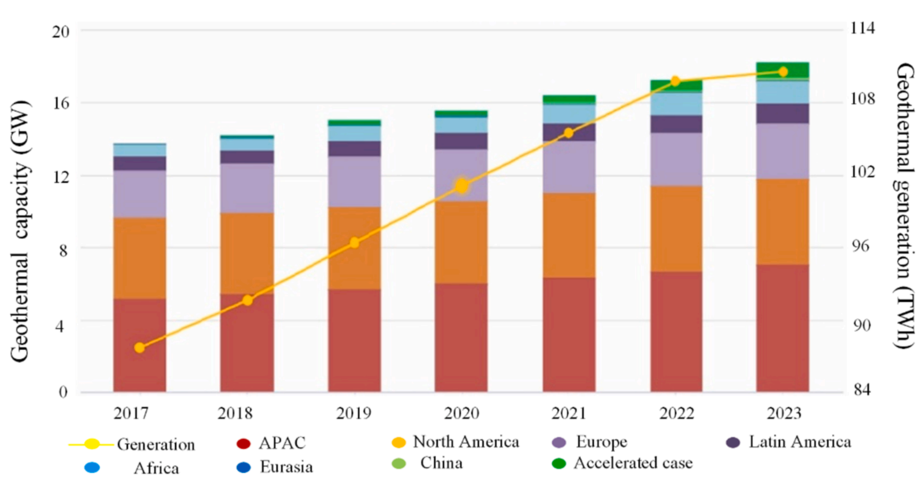

Fig. 15. Geothermal power generation and cumulative capacity by region, 2017–2023 [196].

Table 16a
A macro characterisations on recently published articles on geothermal energy production from the oilfield.

Ref.	Methods	Findings	Limitations	Scope/objectives
[197]	– The simulations used ASPEN HYSYS. The Turkish Kanoglu well and Mexican Prieto field proved the binary cycle and flash steam plant.	– According to the mapping, Egypt's wells can extract low, medium, and high-temperature extractions. – A wide range of temperatures can be extracted from oil wells in the western desert, and the Gulf of Suez was discovered.	– An internal heat study must be carried out to analyse the heat variance using a CFD model.	– Repurposes abandoned oil and gas wells in Egypt for geothermal energy, emphasizing sustainability and cost-efficiency. – Supports integration of renewable energy into Egypt's energy mix, promoting environmental stewardship and economic benefits. – The work investigates geothermal energy extraction using high thermal stability refrigerants like R-134a and cycle efficiency and output improvements.
[198]	The study used three models: a hybrid numerical-analytical model with COMSOL, the GEOPHIRES tool, and Slender-Body Theory.	– Supercritical CO_2 generates electricity more efficiently than water in a direct-drive turbine. – Closed-loop geothermal systems guarantee long-term output temperatures below reservoir temperature and high levelized costs for greenfield projects.	– Due to limited rock contact and slow heat transfer rates, AGS or closed-loop geothermal systems have poor thermal performance.	– The paper evaluates the techno-economic performance of closed-loop geothermal systems for both heat production and electricity generation, with a focus on AGS. – It investigates various design configurations, including co-axial and U-loop systems, across different subsurface conditions, depths, and temperatures. – To systematically assess the thermal and economic performance of different closed-loop geothermal system designs over a 20-year operational period. – To explore the impact of key parameters such as reservoir temperature, well depth, fluid flow rate, and injection temperature on system efficiency.
[199]	– MATLAB was used to create 1D nodes that simulated borehole heat exchanger components. A 3D nodal domain depicting subsurface rock was created from these nodes.	– The initial base case heat rate was −250 kW during charging and 69 kW during extraction (measured at the conclusion of each cycle). – The Deep Borehole Heat Exchanger reduced thermal transmission to less than 19 m during the simulation. – Operational characteristics affected deep borehole thermal energy storage systems more than material thermal conductivities. The analysis used Spearman's and Pearson's Correlation Coefficients to support this.	– The study did not examine the impact of long-term simulations of a Borehole Thermal Energy Storage (BTES) system. – The pre-charge length may improve storage efficiency. Hence, it should be investigated. Additionally, the connectivity of the BTES system to surface demand was not examined.	– The paper investigates repurposing a deep geothermal well for BTES in Newcastle, UK. – The study addresses challenges in storing surplus heat from renewable energy and industrial processes in subsurface systems deeper than 1000 m. – To assess the feasibility and efficiency of repurposing a deep geothermal well for BTES using a coaxial DBHE system. – To analyse the impacts of various design and operational parameters on DBHE heat extraction and storage performance.
[200]	– Two deep closed-loop systems with a shared production well were tested for 25 years for thermal performance and sustainability. Two converging injection wells double flow and reduce heat loss.	– The system maintained over 100 °C, generating 9730 TWth and 817 TWe over 25 years. – Annual thermal and electricity production averaged 389 TWth and 33 TWe, exceeding Magumeri district's demand. – The investigation highlights Nigeria's Chad Basin's potential for socio-economic development and environmental stewardship.	– The main drawback of the DBHE system is its lower heat recovery efficiency compared to conventional geothermal plants. – Additional technological advancements and research are needed to optimize the borehole design. – To improve the model, the numerical simulation must include the abandoned well's reservoir heterogeneity.	– The study focuses on repurposing abandoned petroleum wells in the Nigerian Chad Basin for sustainable geothermal power generation. – The use of a triplet borehole heat exchanger design aims to optimize thermal energy recovery and mitigate heat loss. – The research shows that employing existing infrastructure for sustainable energy supports the shift to clean, renewable sources socio-economically and environmentally.
[201]	– A computational technique optimizes the thermal efficacy of the Deep Closed-Loop Heat Exchanger, validated through analytical solutions and existing studies.	– Deep Closed-Loop Heat Exchanger systems address space heating and domestic hot water needs in many thermal applications. These applications include low-to-intermediate and	– The research exclusively concentrates on the techno-economic performance and optimal design considerations of Deep Closed-Loop Heat Exchanger setups within a limited timeframe.	– The paper evaluates the potential of DCHE systems for geothermal energy production and integration into local heat markets. – Compares DCHE efficiency and sustainability against other

(continued on next page)

Table 16a (*continued*)

Ref.	Methods	Findings	Limitations	Scope/objectives
		high-temperature resource conditions. – Intermittent cycles are more sustainable than continuous heat extraction, as controlling rock cooling reduces thermal depletion and enhances performance.		technologies. The report also covers the economics of geothermal systems and abandoned well studies.

7. Findings from recentlypublishedarticles

Table 16aa and Table 16b present macro characterization of recently published articles on geothermal energy production from the oilfields, and EGS respectively.

8. Current status of geothermal energy production

Prospects for geothermal energy production from hot dry rock and oilfields are promising. Geothermal energy may contribute to a low-carbon, sustainable energy future by addressing difficulties and research gabs, utilizing technology, and promoting supporting legislation.

Reservoir stimulation is essential in HDR and oilfield geothermal projects, but more research is needed to improve it. Research gaps include fracturing procedures, reservoir stimulation's long-term consequences, and sustainable reservoir permeability and heat transport mechanisms. The synergies between geothermal energy and oilfield operations are also unclear. Integrating geothermal systems with oil and gas infrastructure requires technical and economic research. This includes studying heat transmission between geothermal fluids and hydrocarbon reservoirs and finding ways to co-produce both. Geothermal energy is also eco-friendly. HDR and oilfield geothermal production do have environmental implications, such as geothermal fluid disposal and induced seismicity, that must be examined and addressed. Therefore, geothermal energy production needs more research to increase sustainability and environmental performance.

Innovations in geothermal energy production from hot dry rock and oilfields could boost its use and development which offer numerous perspectives:

a) Technology advancements in drilling, reservoir characterization, and heat extraction will enhance the efficiency and cost-effectiveness of geothermal energy production. Advanced materials and nanotechnology may improve heat transfer and system performance.
b) Hybrid energy systems: Combining geothermal energy with other renewable sources like solar and wind can deliver more stable and dispatchable power. Optimizing geothermal integration with other energy technologies will help build sustainable and resilient energy systems.
c) Geothermal energy generation from hot dry rock and oilfields can benefit from government and market support. Investment and geothermal project deployment can be accelerated via feed-in tariffs, tax incentives, and simplified permitting. Creating market systems that value geothermal energy's environmental benefits will also encourage its expansion.
d) Global collaboration and knowledge sharing: Researchers, industry stakeholders, and governments can expedite geothermal energy output. Shared best practices, data, and research can help overcome technical and financial barriers and promote geothermal energy as a reliable and sustainable energy source worldwide.

The recent boom in the US industry has improved drilling technologies and other methods for accessing deeper and hotter geological formations, reducing the costs of geothermal development despite environmental, permitting, and financial challenges. Drilling can account for roughly half of the cost of a geothermal project, thus petroleum sector experience should help this green energy source flourish. Geothermal energy use is rising, although its contribution to the global energy mix is small, countries like Iceland, New Zealand, and the US have used this resource to create sustainable, cost-effective energy solutions.

Recently, Fervo Energy disclosed that their enhanced geothermal system initiative, Project Red, successfully produced 3.5 megawatts of clean electricity during a 30-day trial, setting a new record for enhanced geothermal plants worldwide [210]. This project is poised to supply clean energy to Google's data centre operations in Las Vegas. Recent developments have seen a growing focus on hybrid systems that integrate geothermal energy with other renewable sources to enhance the overall efficiency of geothermal installations.

Researchers have developed numerical modelling methods to improve reservoir resource exploitation while reducing or eliminating hazardous gas emissions. Fluid stimulation and heat recovery rates have improved due to fracture network modelling advances.

8.1. Ongoing challenges in geothermal energy production from EGS

One of the biggest obstacles to developing geothermal projects is the lack of knowledge about potential geothermal energy sources. If you asked people in most developed nations to describe a geothermal energy plant visually, they can show you pictures of volcanic activity in Iceland or New Zealand [211]. Most geothermal investment has been in Iceland, Turkey, Eastern Africa, and the Ring of Fire, a horseshoe-shaped volcanic area which covers Indonesia, Philippines, and the US Fig. 16 [212]. High-enthalpy geothermal wells in these places have average subsurface temperatures above 180 °C at commercially viable depths, making them thermodynamically strong [213,214].

According to the US Energy Department, geothermal cooling and heating systems cost more than standard ones [215]. Alternatively, people resort to a hybrid solar-geothermal system with enormous potential and significant financial benefits, according to a study by Zhou et al. [216]. Geothermal energy has minor environmental issues despite its reputation as a sustainable alternative energy source [217]. During extraction, harmful materials such as carbon dioxide, methane, ammonia, and hydrogen sulphide may be released, but substantially less gas is released compared to fossil fuels [218].

The unpredictability of hydraulic stimulation operations due to a lack of underground knowledge has impeded widespread technological adoption of EGS [219]. Table 17 presents an overview of some closed or suspended EGS projects.

The high expense of drilling geothermal wells 42 % to 60 % of project costs limits geothermal resource development [72]. According to world bank study, approximately 22 % of geothermal wells fail due to insufficient brine output, high non-condensable gases, low wellhead pressure, corrosive brine, and inadequate permeability. These problems often require costly and risky drilling [86].

Earth's crust pressure decreases when geofluids are extracted for geothermal use, which courses crustal rocks compress due to this reduction, causing smooth downward movement. Subsidence occurs mostly in fluid-rich zones in nascent geothermal systems [220]. Geothermal fields subside at varying rates depending on geological structure, the Geysers sinks 4.7 cm every year, while Ohaaki subsides 17

Table 16b
Macro characterisations on recently published articles on geothermal energy production from the EGS

Ref.	Methods	Findings	Limitations	Scope/objectives
[202]	COMSOL Multi-Physics simulation is used, assuming constant rock properties and increasing HDR reservoir temperature with depth.	– Discontinuous mode heat extraction was better than continuous. – A higher injection fluid rate lowers production temperature and enhances engineering parameter heat extraction. – Heat mining reduces mining time and requires U-shaped well spacing greater than 135 m.	– The model did not consider heterogeneity effects during numerical simulation. – The model also ignores reservoir design aspects like well diameter, casing materials, etc.	– The study examines U-shaped well geothermal production systems' heat extraction performance, concentrating on well-layout characteristics and engineering approaches. – For system optimization, the study examines wellbore diameter, horizontal section length, insulating material length, injection fluid rate, and injection fluid temperature. – To establish a thermal–hydraulic model of a U-shaped geothermal production system and analyse the temporal and spatial evolution of the temperature field. – To undertake a parametric study on how well-layout and technical parameters affect heat extraction performance to provide practical advice for designing and operating geothermal systems using U-shaped wells.
[203]	SBRC models employed DFN models for hydraulic stimulation and tracer tests, while LSTM models used numerical models. To match field data, MOHHO inverted parameters.	– In hydraulic stimulation and tracer testing, LSTM models with optimized LSTM layers and HHO algorithm-determined initial learn rates can replace numerical models. These models efficiently predict monitoring data and constrain fracture network inversion.	– Limited datasets are acknowledged in the study. For better prediction accuracy, use a larger training dataset and try different deep learning models.	– Focuses on characterizing fracture networks in EGS using deep-learning models. – Specifically targets the application of induced micro-seismicity and tracer test data for detailed subsurface analysis. – Develop and validate a deep-learning-based model for characterizing complex fracture networks. – Integrate various data sources, such as micro-seismic events and hydraulic tests, to enhance model reliability.
[204]	– COMSOL non-isothermal pipe flow model and 3D transient model with fluid gravity and viscous friction were utilized.	– Simulation reveals that the horizontal section contributes more to heat extraction than the vertical section after 120 days. – DBHE will become the major deep geothermal development method since reinjection of tail water limits geothermal sector growth.	– Under the same total footage drilling and different DBHE application settings, vertical and horizontal well efficiency and economy should be compared.	– The paper focuses on analysing the heat extraction performance of a horizontal-well deep borehole heat exchanger (DBHE) and compares it with that of a vertical well. – It examines the effectiveness of horizontal wells in enhancing heat transfer in geothermal systems, particularly for deep geothermal resources. – To establish and validate a new 3D transient flow and heat transfer model for horizontal-well DBHEs. – To provide guidelines for the design and optimization of horizontal-well DBHE systems for building heating applications.
[205]	The research employed a Python-based analytical model to predict the flow distribution in a multi-fractured doublet Enhanced Geothermal System.	– In the context of a parallel well design, the enhancement of flow distribution is contingent upon establishing a constrained entry condition. – In the anti-parallel well design, the counter-flow direction of the well-bore contributes to an enhanced flow distribution. – In the context of a non-parallel design, the varied lengths of fractures contribute to an improved flow distribution.	– The study only examined dual-pipe setups and ignored the thermal and mechanical effects of the reservoir. – Future research should include triplet or quintuplet well designs for a more complete examination.	– The paper focuses on developing an analytical model to predict fluid flow distribution in Enhanced Geothermal Systems (EGS). – The study aims to optimize flow distribution to ensure efficient heat extraction from the geothermal reservoir. – Create an analytical model using Python based on Kirchhoff's law to calculate fluid flow distribution in a doublet EGS. – Simulate various doublet EGS designs and conduct sensitivity studies on parameters such as perforation size, fracture permeability, and injection rates.

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Table 16b (*continued*)

Ref.	Methods	Findings	Limitations	Scope/objectives
[206]	– The article simulated hydraulic fracturing on real hot dry rock formations, examining failure pressures, fracture networks, and permeability.	– The fractured-filled granite's breakdown pressure depends on rock temperature and stress. – The breakdown pressure for fractured-subsequently-filled granite is about 3 MPa at confining pressures above 25 MPa and temperatures above 300 °C and at 10 MPa and 200 °C. – Fractured-Filled FF-EGS can simplify HDR reservoir building, lower engineering costs, and improve heat exchange between water and rock mass.	– The study focused on hydraulic fracturing of fractured granite at different temperatures and confining pressures.	– The paper investigates hydraulic fracturing characteristics in fractured-filled HDR geothermal formations. – It examines how high temperature and pressure affect HDR system breakdown pressure, fracture patterns, and permeability. – To simulate hydraulic fracturing in filled HDR formations and test temperature and stress on breakdown pressure and permeability. – To provide guidance and support for developing high-permeability HDR reservoirs for commercial geothermal energy use.
[207]	– Transient numerical models study heat transmission and temperature distribution along a U-shaped geothermal system's long horizontal component.	– A comparison between the numerical results and the field data obtained from a well in China shows that the numerical results are highly accurate.	– Future studies should consider the thermal physical features of heat conduction oil with temperature to increase model computational accuracy.	– The paper investigates heat transfer mechanisms in U-shaped geothermal wells with long horizontal sections. – The study examines how fluid type, insulation length, injection temperature, flow rate, and horizontal section length affect system thermal power and performance. – To develop and validate a transient numerical model of heat transfer in U-shaped geothermal wells. – To explore how various operational and design parameters affect heat extraction efficiency in geothermal systems.
[208]	– A COMSOL-based 1D well model considered stratified strata, groundwater movement, and thermophysical characteristics, real case study verified the model.	– Adjusting parameters affects average linear heat transfer by ±50%, influenced by rock and soil conductivity, cement conductivity, inflow rate, and pipe diameter ratio. – The impact of thermal conductivity variations in the inner and outer pipes and changes in their respective thicknesses on the average linear heat transfer rate is minimal. – Over 20 years of continuous operation, the outlet temperature of the working fluid in the MDBHE system gradually decreases each year.	– The study acknowledges certain limitations, utilizing a single-factor sensitivity analysis rather than a multi-factor sensitivity analysis, and omitting the effects of hydro-geochemical circumstances.	– The paper focuses on the long-term sustainability of medium deep borehole heat exchangers in geothermal systems. – The study uses a 1D model to simulate the effects of layered strata, groundwater flow, and thermophysical properties. – To develop and validate a comprehensive numerical model for evaluating the long-term heat transfer performance of systems. – To provide practical insights and guidelines for the design and operation of sustainable geothermal energy systems.
[209]	Granite's elemental composition, micromorphology, pore structure, P-wave velocity, and mechanical strength before and after fluid-rock contact were tested at 240°C and 37 MPa.	– Supercritical carbon dioxide ($ScCO_2$) fluid alters granite mineralogically in water. – Sonic wave velocity studies show that the three fluids reduce granite sample integrity. – $ScCO_2$ fluid reduces rock elastic modulus and uniaxial compressive strength by 24% in the presence of a lot of water.	– The study only examines fluid-rock interaction-induced pore structural changes and granite strength loss.	– The study investigates the changes in pore structure and mechanical strength of granite after fluid-rock interactions in a CO_2-based Enhanced Geothermal System. – Experiments simulate the conditions of CO_2-EGS reservoirs at 240°C and 37 MPa to analyse the effects on granite in different zones of the reservoir.

cm. The extraction and injection of fluids into geothermal wells cause subsurface stress, which can cause seismic activity. According to Lacirignola et al. [221] fluid flow rate affects induced seismicity. High injection rates can also cause damage, including surface swelling and induced earthquakes [222]. The direct use of geofluids in geothermal energy systems can alter heat flow, impact regional water resources, and destabilize sediments. These changes can potentially trigger landslides in geothermal areas [223]. Several management measures can be implemented to control hazards, including balancing production and injection rates, monitoring local deformation and reservoir pressure, conducting fault identification studies, constructing robust barriers for facilities, and establishing warning systems [224].

8.2. *Ongoing challenges in geothermal energy production in the oilfield*

Geothermal performance in low-temperature petroleum fields depends on production rate, reservoir depth, type, and rock composition. However, double pipe installation failures, wellhead malfunctions, and casing integrity loss can delay production and suspend geothermal operations when re-engineering abandoned wells for geothermal usage [226].

Locations of geothermal power plants and producing wells may affect power generation and direct consumption, aside from wells where geothermal energy is used. The majority of wells are situated in low-density residential areas where the demand for heating and electricity

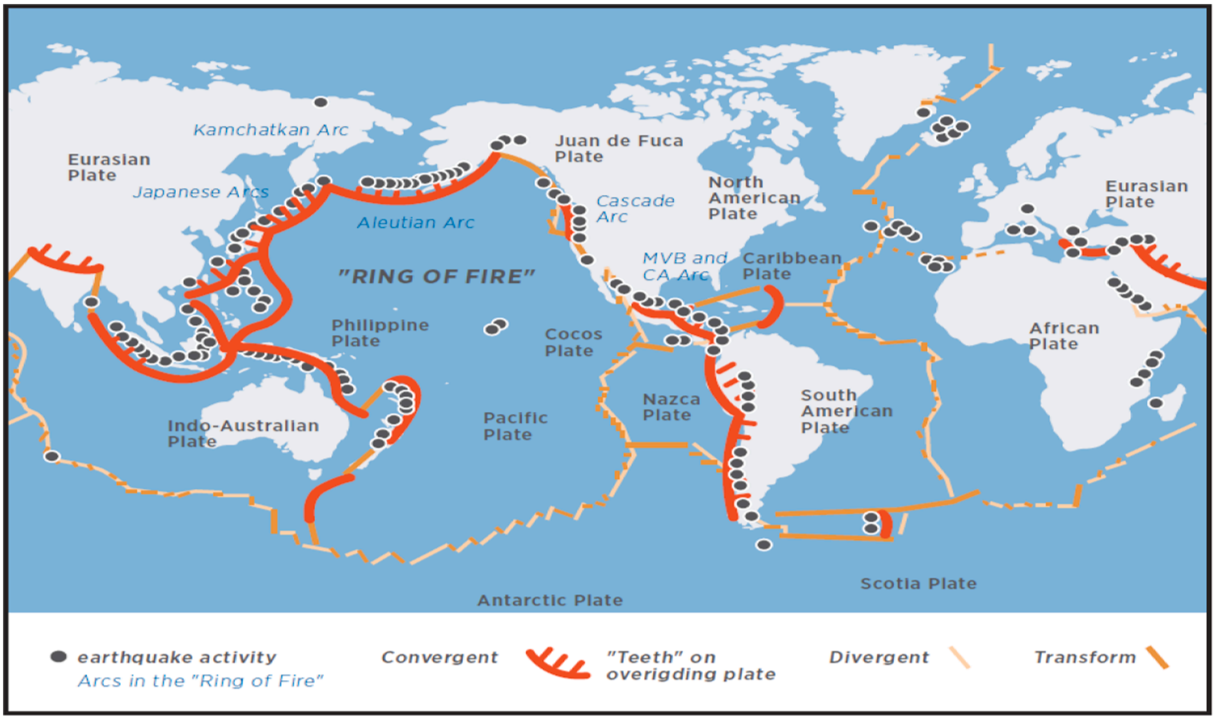

Fig. 16. The Ring of Fire [225].

Table 17
Overview of some closed EGS projects.

Location	Site	Period of operation	Suspended or closed reason
Korea	Pohang	2015–2017	5.4 magnitude earthquake
Germany	Landau	2007–2014	Earthquake
USA	Coso	2002–2012	Accident from drilling fracturing
Australia	Habanero	2002–2013	Insufficient funds to sustain the project coupled with government policy
Japan	Hijiori	1981–1986	Loss of drilling fluid about 75 %
UK	Roseman owes	1976–1992	Loss of drilling fluid by about 70 %; Earthquake 3.1 magnitute
Switzerland	St Gallen	2009–2014	Insufficient flow rate coupled with Earthquake (Mw 3.4)

is minimal [227]. In Turkey, silica scaling is a typical problem at geothermal power facilities, an examination of the facility's exposure to silica scaling showed that geothermal power output reduced over time [228]. Some of the significant challenges can be itemized as follows:

Technical issues plague oilfields. This includes optimizing heat extraction and conversion processes, drilling deep geothermal resources efficiently and cost-effectively, and managing reservoir stimulation and induced seismicity hazards. Maximum production rate determines reservoir technical viability. Field flow rate issues have been mitigated by geothermal development [229].

Oilfield reservoirs must be accurately characterized for geothermal energy generation, but subsurface conditions and rock qualities make data reliability difficult optimizing resource allocation and field development can lower expenditures. This research gap underlines the need to improve reservoir characterisation and comprehend geothermal reservoir behaviour under varied settings [230]. For predictive modelling and strategic planning, exploitable energy resources must be assessed using the entire well flow technique. Unfortunately, abandoned wells generally have only short-term data, making resource appraisal difficult [231].

Geothermal energy projects demand large upfront investments and exploration and development costs. Resource availability, energy prices, and regulations determine oilfield geothermal project viability. Overcoming financial obstacles and developing innovative financing strategies to attract investment and lower geothermal energy production costs is difficult. As observe in Table 9 oil and gas fields can generate power for small-scale operations [229]. The profitability of the Teapot Dome project was achieved only following the enhancement of flow rates through the installation of supplementary pumps [232]. An economic investigation of the Bakken formation in the Williston Basin, US, found that energy generation costs 19.15 to 10.95 cents/KWh. Geothermal energy generation is cheaper than diesel production, especially in the best-case scenario [233].

The long payback period of geothermal energy (GE) installations has pushed several governments to raise electricity tariffs to shorten the process. Advances in R&D to improve equipment efficiency and novel technologies could minimize upfront costs. Drilling may be cheaper with new technologies and abandoned petroleum well conversions. Governments should raise knowledge ofgeothermalenergy's benefits to gain widespread support. The technology for geothermal resource identification and development and reservoir simulation have improved.

8.3. Future of geothermal energy production

Geothermal energy will shape the energy future. Technology has raised awareness of climate change and the need for sustainable energy, making geothermal resources a feasible choice. Energy resources must be used wisely to benefit humanity and the environment. Given its benefits, geothermal energy has a bright future. It provides a steady supply of clean, renewable energy from the Earth's crust's thermal energy. It seems like a good alternative to decreasing greenhouse gas emissions and fighting global warming.

The low greenhouse gas emissions of geothermal energy make it an environmentally sustainable choice for worldwide decarbonization. The flexibility of this technology allows its use in power generation, thermal regulation, and refrigeration. Its adaptability makes it suitable for residential, commercial, and industrial use. There are also socioeconomic benefits to geothermal energy. Regional geothermal power jobs include

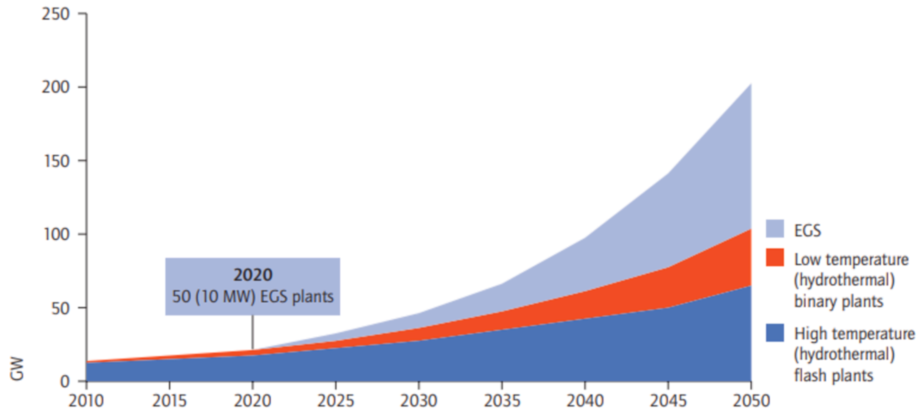

Fig. 17. Growth of geothermal power capacities by technology (GW) [238].

drilling, construction, and power plant operations.

The US Department of Energy expects geothermal energy production to rise to 90 GW by 2050 from 3.7 GW. The Department allocated $75 million to enhanced geothermal systems pilot projects in February 2023, demonstrating its commitment to geothermal development [234].

Geothermal energy has fluctuated in electricity generation, but recent advances have made it viable. Modern technologies and equipment have made flash plant technologies commercially viable, advancing the geothermal energy sector. Technical advances are needed to boost power generation. Most geothermal sector improvement efforts are not addressed by current initiatives, instead they emphasize sector activity evolution, indicating deployment readiness. Geothermal energy is becoming more popular worldwide for direct-use applications like heating, cooling, and electricity generation despite the high upfront cost.

Geothermal energy (GE) development through 2050 was projected by the US Department of Energy (DOE) using various technologies and principles. Three scenarios were examined: BAU, IRT, and TI. In comparison to the BAU scenario, the TI scenario mitigates emissions and water usage better [235]. Another study demonstrated that replacing coal-fired energy with geothermal energy by 2050 could reduce CO_2 emissions by over 1 gigaton annually [236].

The DOE has created a roadmap with community participation to guide geothermal technologies office investment decisions to improved geothermal systems and their commercialization [237]. As shown in Fig. 17, the international energy agency evaluates engineering resources, geothermal heat utilization, enhanced geothermal systems, and other relevant issues in the context of technological development and geothermal growth and predicts geothermal growth by 2050, demonstrating EGS's greater potential and capacity.

9. Conclusion

This comprehensive review has provided a detailed synthesis of the current advancements, challenges, and future prospects in geothermal energy production, offering critical insights for researchers, industry practitioners, and policymakers. The key conclusions drawn from this review are as follows:

- Technology advances: Geothermal technology, especially drilling and reservoir stimulation, has advanced significantly. Directional drilling and rotary steerable technologies make deep geothermal resources more accessible. Hydraulic, chemical, and thermal stimulation methods have increased the permeability of low-permeability rock formations, boosting geothermal system energy yield.
- Reusing abandoned and active oilfields for geothermal energy production reduces capital costs and environmental implications, according to the research. US and Chinese pilot programs show that oilfields can co-produce geothermal energy. Geothermal systems in petroleum fields have limited information of their long-term viability. Since the 1970 s, government-sponsored enhanced geothermal systems (EGS) initiatives have failed to reach their full potential.
- The sector still confronts high upfront investment costs, especially in complicated subsurface settings, and environmental issues including induced seismicity and groundwater contamination, despite geothermal technology advances. To solve these issues and maximize geothermal energy's potential, the assessment emphasizes cost-effective technologies, risk mitigation techniques, and rigorous regulatory frameworks.
- The integration of artificial intelligence (AI) and advanced modelling software like COMSOL Multi-Physics for optimizing system performance has become a significant advancement, with AI-driven models like LSTM algorithms enhancing the accuracy of resource characterization, optimizing well placement, and improving overall system performance. Continued AI innovation is expected to reduce operational costs and increase geothermal energy's competitiveness within the broader renewable energy market.
- Geothermal energy will be crucial to the global low-carbon economy trend. By combining geothermal energy with wind and solar energy, hybrid systems can make it more reliable and sustainable. Research, technological innovation, and supportive legislation can help geothermal energy reduce global carbon emissions and achieve energy sustainability.

In conclusion, this review underscores the strategic importance of geothermal energy in the global energy transition. By harnessing technological advancements and addressing the identified challenges, the geothermal industry has the potential to become a cornerstone of a sustainable energy future. Continued investment in research and development, along with the integration of emerging technologies such as AI and advanced modelling software will be essential in fully realizing geothermal energy's potential and ensuring its role in achieving global sustainability goals.

Funder

This research was supported by The National Key Research and Development Programs of Henan Province (grant number 231111320800), Guangdong Basic and Applied Basic Research Foundation (No.2023A1515110800) Natural Science Foundation of Hubei Province (No.2024AFB044), the Fundamental Research Founds for National University, China University of Geosciences (Wuhan) (grant number 2024XLB79).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We wish to thank the six anonymous reviewers that with their comments have significantly improved this manuscript.

Data availability

No data was used for the research described in the article.

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