Geosciences

AIMS Geosciences, 9(4): 734–753.
DOI: 10.3934/geosci.2023039
Received: 07 July 2023
Revised: 27 October 2023
Accepted: 16 November 2023
Published: 29 November 2023

http://www.aimspress.com/journal/geosciences

Mini review

Present status and sustainable utilization of hydrothermal geothermal resources in Tianjin, China: a critical review

Hongmei Yin[1,2], Mohamed E Zayed[3,*], Ahmed S Menesy[4], Jun Zhao[2], Kashif Irshad[3] and Shafiqur Rehman[3]

[1] Science and Technology Research Institute, China Three Gorges Corporation, Beijing, China
[2] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy, Tianjin University, MOE, Tianjin 300350, China
[3] Interdisciplinary Research Center for Renewable Energy and Power Systems, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
[4] Electrical Engineering Department, King Fahd University of Petroleum & Minerals, 31261 Dhahran, Saudi Arabia

* **Correspondence**: Email: mohamed.zayed@kfupm.edu.sa; Tel: +966508499514.

Abstract: Tianjin, as one of the pioneering and most prominent cities in China, has a long history of harnessing geothermal energy. The geothermal resource available in Tianjin is primarily characterized as a low- to medium-temperature hydrothermal geothermal resource. This manuscript introduces the ongoing status and potential of geothermal utilization in China, with a particular focus on the characteristics and utilization status of geothermal resources in Tianjin, China. Moreover, the relevant strategies and challenges for cost-efficient sustainable utilization of Tianjin geothermal resources are identified. The formation parameters of heat storage characteristics of Tianjin geothermal resources are also discussed. In addition, the key paths, guidelines and challenges on how to solve the obstacles related to the geothermal resources development in Tianjin are also suggested. The summarized results indicate that the geothermal reservoirs exploited in Tianjin vary greatly, which include sandstone of Neogene Minghuazhen formation, Guantao formation, Ordovician and Cambrian and carbonate of Proterozoic Wumishan formation. Most of the exploitative geothermal resources (146 geothermal wells) in Tianjin have mainly been produced from the Wumishan formation of the Jixian system and the Guantao formation of the Neogene system. The current production capacity has been doubled, and a two-stage cascade utilization system has been established, incorporating geothermal power generation and geothermal heating. The geothermal utilization share in Tianjin is estimated to be

81.66% for heating, 16.6% for domestic hot water and 1.35% for bathing. In conclusion, notwithstanding the diversity of geothermal resources in Tianjin, it is difficult to guarantee the sustainable development and utilization of geothermal resources in Tianjin due to the unreasonable layout of geothermal wells, imbalance of production and reinjection. Hence, the integration of distributed temperature sensing and distributed strain sensing monitoring demonstrates significant promise and effectiveness in tracking water circulation and detecting flow localization problems as dynamic monitoring processes and smart thermal response tests should be recommended and established as a substantial feature required in the future utilization and development of geothermal resources in Tianjin.

Keywords: geothermal resources; geothermal reinjection wells; utilization modes; case study; geothermal resources development

Abbreviations: CP: Carboniferous Permian; DOM: Degree of materialization; ED: Paleogene Dongying Formation; IEA: International Energy Agency; JX: Jixian system; JXW: Jixian Wumishan formation; SF: Shahejie Formation; NG: Guantao Formation; Nm: Neogene Minghuazhen Formation; PO: Paleozoic Ordovician; QB: Qingbaikou system;
Subscripts: d: Devonian; n: Neogene; o: Ordovician; q: Quaternary; s: Silurian; €: Paleogene; ∈: Cambrian; ∈ 1: Cambrian Changping formation; th: thermal; max: maximum; temp: tempeaarture

1. Introduction

Currently, as climate change and global warming become increasingly apparent and concerns over the depletion of fossil fuels intensify, there has been a notable surge in interest and research into alternative technologies [1–3]. This surge is pivotal in the shift towards sustainable energy sources and the pursuit of sustainable development [4,5]. Energy transformation is mainly dependent on three aspects: the large-scale demand for energy, the global carbon-neutral goals and the exploitation for a long time [6–8]. At present, geothermal energy is distinguished by many advantages over the other renewable energies like solar energy and wind energy, such as green resource, reliable stability and high energy utilization coefficient of more than 0.70, which should be considered as the primary energy for energy transformation [9]. The IEA has reported that global geothermal power capacity rises to over 16 GW in 2020 [10]. By 2050, global geothermal electricity can annually reach 1400 TWh, about 3.5% of global electricity production, simultaneously; and geothermal heating will attribute 5.8 EJ, 3.9% of projected final energy for heat [10].

The estimated annual utilization of geothermal energy in China is approximately 6.0×10^5 TJ [9,10]. Geothermal energy is a rich resource with superior characteristics such as clean energy and high stability [11,12]. However, in recent years, unreasonable exploitation of geothermal energy in some areas has led to various problems, such as surface pollution and bottom subsidence. Besides, the momentum imbalance within geothermal reservoirs may lead to surface water pollution, formation subsidence and geothermal resource depletion [13]. In fact, there are policies to prohibit the exploitation of new geothermal wells, which is a great loss for clean and stable renewable energy [14]. Therefore, it is necessary to study whether large-scale development of geothermal energy can achieve sustainable utilization [15–17].

At present, the energy balance, ecological balance, and reinjection of geothermal energy exploitation of 100% raw water reinjection in the same layer are currently recognized as a new research topic, which has received great interest from researchers and governments. In this aspect, four important issues should be considered in geothermal reinjection. The first important one is the reasonable selection of reinjection temperature, which is one of the operation strategies to ensure the sustainable utilization of geothermal energy. The key question of this vital parameter is should the utilization of geothermal energy be “dried up” or relatively high-temperature reinjection. The usage of geothermal wells with low reinjection temperature can ensure a high heat utilization rate. However, it may lead to the recovery rate of the reservoir being lower than the heat extraction rate and eventually the attenuation of reservoir temperature. Moreover, the low reinjection temperature may destroy the ecological balance of the underground reservoir, particularly with the use of water with high salinity, due to the chemical microbial reaction effect from the temperature difference and abiological flora of the geothermal reservoir. On the other hand, the selection of reinjection pressure is also a crucial operating parameter, which is limited by the water quality. For geothermal water with a high concentration of dissolved salt, it is necessary to consider the scaling and corrosion problems caused by the precipitation of some components when the reinjection fluid is at lower than a certain temperature and pressure. Furthermore, the reinjection flow rate is limited to avoid the need for hydraulic fracturing, which will lead to a change in permeability and have adverse effects on the heat storage of the system. The last vital issue is that it is important to explore an efficient geothermal exploitation technology, due to the conventional geothermal direct usage of extracting hot water has various bottlenecks, such as reinjection difficulties, geographical limitations and thermal pollution emissions. There are diversified techniques to extract heat from the geothermal systems accounting for the hydrogeological circumstances of the well. For instance, most borehole geothermal heat exchangers (BGHE) are appreciated for shallow systems with low permeability [17]. Improved geothermal systems are most proper for low permeability deep systems [18]. In contrast, for high permeability aquifers, it is desired to utilize reinjection and pumping with a doublet geothermal system (DGS) [19], or downhole geothermal heat exchangers (DGHEs) [20]. For the doublet systems, more bottlenecks exist in reinjection than in production in real projects [21]. Since the conventional techniques of extracting hot water have obstacles in reinjection and environmental problems, the “no water withdrawn but heat only” deep single well systems, such as leaky downhole coaxial open loop geothermal system (LDCOLGS), have recently been considered a promising technique [22]. These systems have many advantages over the borehole heat exchangers such as less reinjection, efficient resources, nonlimited geography and high heat extraction rates [23]. The uniqueness between LDCOLGS and BGHEs is the cold water in the loop (coaxial tube-in-tube or U tube) is straightaway connected to the geothermal fluids in the well. The BGHEs at most transfer heat from the porous formation (unsaturated or saturated) around the wellbore to the circulating water in the tube through heat conduction. However, in the LDCOLGS, free convection will take place when the U-tube is suspended in a well filled with water, a booster tube is placed parallel with the tube and airlift is used to improve the convective heat transfer.

Therefore, based on the multiple advantages mentioned above for the LDCOLGS over the other geothermal systems, it can be proposed as a technically feasible tool to effectively obtain a full reinjection strategy and boost the heat transfer extraction of the geothermal system.

At present, some Chinese provinces have banned geothermal wells without reinjection, such as Hebei Province, and no longer approve the exploitation of new wells. There are about 160000 oil wells in China, 30% of which are about to be abandoned. Therefore, how to revitalize the existing abandoned oil wells and geothermal wells without recharge support is still a challenging problem that should be a concern at present. Geothermal heating remains the predominant method for harnessing geothermal resources in the Beijing-Tianjin-Hebei region at this current stage. As of now, the cumulative area employing geothermal heating in this region encompasses approximately 150 million square meters. Nevertheless, the quantity of geothermal fluid extraction from hydrothermal resources remains below 10% of the recoverable resources and falls even further to less than 0.5% when reinjection is taken into account. Consequently, this region still holds substantial untapped potential for the development and utilization of hydrothermal resources.

Hence, this paper briefly reviews the characteristics and utilization status of geothermal resources in Tianjin, China, and also identifies the relevant strategies for cost-efficient sustainable utilization of geothermal resources. The formation parameters of heat storage characteristics of Tianjin geothermal resources are also discussed. In addition, the key paths, guidelines and challenges on how to solve the obstacles related to the geothermal resources development in Tianjin are also suggested. Figure 1 shows a flowchart describing the overall framework and organization of the literature research reported in this paper.

2. Current situation of geothermal utilization in China mainland

Geothermal resources in China are mainly hydrothermal geothermal resources, which are divided into shallow geothermal energy resources, hydrothermal geothermal resources, and dry hot rock resources. The geothermal potential in China is widely recognized for its abundance, estimated at $3.06 \times 10^{\wedge 18}$ kWh per year, representing approximately 7.90% of the global geothermal energy reserve, as illustrated in Figure 2 [23–26]. This is attributed to that the earth's heat flow is the only physical quantity that can be directly measured by the earth's internal heat on the earth's surface over the surface area of China. Hence, it is evident that the regional temperature field outperforms temperature, geothermal gradient, and other geothermal parameters when comparing different regions. Furthermore, the distribution of geothermal values in China's sedimentary basins exhibits significant disparities. It can be seen that the overall distribution pattern is high in the east and southwest and low in the middle and northwest. Geothermal resources are spread across the country, with high-temperature hydrothermal systems primarily found in the Tibet autonomous yegion and Yunnan province, while low to medium-temperature hydrothermal systems are situated in various sedimentary basins and elevated mountainous regions. It's worth noting that extensive geological explorations over the past few decades have led to the discovery of more than 2300 natural geothermal springs, and the establishment of 5800 geothermal wells in China. However, in around 3000 of these geothermal wells, the temperature of geothermal fluids falls below 150 °C. According to the existing literature, geothermal resources with temperatures below 150 °C are categorized as low to medium-temperature resources on a global scale. In essence, it is important to recognize that the current geological surveys categorize the energy grade as low to medium-temperature. In addition, the current status estimations values of China, geothermal resources are presented in Figure 3. It is reported that the shallow resources and plain sedimentary basins geothermal resources are equivalent to 9.5000 and 853.20 billion tons of standard coal, respectively [27].

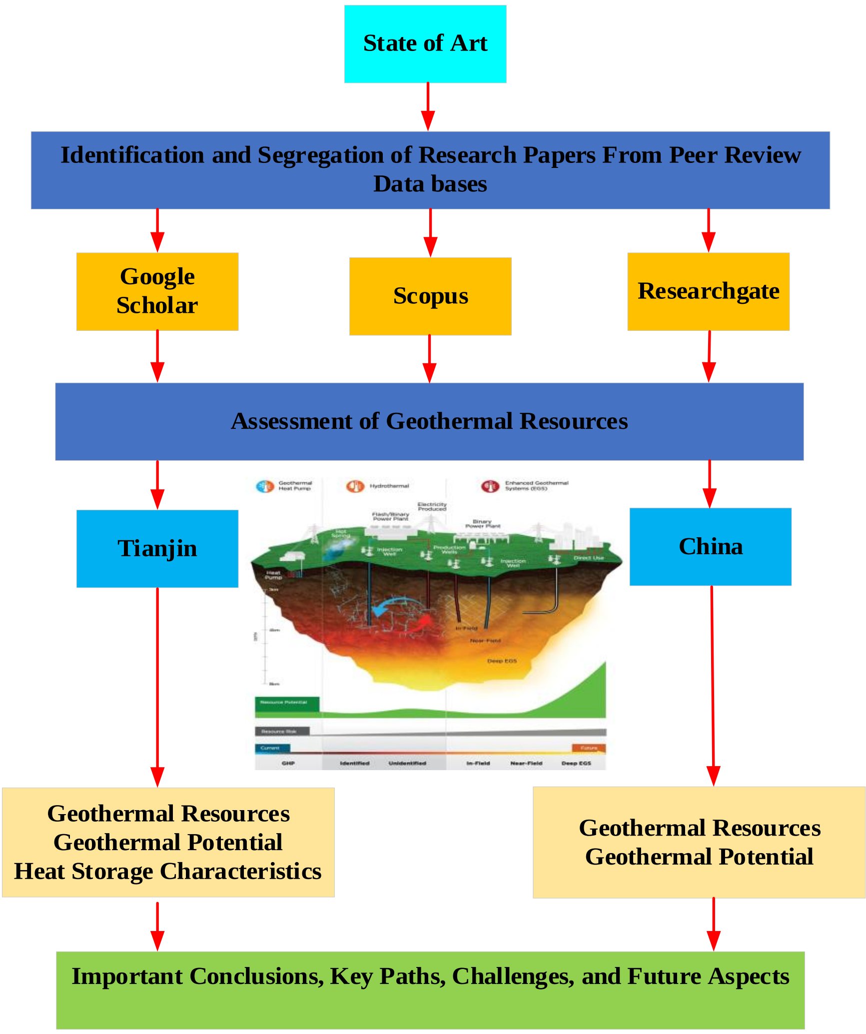

Figure 1. Flowchart of the overall framework and organization of the literature research reported.

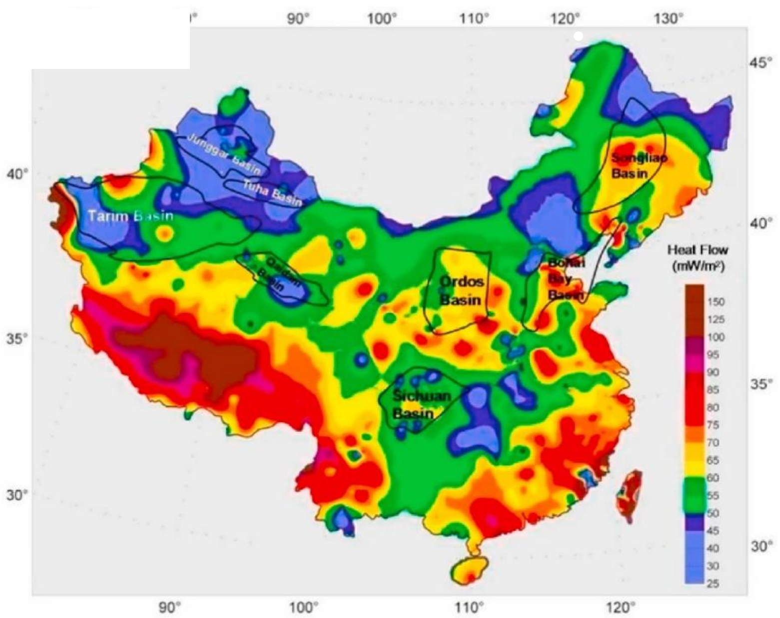

Figure 2. Distribution of geothermal resources in China [27].

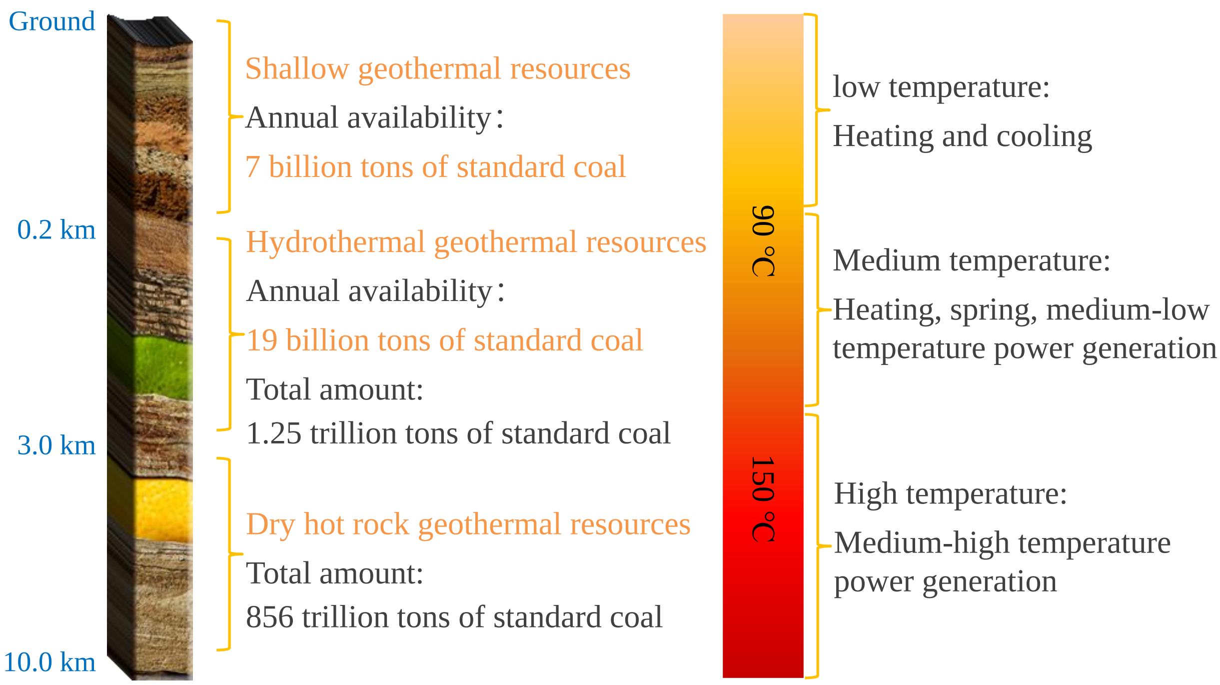

Figure 3. Current status of geothermal resources in China.

According to the temperature levels, China's geothermal resources can be categorized into three temperature levels: low temperature (<90 ºC), medium temperature (90–150 ºC) and high temperature (>150 ºC). The high-temperature resources are mainly distributed in southern Tibet, western Yunnan, western Sichuan and Taiwan. The medium- and low-temperature geothermal resources are mainly distributed in large sedimentary basins and mountain fault zones [28]. The amount of geothermal resources in fault zones is relatively small, whereas the amount of geothermal resources in large sedimentary basins is abundant. Moreover, Figure 2 also shows that the strata formation of the China geothermal resources include Cenozoic, Mesozoic, Paleozoic, Neoproterozoic and Mesoproterozoic from top to bottom, respectively. The Cenozoic layer includes the Quaternary and Neogene layers, which the upper part of the Quaternary (350 m) belongs to shallow geothermal with low temperatures, whereas the Guantao and Wumishan formations are rich in geothermal water resources with high temperatures up to 70–113 °C.

The distribution of geothermal resources in China's plain sedimentary basins is also shown in Figure 3 and Table 1 [29]. It was revealed that the geothermal resources are included in fifteen sedimentary basins/plains, which are equivalent to 1060 billion tons of standard coal. It is also indicated that 30.9% of these resources are concentrated in the Sichuan Basin, while the North China Plain and the Hehuai Plain represented 23.3% and 17.2% of sedimentary basins resources, respectively. Figure 4 also shows the contribution of plains (basins) to the total geothermal resources of China in terms of the temperature level. It is seen that the high-temperature geothermal resources are mainly located in the southern Tibetan, western Sichuan, western Yunnan and southeastern coastal areas, as well as the Jiaoliao Peninsula and Taiwan's hydrothermal activity/intensive belts. From the geothermal infrastructure, the geothermal reservoir in the sedimentary basin can be divided into sandstone pore and bedrock karst fissure types. The sandstone pore-type thermal reservoirs are deposited from Cenozoic sedimentary layers, which are usually buried shallowly with large-area geothermal storage areas and low temperatures. While the bedrock thermal reservoirs are covered by the Cenozoic sedimentary layer, which is conducive to heat accumulation and insulation of reservoirs with relatively high temperatures. There are formatively differences in geothermal resources between the east and the west of China. Particularly, in the east of North China and Northern Jiangsu, the asthenosphere is arched up, the crust became thinner and the deposition is extremely thick, which easy to form a multi-layer superimposed heat storage system. Furthermore, the main heat reservoirs are the Cenozoic sandstone pore and the Paleozoic and Meso Neoproterozoic carbonate karst fissure heat storage types. The heat reservoirs are mainly located in the central Sichuan, Ordos and other basins, with a thick crust. In contrast, the main thermal reservoirs are the Mesozoic sandstone pore and Paleozoic carbonate karst fissure types, which are generally hot water low-temperature. Additionally, there are medium-temperature hot brine basins with deep depression. These basins are stationed in the western part, which includes Tarim, Qaidam and Junggar basins with thick crusts and low heat flow value. The main brine heat reservoirs are Paleogene gravel pore and Paleozoic carbonate karst fissure types, which are distinguished with a high degree of mineralization. One of the most important of these reservoirs in the Chinese mainland is the Songliao and Liaohe basins, which are mainly located in the north, with thick crust and multi-layer thermal reservoir systems. The main thermal brine reservoir is the Meso Cenozoic sandstone pore-type thermal reservoir.

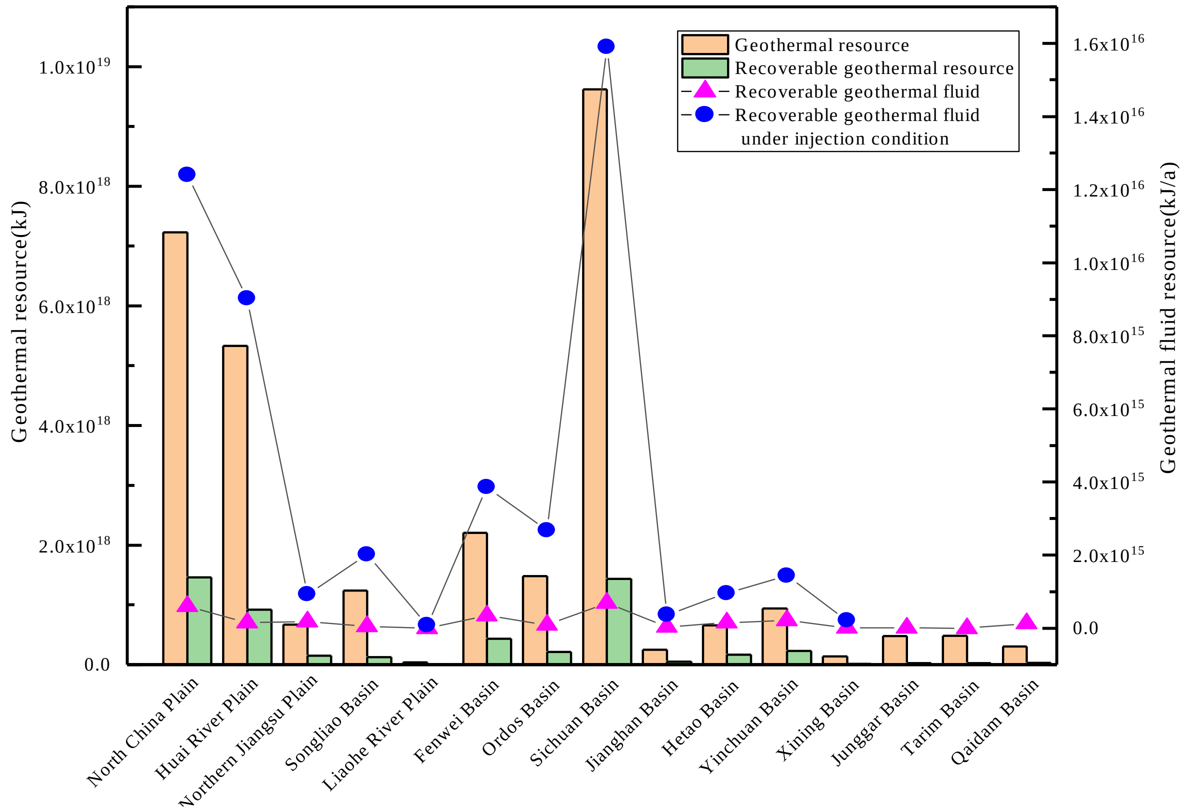

Figure 4. Distribution of geothermal resources in sedimentary basins of China.

From the perspective of utilization patterns, geothermal resources are globally used for heating and power generation. High-temperature geothermal resources (>150 °C) can be used for power generation, while medium and low-temperature geothermal resources can be used for heating, cooling, bathing, medical treatment, tourism, agriculture and irrigation applications. As shown in Figure 5, the top three geothermal utilization modes in China are heating (32.70%), tourism

(32.32%) and agriculture (17.93%). However, power generation only accounted for 0.5% of China's geothermal utilization modes. As shown in Figure 6a, China has basically formed a pattern of geothermal power generation that is represented by Yangbajing, Tianjin and Xi'an geothermal power systems. The patterns of recuperation and tourism are represented by the southeast coast, as well as the utilization pattern of agriculture and breeding represented by the North China Plain. Preliminary investigations have indicated that certain regions possess the capability to fulfill conventional geothermal electricity needs. Notable examples include the southern Tibet area, western Yunnan, regions west of the Tarim Basin and the southern China fold belt. Conversely, other areas have the potential to employ CO_2-geothermal extracted technology for electricity generation or direct production of hot water. These areas encompass the Bohaiwan, south Huanghai-Subei and Songliao basins, among others, e.g. refer to Figure 6b. When taking into account factors such as safety, economic viability, environmental impact and feasibility, the top three basins for pure CO_2 sequestration purposes are the Tarim, Ordos and Chaidamu basins.

Globally, it is noteworthy to state that China's geothermal energy utilization is the lead country in the world, accounting for 29.70% of the total global geothermal energy utilization, which has been reached about 25.39% of global direct utilization of geothermal energy and 30.90% of world ground source heat pump utilization [26,27]. The sustainable growth of hydrothermal geothermal utilization in China, the installed capacity of hydrothermal geothermal heating, ground source heat pump and power generation are clearly shown in Figure 7. Based on China's geothermal systems, the middle and deep geothermal heating systems have been widely used, while the scales of medium and deep (200–2000 m) heating geothermal systems are gradually increased in the last past, compared with the technical breakthrough of shallow ground source heat pumps. It is technically indicated that the "Xiongxian model" in Hebei Province had a geothermal heating area of 4.5 million m^2 with a 100% geothermal tail water reinjection, as well as the heating area of the "Xiong county model" and "geothermal city" with 50 million m^2 are one of the largest geothermal projects not only in China but also around the world.

At present, the installed capacity of geothermal power generation in China has reached about 45.46 MW with an increase of 45%. With the progress of technology, the problem of difficult reinjection has been gradually solved. The current situation of different geothermal reinjection geothermal wells in China is clearly shown in Table 2.

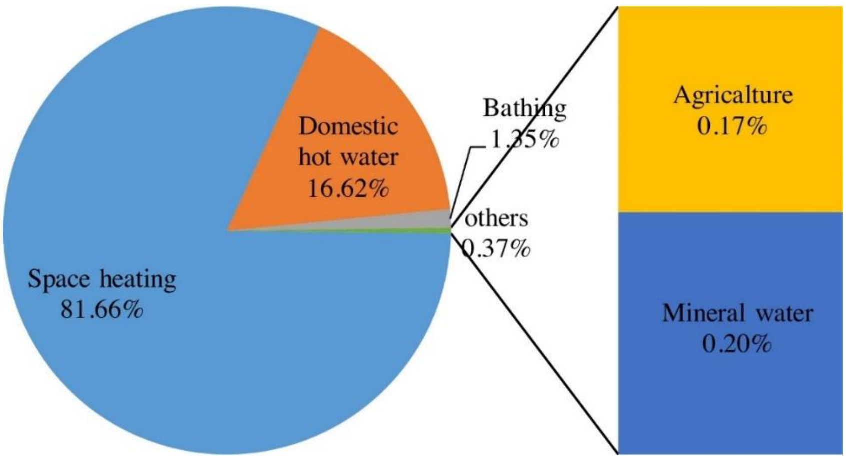

Figure 5. Schematic diagram of geothermal exploitation and utilization in China.

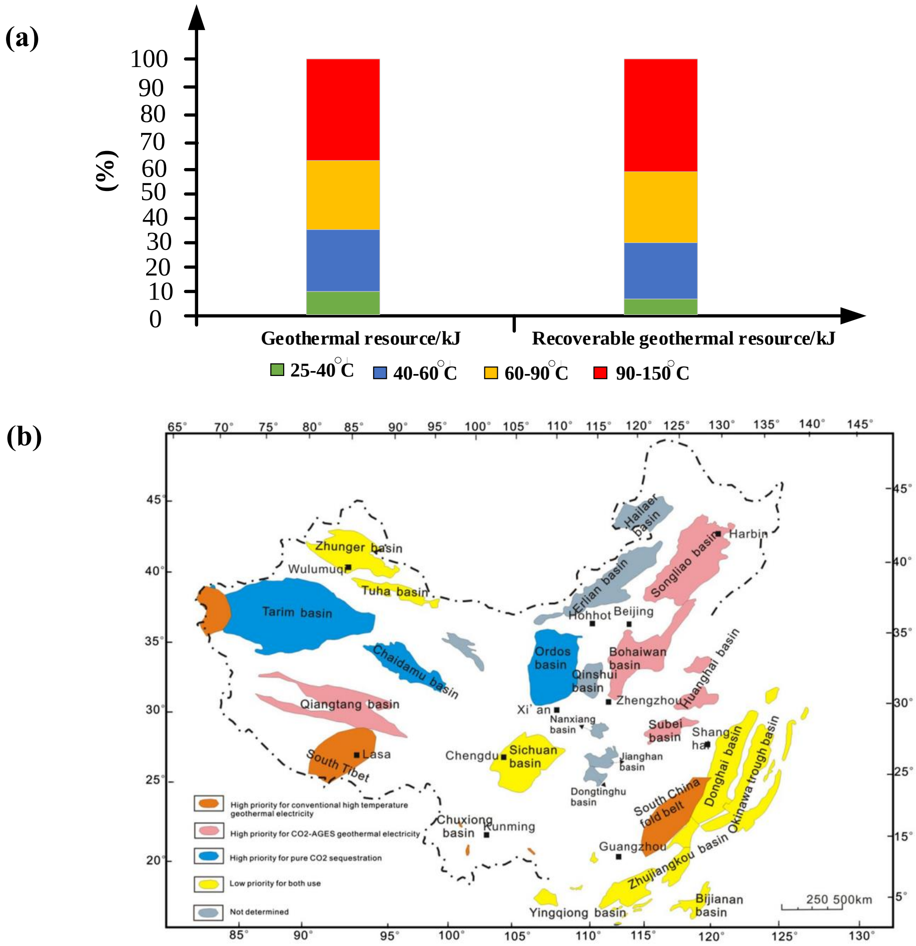

Figure 6. (a) Comparison of geothermal reserviours at different temperature ranges in the main sedimentary basins in China; (b) Suitability levels for the geothermal production of several main sedimentary basins in China [24].

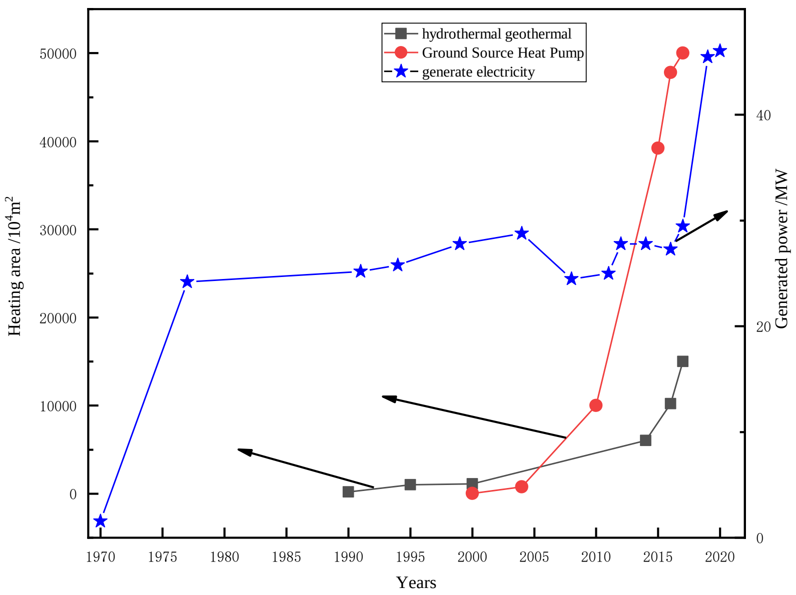

Figure 7. Utilization of shallow, middle and deep geothermal resources in China.

Table 1. The allocation of geothermal reserves within China's sedimentary basins.

Basin/Plain	North China	Huai river	North Jiangsu	Song liao	Liaohe river	Fenwei	Ordos	Sichuan	Jianghan	Hetao	Yinchuan	Xining	Junggar	Tarim	Qaidam
Cenozoic	√	√	√		√	√			√	√	√	√		√	√
Mesozoic				√		√	√	√	√			√	√	√	
Plaeozoic	√	√	√			√	√	√			√	√	√		
Neoproterozoic						√		√							
Mesoproterozoic	√					√						√			
Archaeozoic						√									

3. Present situation of geothermal utilization in Tianjin, China

The strata formation drilled in Tianjin includes Cenozoic, Mesozoic, Paleozoic and Meso Neoproterozoic. More specifically, the Cenozoic includes Quaternary (q), Neogene (n) and Paleogene €; the Mesozoic includes Jurassic Cretaceous (K-J) and the Paleozoic includes Carboniferous Permian (CP), Ordovician (o), Cambrian (∈), Devonian (d) and Silurian (s). Moreover, Meso Neoproterozoic includes the Qingbaikou system (QB) and the Jixian system (JX). There are diversified formations of the thermal reservoirs in Tianjin, namely, Neogene Minghuazhen formation (nm), Guantao formation (Ng), Paleogene Dongying formation (ED), Shahejie formation (ES), Paleozoic Ordovician (PO), Cambrian Changping formation (∈ 1) and Jixian Wumishan formation (JXW). The formation parameters of heat storage characteristics of Tianjin geothermal resources are listed in Table 3.

Tianjin's resources can serve as a valuable reference model for the management of geothermal resources in various countries. Nevertheless, due to the continuous large-scale utilization of geothermal resources, certain regions within Tianjin have shown a declining trend in geothermal reservoir pressure. The geothermal reservoirs exploited in Tianjin vary greatly, which include sandstone of Neogene Minghuazhen formation, Guantao formation, Ordovician and Cambrian and carbonate of Proterozoic Wumishan formation. Most of these geothermal reservoirs are represented by Guantao and Wumishan formations with abundant geothermal water resources, with high temperatures up to 70–113 °C. Additionally, as depicted in Figure 8, the northern regions of geothermal resources in Tianjin have remained untapped. Further exploration is warranted in these areas. Notably, there have been successful drilling operations for two geothermal exploitation wells in Jixian County, located to the north of Tianjin, signaling a new direction for geothermal resource development in the northern mountainous regions of Tianjin. All of these factors should be carefully considered when exploiting low- to medium-temperature hydrothermal geothermal resources in Tianjin.

Table 2. Current situation of geothermal reinjection in China.

Rejection well	Dagang	Tanggu	Wuqing	Dongli	Tanggu east	Binhai New Area	Huanghua
Rejection Year	2019	1995–1996	2003–2004	2010	2008	2011	2015–2018
Lithology	Fine siltstone with gravel	Glutenite	Sandstone	Glutenite	Glutenite	Sandstone	Sandstone
Cementation degree	worse	better	better	bad	better	better	bad
Particle size (mm)	2–4	5–10	0.5–1	5–10	5–10	1–4	NA
φ (%)	29.9	20	20.1–31.6	24–32	26–31	24–32	25–35.9
K (mD)	400–1700	740–1270	171–874	421–1077	450–950	347–937	385–1638
Depth (m)	1871.68	2025.26	2346.8	1362.39	1950	2105	1960
Well completion technology	Perforation	Single-layer	Double layer	Single-layer	Perforation	Perforation	Single-layer
Winding Distance (mm)	Φ444.5 mm Total length of casingrn 318m	0.5–0.7	0.5-outer 0.7-inner	0.8–0.85	Φ244.5 mm Total length of casing perforation 75.2 m	Φ244.5 mm Total length of casing perforation96m	No information available
Filter diameter (mm)		Φ219	Φ177.8	Φ219			Φ177.8
Total length of filter		60.99	93.87	95.11			183
Rejection Temperature (°C)	34–41	25–30	47–52	19–48	30.7	18-36	35
Rejection Volume (m3/h)	34–91	20–50	21–49	30–66	63.79	102	120–200

Table 3. Heat storage characteristics of Tianjin geothermal resources.

Geologic age			Roof depth (m)	Thickness (m)	Distribution	Temp (°C)	Aquifer yield (m3/)	Permeability (m2)	Porosity (%)	Chemical composition	Degree of materialization (g/L)	Thermal conductivity (m2/s)	Elastic Storativity (1/m)	Ref.
Era	Period	Group												
Cenozoic	Quaternary	Plain group (Q)	250–350	250–350	Widely distributed	10–48	25–50	(2.16–2.43) ×10−12	35–40	Ca-HCO3 Ca-HCO3-SO4	<1	8.33×10−7		[30, 31]
	Neogene	Minghuazhen (Nm)	250–350	950–1150	Widely distributed	52–80	60–80	(0.51–1.36) ×10−12	15–34	Cl·HCO3-Na	1–2.7	8.41×10−7	(0.35–2.47) ×10−4	[31, 32]
		Guantao (Ng)	1420–1530	360–440	Partial absence	42–82	60–120	(0.4–1.7) ×10−12	27–32	Cl·HCO3-Na	1.8–6	1.09×10−6	(1.7–3.02) ×10−4	[33-35]
Paleozoic	Ordovician	PO	1674–3104	22–419	Unbalanced distribution	48–76	80–424	(0.12–2.77) ×10−15	5–6	SO4·Cl-Na HCO3·Cl-Na	1.7–4.5	1.27–1.55 ×10−6	(0.23–0.26) ×10−4	[36]
	Cambrian	∈	1550–2472	80–300	Developmental instability	80–90	36–133	(1.6–102) ×10−16	2.6–5	CL·HCO3·SO4-NaCl	1.5–1.75	1.25–1.66 ×10−6	(0.15–0.24) ×10−4	[37]
Mesoproterozoic	Jixian	Wumishan (Jxw)	1600–2000	500–600	Widely distributed	70–113	110–720	(0.21–1.25) ×10−12	4–7	Cl·HCO3·SO4-Na	1.7–2.2	2.22–4.51 ×10−6	(0.16–0.45) ×10−4	[32]

Note: **Degree of materialization (DOM):** typically refers to the extent to which a rock or sediment formation is saturated with groundwater. DOM is a measure of how much pore space within a geological formation is filled with water. It is expressed as a percentage, with 100% indicating that all of the pore space is filled with water and 0% indicating that none of the pore space is filled. This parameter is essential in hydrogeology because it affects the movement of water within the subsurface and influences various aspects of groundwater flow and storage. **Elastic storativity** referred to as specific storage, is a fundamental parameter in the hydrogeology that describes the ability of an aquifer to compress or expand in response to changes in groundwater pressure. It represents the capacity of an aquifer to store water within its pore spaces as the pressure in the aquifer changes, similar to how a sponge can expand or contract as it absorbs or releases water.

Overall, despite an increase in the number of injection wells, geothermal resource extraction has led to the expansion of underground cavities. Therefore, it is imperative to strengthen the injection process sequentially. Furthermore, it’s worth noting that the current monitoring methods in Tianjin are somewhat outdated, relying primarily on manual monitoring [38]. Consequently, dynamic monitoring is a fundamental and essential feature for future developments in geothermal resource management. For example, in fractured reservoirs with several highly conductive fractures, incorrect identification of these fractures can result in unsuccessful well operations or adjustments that fail to enhance heat recovery. The integration of distributed temperature sensing and distributed strain sensing monitoring demonstrates significant promise and effectiveness in tracking water circulation and detecting flow localization problems [39]. Moreover, it would be valuable to explore the fiber-optic responses in enhanced geothermal systems with more intricate fracture networks in future research.

At present, the regional authorities are actively advocating the adoption of cascade technology for harnessing geothermal resources. They are intensifying injection processes and continuously adapting the mining layout and the resource utilization structure to secure the sustainable extraction and use of geothermal resources. Figure 9 depicts the main mining layer, and the geological model of the geothermal reservoirs exploited in Tianjin [40,41]. In this regard, the prospects for the utilization of hydrothermal geothermal resources at low to medium temperatures are clearly demnestrated in Figure 10. The studies reported that the medium- and low-temperature hydrothermal utilization modes in Tianjin has waitnessed a greet proportion in several sectors as shown in Figure 11. It can be found that the geothermal utilization share is estimated to be 81.66% for heating, 16.6% for domestic hot water and 1.35% for bathing [25,42–44]. The production capacity has doubled, and a two-stage cascade utilization system has been established, incorporating geothermal power generation and geothermal heating. The initial stage includes an installed capacity of 280 kW and a geothermal heating area of 30,000 m^2 [45,46].

4. Conclusions

Geothermal reinjection is recently regarded as a crucial practice in geothermal utilization as it provides environmental wastewater disposal and management tool for the geothermal reservoir. Despite the diversity of geothermal resources in Tianjin, China, they are dominated by low-medium temperature geothermal utilization, imbalance of production and reinjection and high heating cost. Therefore, how to revitalize the existing geothermal wells without reinjection support is still a challenging problem.

Hence, this paper reviews the characteristics and utilization status of China’s geothermal resources, with a particular focus on Tianjin, China, as a case study. Moreover, the relevant strategies and challenges for cost-efficient sustainable utilization of Tianjin’s geothermal resources are identified. The formation parameters of heat storage characteristics of Tianjin geothermal resources are also discussed. In addition, the key paths, guidelines and challenges on how to solve the obstacles related to the geothermal resources development in Tianjin are also suggested.

The survey shows that a miscellaneous number of single geothermal wells have been established in Tianjin city in the recent past. The geothermal reservoirs exploited in Tianjin vary greatly, which include sandstone of Neogene Minghuazhen formation, Guantao formation, Ordovician and Cambrian and carbonate of Proterozoic Wumishan formation. Most of the exploitative geothermal resources (146 geothermal wells) in Tianjin, which are mainly produced from the Wumishan formation of the Jixian system and the Guantao formation of the Neogene system. Furthermore, the medium- and low-temperature hydrothermal utilization modes in Tianjin are estimated to be 81.66% for heating, 16.6% for domestic hot water and 1.35% for bathing.

In general, despite the diversity of geothermal resources in Tianjin, it is difficult to guarantee the sustainable development and utilization of geothermal resources in Tianjin due to the unreasonable layout of geothermal wells, imbalance of production and reinjection, continuous decrease of geothermal water head, and decrease of heat storage pressure and temperature. Subsequently, more reinjection geothermal processes should be highly strengthened for further geothermal resource explorations in these regions.

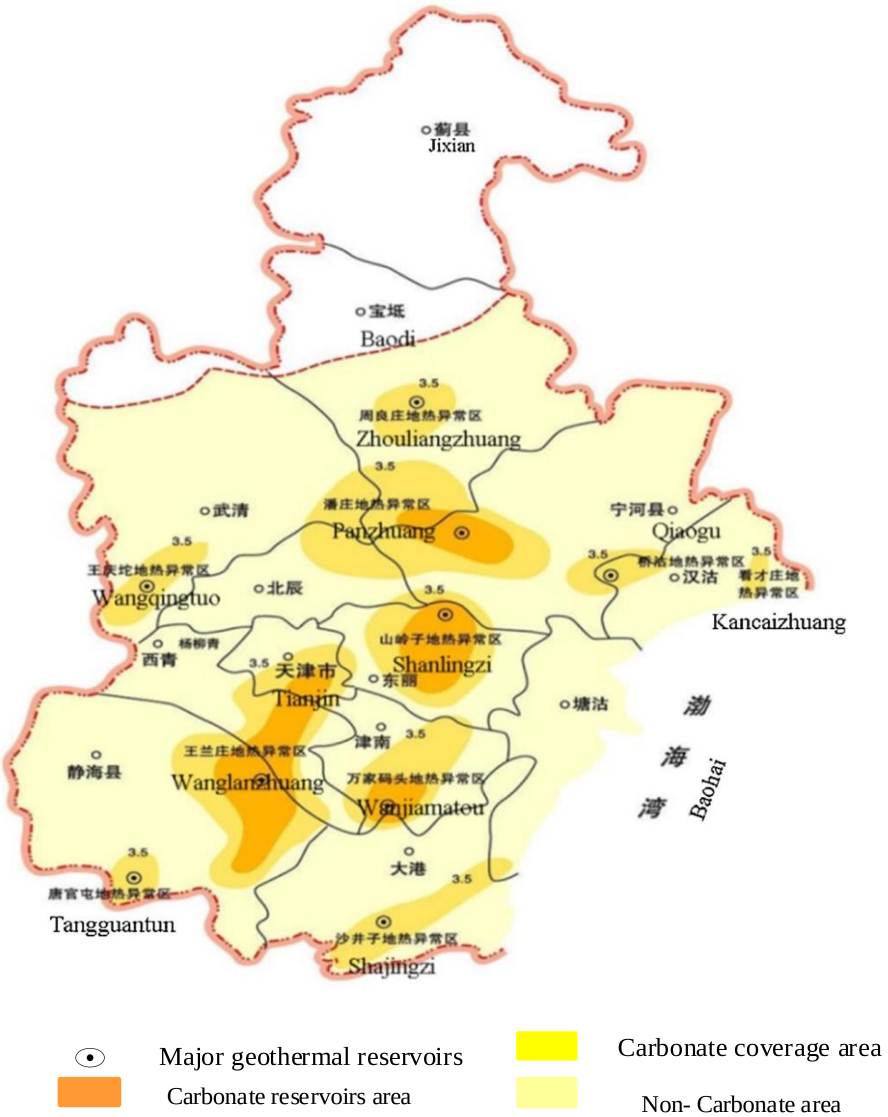

Figure 8. Ten geothermal resource regions in Tianjin [26].

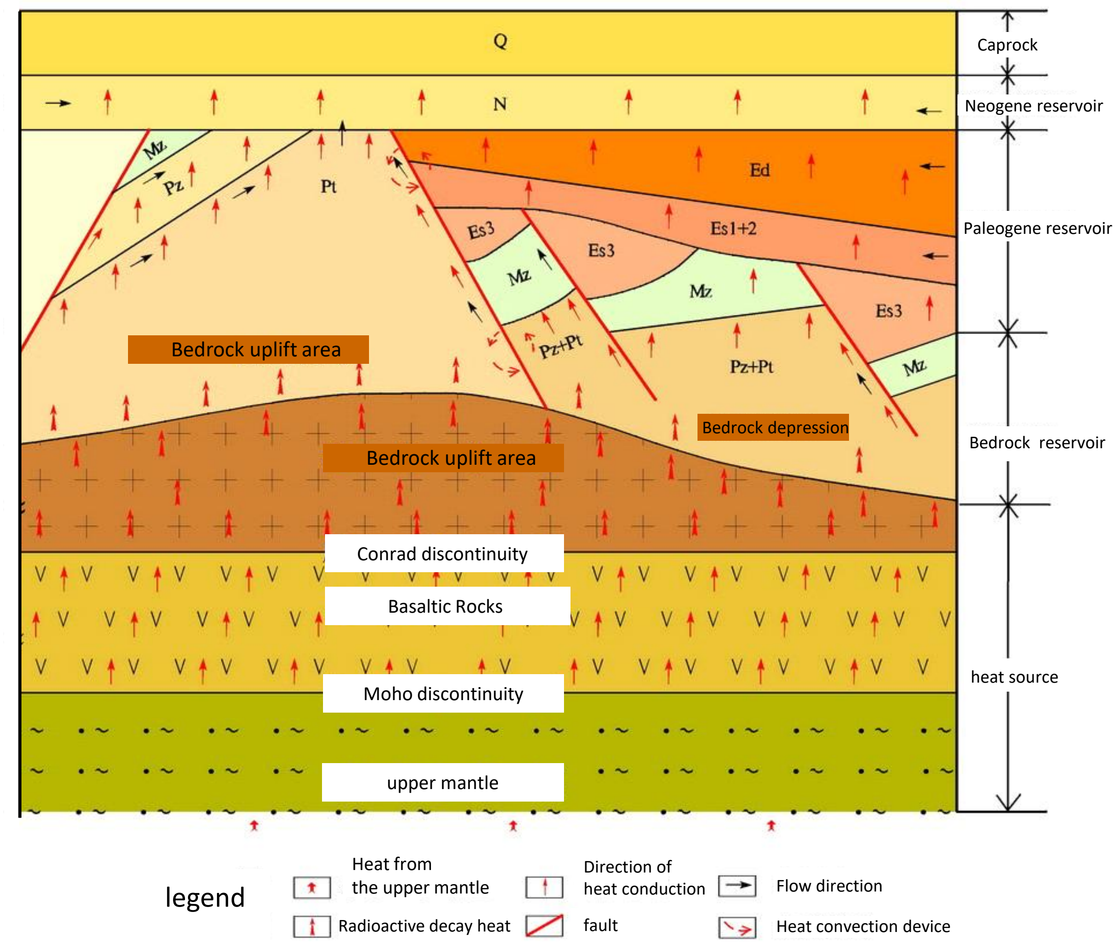

Figure 9. Geothermal geological model of Tianjin, China.

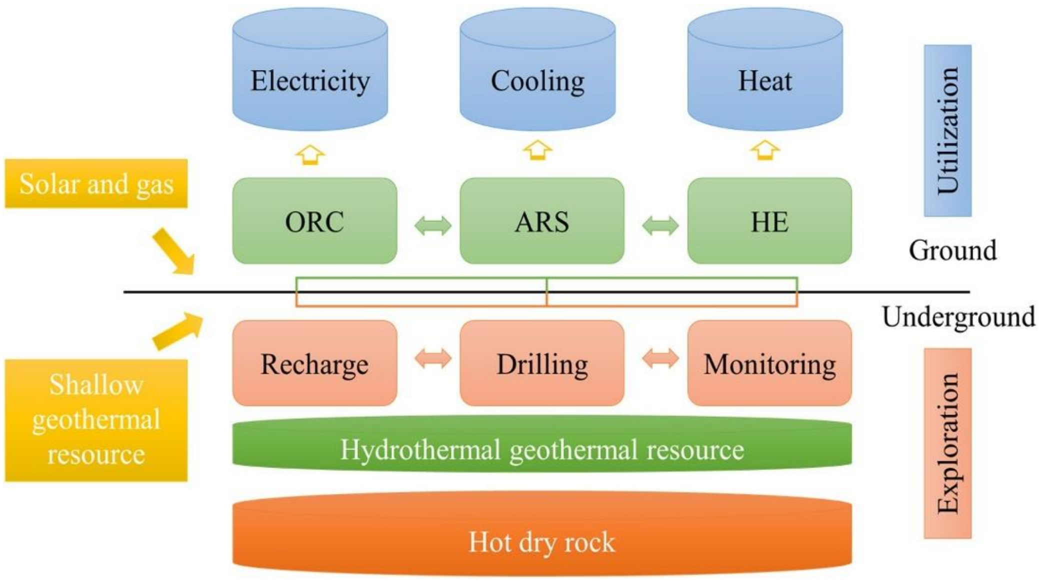

Figure 10. Prospects for the utilization of geothermal resources at low to medium temperatures.

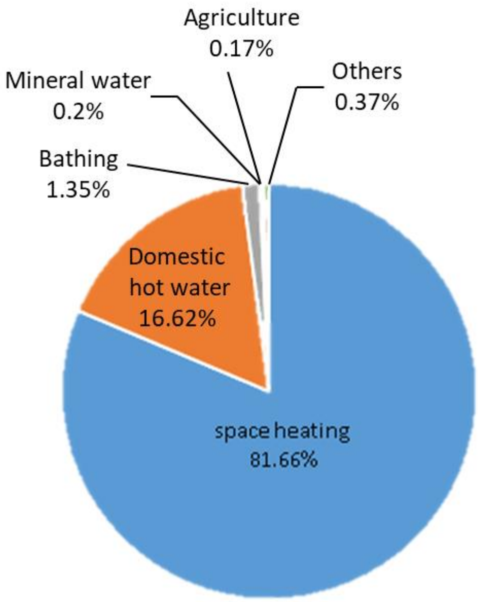

Figure 11. Proportion distribution of utilization patterns of the geothermal resources in Tianjin.

5. Challenges and future recommendations

Exploring and harnessing geothermal resources in a specific region like Tianjin, China, involves a systematic approach and careful planning. Here are key paths and guidelines for active exploration of geothermal resources in Tianjin:

1. Significant endeavors should be undertaken to attain advancements in reinjection techniques, geothermal reservoir reconstruction methods, thermoelectric innovations and subsurface heat exchange technologies.
2. The integration of distributed temperature sensing and distributed strain sensing monitoring demonstrates significant promise and effectiveness in tracking water circulation and detecting flow localization problems as dynamic monitoring processes and smart thermal response tests should be recommended and established as a substantial feature required in the future utilization and development of geothermal resources in Tianjin.
3. It is essential for the government to establish relevant policy mechanisms that facilitate the progression of geothermal energy utilization from its early stages to maturity.
4. The government should enhance technological innovation in the field of geothermal utilization and achieve significant advancements in key technologies to ensure the efficient use of geothermal energy such as enhancing financial incentives, reducing taxes, exploring innovative financing approaches and providing training for energy internet professionals.
5. Additionally, integrating geothermal energy with other resources, such as solar power, establishes a multi-energy system. In this system, geothermal energy serves as the foundation for base loads, solar energy complements it for peak loads and supplementary resources like natural gas are used to meet additional energy demands. For instance, several regions are well-suited for hybrid solar and geothermal solutions, as they offer favorable irradiance levels for solar power plant installations and coincide with abundant geothermal resources. Notably, several regions in China, including Tibet, Shannxi, Tianjin and Guangdong, exhibit these characteristics.

6. Furthermore, there is a need for in-depth research on the utilization of both deep and shallow geothermal resources. This entails combining the utilization of these resources to bolster the development of geothermal power stations, facilitating large-scale energy supply for communities

These guidelines can serve as a framework for the active exploration of geothermal resources in Tianjin or any other region, with the aim of harnessing this clean and sustainable energy source for various applications.

Acknowledgement

Authors would like to acknowledge the support of the Interdisciplinary Research Center for Renewable Energy and Power systems (IRC-REPS), King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

All authors declare no conflicts of interest in this paper.

References

1. El-Hadary MI, Senthilraja S, Zayed ME (2023) A hybrid system coupling spiral type solar photovoltaic thermal collector and electrocatalytic hydrogen production cell: Experimental investigation and numerical modeling. *Process Saf Environ Prot* 170: 1101–1120. https://doi.org/10.1016/j.psep.2022.12.079
2. Zayed ME, Zhao J, Li W, et al. (2020) Recent progress in phase change materials storage containers: Geometries, design considerations and heat transfer improvement methods. *J Energy Storage* 30: 101341. https://doi.org/10.1016/j.est.2020.101341
3. Zayed ME, Zhao J, Elsheikh AH, et al. (2021) A comprehensive review on Dish/Stirling concentrated solar power systems: Design, optical and geometrical analyses, thermal performance assessment, and applications. *J Clean Prod* 283: 124664. https://doi.org/10.1016/j.jclepro.2020.124664
4. Zhao J, Ma L, Zayed ME, et al. (2021) Industrial reheating furnaces: A review of energy efficiency assessments, waste heat recovery potentials, heating process characteristics and perspectives for steel industry. *Process Saf Environ Prot* 147: 1209–1228. https://doi.org/10.1016/j.psep.2021.01.045
5. Zayed ME, Zhao J, Elsheikh AH, et al. (2020) Optimal design parameters and performance optimization of thermodynamically balanced dish/Stirling concentrated solar power system using multi-objective particle swarm optimization. *Appl Therm Eng* 178: 115539. https://doi.org/10.1016/j.applthermaleng.2020.115539

6. Aboelmaaref MM, Zayed ME, Zhao J, et al. (2020) Hybrid solar desalination systems driven by parabolic trough and parabolic dish CSP technologies: Technology categorization, thermodynamic performance and economical assessment. *Energy Convers Manag* 220: 113103. https://doi.org/10.1016/j.enconman.2020.113103
7. Ma L, Li Y, Wang JY, et al. (2019) A thermal-dissipation correction method for in-situ soil thermal response test: Experiment and simulation under multi-operation conditions. *Energy Build* 194: 218–231. https://doi.org/10.1016/j.enbuild.2019.04.014
8. Al-Kbodi BH, Rajeh T, Li Y, et al. (2023) Heat extraction analyses and energy consumption characteristics of novel designs of geothermal borehole heat exchangers with elliptic and oval double U-tube structures. *Appl Therm Eng* 235: 121418. https://doi.org/10.1016/j.applthermaleng.2023.121418
9. Nian YL, Cheng WL (2018) Insights into geothermal utilization of abandoned oil and gas wells. *Renewable Sustainable Energy Rev* 87: 44–60. https://doi.org/10.1016/j.rser.2018.02.004
10. Kamazani M, Aghanajafi C (2022) Numerical simulation of geothermal-PVT hybrid system with PCM storage tank. *Int J Energy Res* 46: 397–414. https://doi.org/10.1002/er.7279
11. Ma L, Zhao Y, Yin HM, et al. (2019) A coupled heat transfer model of medium-depth downhole coaxial heat exchanger based on the piecewise analytical solution. *Energy Convers Manage* 204: 112308. https://doi.org/10.1016/j.enconman.2019.112308
12. Gilbert GL, Instanes A, Sinitsyn AO, et al. (2019) Characterization of two sites for geotechnical testing in permafrost: Longyearbyen, Svalbard. *AIMS Geosci* 5: 868–885. https://doi.org/10.3934/geosci.2019.4.868
13. Marmelia PD, Andri DS, Yusuf L (2022) Investment decisions under uncertainties in geothermal power generation. *AIMS Energy* 4: 844–857. https://doi.org/10.3934/energy.2022038
14. Kelly JJ, McDermott CI (2022) Numerical modelling of a deep closed-loop geothermal system: evaluating the Eavor-Loop. *AIMS Geosci* 8: 175–212. https://doi.org/10.3934/geosci.2022011
15. Zayed ME, Shboul B, Yin H, et al. (2022) Recent advances in geothermal energy reservoirs modeling: Challenges and potential of thermo-fluid integrated models for reservoir heat extraction and geothermal energy piles design. *J Energy Storage* 62: 106835. https://doi.org/10.1016/j.est.2023.106835
16. Su Y, Yang F, Wang B, et al. (2018) Reinjection of cooled water into sandstone geothermal reservoirs in China: a review. *Geosci J* 22: 199–207. https://doi.org/10.1007/s12303-017-0019-3
17. Song W, Liu X, Zheng T, et al. (2020) A review of recharge and clogging in sandstone aquifer. *Geothermics* 87: 101857. https://doi.org/10.1016/j.geothermics.2020.101857
18. Dijkshoorn L, Speer S, Pechnig R (2013) Measurements and design calculations for a deep coaxial borehole heat exchanger in Aachen, Germany. *Int J Geophys* 2013: 916541. https://doi.org/10.1155/2013/916541
19. Wu BS, Zhang X, Jeffrey RG, et al. (2016) A simplified model for heat extraction by circulating fluid through a closed-loop multiple-fracture enhanced geothermal system. *Appl Energy* 183: 1664–1681. https://doi.org/10.1016/j.apenergy.2016.09.113
20. Willems CJL, Nick HM, Weltje GJ, et al. (2017) An evaluation of interferences in heat production from low enthalpy geothermal doublets systems. *Energy* 135: 500–512. https://doi.org/10.1016/j.energy.2017.06.129
21. Lund JW, Boyd TL (2016) Direct utilization of geothermal energy worldwide: review. *Geothermics* 60: 66–93. https://doi.org/10.1016/j.geothermics.2015.11.004

22. Babaei M, Nick HM (2019) Performance of low-enthalpy geothermal systems: interplay of spatially correlated heterogeneity and well-doublet spacings. *Appl Energy* 253: 113569. https://doi.org/10.1016/j.apenergy.2019.113569
23. Holmberg H, Acuña J, Næss E, et al. (2016) Thermal evaluation of coaxial deep borehole heat exchangers. *Renew Energy* 97: 65–76. https://doi.org/10.1016/j.renene.2016.05.048
24. Liu H, Hou Z, Li X, et al. (2015) A preliminary site selection system for a CO_2-AGES project and its application in China. *Environ Earth Sci* 73: 6855–6870. https://doi.org/10.1007/s12665-015-4249-2
25. Zhu JL, Hu K, Lu X, et al. (2015) A review of geothermal energy resources, development, and applications in China: Current status and prospects. *Energy* 93: 466–483. https://doi.org/10.1016/j.energy.2015.08.098
26. An QS, Wang YZ, Zhao J, et al. (2016) Direct utilization status and power generation potential of low-medium temperature hydrothermal geothermal resources in Tianjin, China: A review. *Geothermics* 64: 426–438. https://doi.org/10.1016/j.geothermics.2016.06.005
27. Wang YZ, Li CJ, Zhao J, et al. (2021) The above-ground strategies to approach the goal of geothermal power generation in China: State of art and future researches. *Renewable Sustainable Energy Rev* 138: 110557. https://doi.org/10.1016/j.rser.2020.110557
28. Zhang L, Chen S, Zhang C (2019) Geothermal power generation in China: Status and prospects. *Energy Sci Eng* 7: 1428–1450. https://doi.org/10.1002/ese3.365
29. Xu YS, Wang XW, Shen SL, et al. (2020) Distribution characteristics and utilization of shallow geothermal energy in China. *Energy Build* 229: 110479. https://doi.org/10.1016/j.enbuild.2020.110479
30. He Z, Feng J, Luo J, et al. (2023) Distribution, exploitation, and utilization of intermediate-to-deep geothermal resources in eastern China. *Energy Geosci* 4: 100187. https://doi.org/10.1016/j.engeos.2023.100187
31. Luo J, Zhang Q, Liang C, et al. (2023) An overview of the recent development of the Ground Source Heat Pump (GSHP) system in China, Renew. *Energy* 210: 269–279. https://doi.org/https://doi.org/10.1016/j.renene.2023.04.034
32. Duan YH, Wang JB, Wang YB, et al. (2004) Groundwater resources and its sustainable development in Tianjin. *Hydrol Eng Geol* 31: 29–39.
33. Zhang WK, Wang KX, Guan CM, et al. (2023) Analysis and optimization of the performance for the ground source heat pump system with the middle-deep U-type well. *Appl Therm Eng* 219: 119404. https://doi.org/10.1016/j.applthermaleng.2022.119404
34. Tian P (2015) Evaluation on the Potential of Geothermal Resource in Tianjin. China University of Geosciences, Thesis.
35. Yu Y (2014) Evaluation of geothermal resources in the Neogene geothermal reservoir in the New Coastal Area of Tianjin. China University of Geosciences, Thesis.
36. Lei HY, Zhu JL (2013) Numerical modeling of exploitation and reinjection of the Guantao geothermal reservoir in Tanggu District, Tianjin, China. *Geothermics* 48: 60–68. https://doi.org/10.1016/j.geothermics.2013.03.008
37. Rajeh T, Al-Kbodi BH, Li Y, et al. (2023) Modeling and techno-economic comparison of two types of coaxial with double U-tube ground heat exchangers. *Appl Therm Eng* 225: 120221. https://doi.org/10.1016/j.applthermaleng.2023.120221

38. Qian H (2014) Study of the feasibility of geothermal well drilling technology in the Cambrian in the Dongli District of Tianjin. China University of Geosciences. A thesis.
39. Parisio F, Yoshioka K (2020) Modeling fluid reinjection into an enhanced geothermal system. *Geophys Res Lett* 47. https://doi.org/10.1029/2020GL089886
40. Ke TT, Huang SP, Xu W, et al. (2022) Evaluation of the multi-doublet performance in sandstone reservoirs using thermal-hydraulic modeling and economic analysis. *Geothermics* 98: 102273. https://doi.org/10.1016/j.geothermics.2021.102273
41. Rajeh T, Al-Kbodi BH, Li Y, et al. (2023) A novel oval-shaped coaxial ground heat exchanger for augmenting the performance of ground-coupled heat pumps: Transient heat transfer performance and multi-parameter optimization. *J Build Eng* 79: 107781. https://doi.org/10.1016/j.jobe.2023.107781
42. Wang GL, Wang WL, Zhang W, et al. (2020) The status quo and prospect of geothermal resources exploration and development in Beijing-Tianj in-Hebei region in China. *China Geol* 3: 173–181. https://doi.org/10.31035/cg2020013
43. Wang Y, Liu Y, Dou J, et al. (2020) Geothermal energy in China: Status, challenges, and policy recommendations. *Utilities Policy* 64: 101020. https://doi.org/10.1016/j.jup.2020.101020
44. Wang L, Bi Y, Yao J, et al. (2022) Comprehensive Utilization of Resources, *Interpretation of Green Mine Evaluation Index*, Springer, Singapore. https://doi.org/10.1007/978-981-16-5433-6_6
45. Jian Z, Gui F, Yubei H (2023) The deep high temperature characteristics and geodynamic background of geothermal anomaly areas in Eastern China. *Earth Sci Front* 30: 316–332.
46. Bing MR, Jia LX, Yang Y, et al. (2021) The development and utilization of geothermal energy in the world. *Chin Geol* 48: 1734–1747. https://doi.org/10.12029/gc20210606

AIMS Press

© 2023 the Author(s), licensee AIMS Press. This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0)