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Extracting geothermal energy in oil and gas fields; methods and case studies

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ABSTRACT

In recent decades, by increasing concerns about climate change as a result of global warming, the development of renewable energy has increased significantly across the world. Geothermal is a clean energy that plays an important role in eliminating carbon footprint. The high costs of exploration and drilling stages of conventional geothermal projects have caused their growth rate to be less than solar and wind energies. By reviewing practical reports and papers, this research focuses on harvesting geothermal energy from oil and gas fields that are matured. The two important features of aged hydrocarbon fields include a large volume of co-produced water and existing facilities at the surface that make geothermal extraction more feasible from an economical point of view. There are also exploration and production data that can help to reduce the costs and risks of geothermal projects. Then, methods of repurposing the aged hydrocarbon fields for geothermal utilization are reviewed and their applications in oil fields or other industries which need heat are conducted. In addition to using the produced heat directly, it could be used for power generation by Organic Rankin Cycle (ORC) systems which are suitable for low to intermediate geothermal resources. There are installed capacities in China and USA which use geothermal energy for power generation. Finally, by reviewing four practical instances of individual retrofitting, the details of the processes are listed. The results show that the costs of retrofitting disused wells are two times less than drilling a new well at least. Furthermore, the environmental risks of geothermal production are discussed. This paper helps decision makers for repurposing the oil and gas fields for geothermal utilization.

1. INTRODUCTION

By increasing depth, the temperature of the earth raises commonly around 30°C per kilometer which is related to the geothermal gradient of the region, the stored thermal energy in subsurface layers is called geothermal which is a type of sustainable and renewable energy. Based on the temperature of resources, they are classified into three groups, High temperature (>150 °C), moderate temperature (90-150 °C), and low temperature (30-90 °C). High temperature reservoirs are located in magmatic regions and near the volcanos where there are many faults, so their powerful potentials are detected in rear fields across the World in comparison to low to moderate temperature sources which could be found more commonly (Chiasson, 2016).

The produced heat from geothermal energy reservoirs is used directly, and indirectly to generate electricity which depends on the temperature of resources. Direct usage provides the required heat for different purposes such as space heating, the food industry, agriculture, aquaculture, water desalination, etc. The noticeable power of installed capacity for using the heat directly is equal to 107 GW_{th} in 2020 (Lund and Toth, 2021). Although the flash cycles (single and double) are well-known for power generation from high temperature reservoirs, in recent decades, Organic Rankin Cycles (ORC) have been utilized for power generation from reservoirs with intermediate temperatures that the common power generation methods are not feasible way from an economic point of view. Altogether, the value of electricity generation from geothermal power plants is equal to 95,100 GWh/yr in 2020 which is related to 16.0 GW_e of installed capacity worldwide (DiPippo, 2015; Ahmadi et al., 2020; Haghighi et al., 2020).

Drilling is an essential activity of geothermal development which corresponds to more than half of the total cost (Figure 1). As it is shown in figure 1, due to the high risks and costs of exploration and drilling processes at the beginning of geothermal projects, its growth rate is not as high as other renewable energies (Gehringer and Loksha, 2012; Clauser and Ewert, 2018). However, if there is data from previous exploration surveys and drilling activities in the region, the uncertainties and risks could be fallen and the construction stages are continued with lower risks and costs (Gehringer and Loksha, 2012).

In recent decades, researchers and oil producer companies are interested in extracting geothermal energy from oil and gas fields to increase revenue and enhance the management of hydrocarbon fields. This theory is based on a large volume of co-produced water with oil or gas production at the surface and many existing deep wells that are active or abandoned. The large amount of water in oilfields refers to water injection processes in increasing or enhancing oil recovery stages and existing of great aquifers under the hydrocarbon layers (Nasiri et al., 2017). The co-produced water has a temperature more than the ambient temperature because it is produced from deep layers where the geothermal energy warms the water up. Also, there are infrastructures such as existing wells (active and abandoned) surface facilities and access roads that could be reused for geothermal energy extraction cheaply and safely. Also, there are data about exploration and production surveys in the hysteresis of the field which reduce the costs and risks significantly for geothermal projects (Wang et al., 2018). In addition, water production at the surface makes field management more difficult which leads to suspending the oil production from wells or even resulting in good abandonment. Therefore, high abandonment costs and risks of methane emissions from decommissioned wells make them candidates to produce geothermal energy (Ebrahimi et al., 2022).

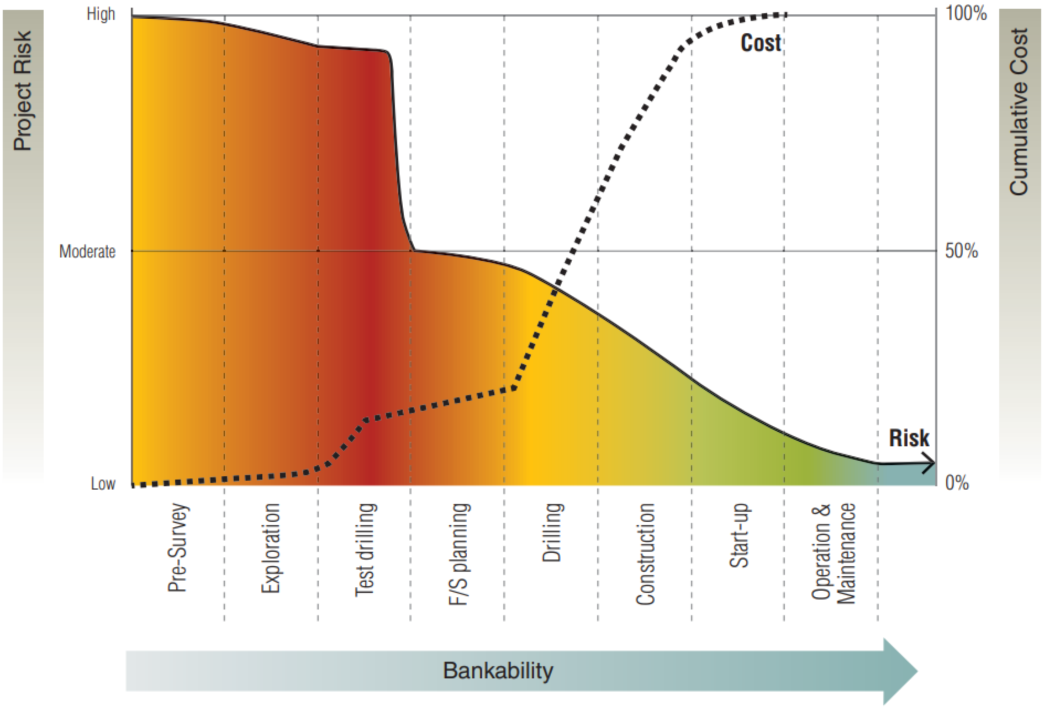

Figure 1: Risk and cost equities during the stages of conventional geothermal projects (Gehringer and Loksha, 2012).

As mentioned, there are great opportunities in oil and gas fields that could be reused to extract geothermal energy which might be beneficial for oil producer companies, and it helps to extend the life and revenue of operation. In continue, this paper demonstrates the amount of stored geo-energy in regions that are enriched with oil and gas by studies that have been done around the world. Then, the identification of Utilization methods and possible geothermal extraction ways is conducted. Finally, there is a discussion about the financial and environmental aspects of geothermal development in oil and gas fields.

2. GEOTHERMAL RESOURCES IN OIL AND GAS FIELDS

Theoretically, the power of geothermal energy inside the subsurface layers increases in depth and it depends on the geothermal gradient of the region. Based on previous studies, it has been recognized that the geothermal energy potential in conventional oil and gas fields are classified as low to moderate temperature resources which have temperatures in the range of 60-150°C that could be utilized in providing heat or even power generation (Liu et al., 2018).

As mentioned, one of the options for using geothermal energy is the large volume of co-produced water in conventional oil and gas fields. To evaluate the hysteresis of water production (water cut) at the surface there are two definitions, water to oil ratio (WOR) and water to gas ratio (WGR) which quantify the ratio of water to hydrocarbon production for a well at the surface. At the global scale, the Volume of water production has experienced more than 78% growth between 1990 and 2015 from 10.6 to 18.9 billion cubic meters compared to 38% growth of oil production from 3.7 to 18.9 billion cubic meters respectively. Predictions are expected that by this elevated trend, the global volume of water production from hydrocarbon fields will meet a value between 29 to 54 billion cubic meters in 2020 which needs to be enquired (Echchelh et al., 2018). That means by maturing of hydrocarbon fields, the volume of co-produced water and WOR or WGR are increasing year by year which causes higher costs and risks of management for operational companies (Healy et al., 2015; Veil et al., 2004).

By reviewing the papers, the unsuccessful drilling process in the development stages and large volume of co-produced water in an uneconomic manner has caused that there are lots of suspended, decommissioned and abandoned deep wells in oil and gas fields around the world which make use of geothermal energy possible by repurposing or reusing them (Javadi, 2021). For example, table 1 summarized the numbers and types of oil wells in Alberta of Canada whose number of inactive wells is more than 300 thousand. This conversion leads to taking steps in the green way of providing energy, also, it could reduce the cost of operation and expand the life and gain revenue of matured fields. To investigate the importance of existing suspended or abandoned wells and reveal the potential of stored geothermal energy in hydrocarbon fields, a study in the UK showed that from 2242 hydrocarbon wells in two large oilfields of the Wytch Farm and Wareham, only 292 wells are operating and 560 of them are suitable to be repurposed for geothermal operations. This study showed that there is a feasible opportunity to produce the thermal output of around 90 MW in the Wytch Farm, the largest oilfield in Europe which has a high flowrate of co-produced water at a temperature of almost 65°C (Watson et al., 2020). (Augustine and Falkenstern, 2014) studied the temperature distribution at a depth of 3500 (m) of 48 states in the United States to illustrate there are intermediate to high temperature regions which are located near oil or gas production activities, such as Oklahoma, Texas, North Dakota and Louisiana. Tester´s group (Tester et al., 2006) approved that some wells in Oklahoma, Louisiana and Texas have relatively high downhole temperatures (150-200°C). Only in Texas, there are ten thousand wells whose downhole temperatures are in the range of 121-204°C (Erdlac Jr et al., 2007). As shown in table 2, the geothermal potentials in three giant oilfields of China (Huabei, The Liaohe and Daqing oilfields) have been calculated where the total value of recoverable Geo-energy meets up to 424 EJ (1EJ= 1018J). Other investigations illustrate the significant numbers of abandoned wells and their great potential for repurposing for geothermal activities across the world such as in Poland, Italy, Hungary and Pakistan which have lower temperatures than mentioned instances in the United States (Munawar et al., 2022; Alimonti et al., 2021; Bujakowski et al., 2020; Toth et al., 2018;).

Table 1: Number and status of hydrocarbon wells in Alberta (Alboiu and Walker, 2019).

Well type	Number of wells	Percent from total (%)
Active	143,984	47.93
Inactive but not suspended	17,527	5.83
Suspended	75,479	25.13
Abandoned	42,571	14.17
Reclaimed	17,723	5.90
Orphaned	3117	1.04
Total number of wells	**300,401**	

Table 2: Value of stored geothermal energy in three giant oilfields in China (Wang et al., 2016).

Oilfield	Total geothermal energy (EJ)	Recoverable geothermal energy (EJ)
Hubaei	7100	306
Daqing	2900	89
Liaohe	1010	29
Total	**11,010**	**424**

3. METHODS OF GEOTHERMAL ENERGY EXTRACTION IN OIL AND GAS FIELDS

Although geothermal energy has vast applications, the temperature of gained heat indicates the suitable application. At first, this section concerns geothermal usage in industrial direct heating, then, the cycles of the power generation systems from high to moderate temperature resources are identified and case studies in oilfields are gathered. Finally, the methods of reusing wells to harness geothermal energy in oil and gas fields are reviewed.

3.1. Utilization methods of geothermal energy in oil and gas fields

Figure 2 shows the history of geothermal applications in the world and their dependency on the temperature of resources. For high temperature ones, hydrogen and electricity are preferable from an economical point of view which uses superheated steam for these purposes. Despite strong geothermal regions, low to moderate temperature sources are suitable for heating different industrial, commercial and residential units. Geothermal heat pump systems which consume electricity provide heating and cooling from too low temperature reservoirs (Batir et al., 2022). In continue, both direct and indirect usage of geothermal energy are discussed and their applications in oil and gas fields are investigated.

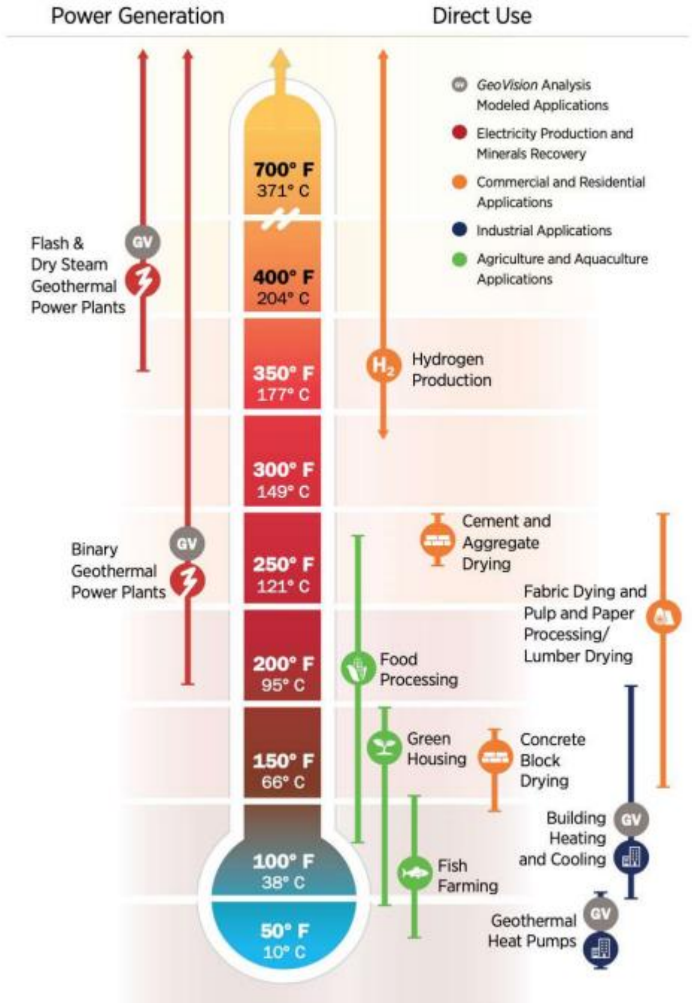

Figure 2. Vast geothermal usage based on the temperature of resources (US Department of Energy, 2019)

3.1.1. Direct utilization

Non-electricity applications are more common in regions with temperatures less than 150°C. European countries were the first producer of geothermal energy in the world. For instance, in Austria, there are spa resorts that take advantage of the stored geothermal energy from abandoned wells that were drilled for oil exploration goals. Also, in Albania, some greenhouses have used abandoned oil wells with temperatures over 65°C. In Hungary, Geothermal water has been used for the water flooding process as improving the oil recovery (IOR) stage and heating of gathering pipes in crude oil production (Lund and Boyd, 2016). In addition to Europe, house heating and heat tracing systems for the oil gathering process are methods that have been utilized in China since 2002. During 10 years from 2002 until 2012, The total saved energy by residential region is up to 10.3 EJ (EJ= 10^{18}J) which caused a reduction in burning coal and oil by values of 3×10^4 and 2×10^4 tons, respectively and resulted in the reduction of 9.8×10^8 tons of carbon dioxide and 500 tons of sulfur dioxide emissions (Liu et al., 2014; Chandhana et al., 2018). China retrofitted two abandoned wells in the Huabei oil field which provide 600 m^3\day of heated water at 100-110°C to use in heat-trace oil gathering system and crude oil transportation which resulted in conserving approximately 5 tons of oil and 3500 m^3 of gas daily. Some reports show there are other oilfields such as Daqing, Liaohe and Zhongyuan which use the co-produced water for space heating and crude oil transportation similarly (Wang et al., 2016).

3.1.2. Indirect utilization

Power generation from oil and gas fields that have low to moderate temperatures is possible by implementing ORC units which are economically feasible in comparison to flash cycles which are appropriate for conventional high temperature geothermal reservoirs (Li et al., 2012; Liu et al., 2015; Ahmadi et al., 2020; Zhang et al., 2021). Therefore, there are numerous studies investigating the performance of ORC at oilfields by using co-produced water or retrofitted abandoned wells (Noorollahi et al., 2015; Hu et al., 2017; Yang et al., 2017; Nian and Cheng, 2018, Céspedes et al., 2022). But in practice, there are only three well-known implemented examples worldwide where ORC units have made power generation possible on moderate temperature co-produced water at oilfields (Wang et al., 2018). As mentioned in table 3, In the USA, Wyoming oilfield and one oilfield in North Dakota have installed ORC power generation units with the power of 180 kW_e and 250 kW_e respectively, which use the hot co-produced water at the surface. Also, China has utilized the co-produced water at 110°C to generate net power of 310 kW_e.

Table 3. Installed ORC power plants utilizing co-produced water at oilfields (Wang et al., 2018).

Oilfield	Temperature [°C]	Flowrate [Kg/s]	Net power output [KWe]	ORC Efficiency [%]
Wyoming, USA	76.6	73.6	132	4.27
North Dakota, USA	98	55.2	250	3.85
Huabei, China	110	33.33	310	5-6.8

3.2. Methods of harnessing geothermal energy in oil and gas fields

In the previous section, applications of geothermal energy have been studied and this part of the paper deals with methods of extracting geothermal energy from deep layers by using existing facilities in hydrocarbon fields. Based on studies, there are three practical methods such as using the co-produced water, retrofitting the abandoned wells and combined systems. Also, some novel studies offer theoretical models to take advantage of geothermal energy in oil and gas fields. These methods are discussed as follows.

3.2.1. Co-produced water

Conventional oil and gas fields produce a large volume of formation water from deep aquifers as a byproduct that is heated by geothermal energy in depths. As shown in figure 3, the produced fluid flows in a separator to separate hydrocarbon from water. The stored heat in co-produced water could be used directly in space heating, heat-trace systems, enhancing oil recovery, etc., or indirectly to generate electricity. The feasibility of electricity generation from co-produced water mainly depends on the flowrate and temperature of the stream. There are threshold values of 15,000 bbl/day of co-produced water at a temperature of 101.7°C for power generation in an economic manner (Liu et al., 2015). In addition to the flowrate and temperature of co-produced water, the chemical composition of fluid also must be taken into consideration to avoid corrosion and scaling in power generation cycles or heat exchangers. Therefore, these conditions should be used as critical factors to identify the candidate wells.

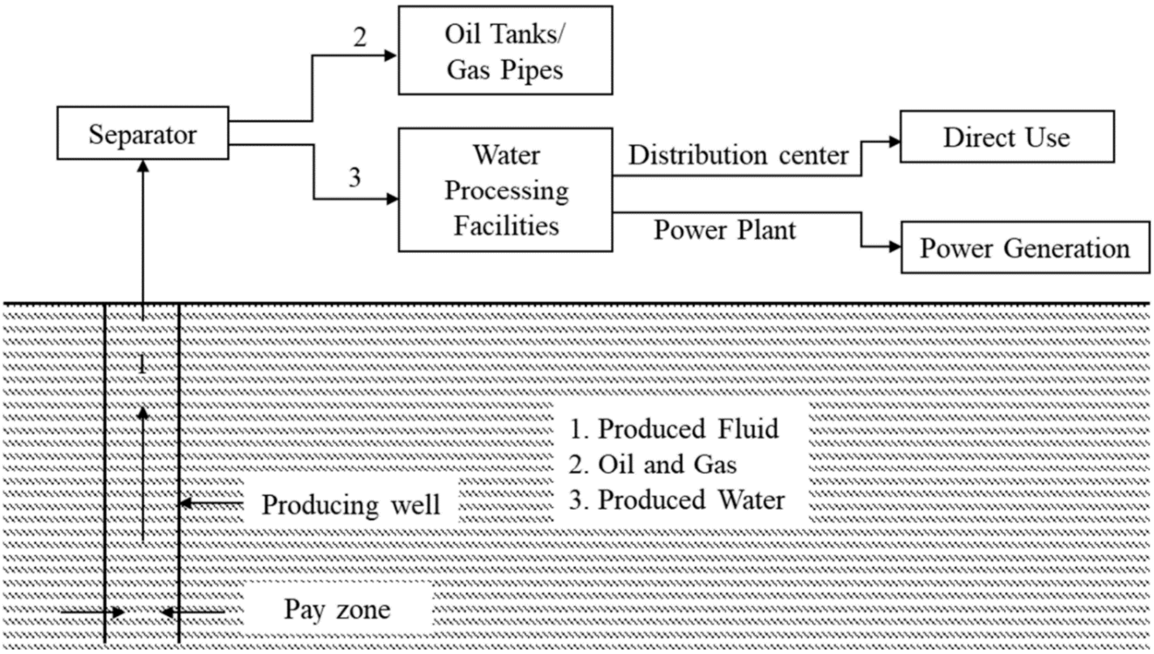

Figure 3. schematic of surface facilities and use of the co-produced water for geothermal power generation (Wang et al., 2018)

3.2.2. Repurposing the abandoned wells (Utubes or co-axial borehole heat exchanger)

As shown in figure 4, There are mainly two types of repurposing abandoned wells to develop a closed loop inside the well including co-axial borehole heat exchangers or installed U-tubes in abandoned wells. These borehole heat exchangers provide a flow path for the downward and upward flow of working fluid to capture heat from the surrounding deep layers and produce warm water at the surface. U-tube heat exchangers shall be placed inside the abandoned well before filing it with materials with desirable thermal properties. In general, U-tube heat exchangers are used in shallow depths due to the risks of collapsing and their applications are space heating and cooling. On the other side, the existing space between the outer pipe and inner pipe called the annulus is used as a downward path for flow and working fluid goes up inside the inner pipe with insulation to prevent exchanging heat between cool and warm fluids (Ebrahimi et al., 2022). In comparison to U-tubes, the co-axial heat exchanger has advantages such as larger surface area, lower pressure drop and required pump power which result in better heat extraction performance. Therefore, the co-axial heat exchanger is a preferable choice for converting the abandoned wells to geothermal heat exchangers because it uses the existing casing from the previous oil production stage, therefore there are valuable saving in cost and time during the reconstruction process. Also, this configuration offers lower thermal resistance between circulating fluid and the surrounding rocks (Kurnia et al., 2022).

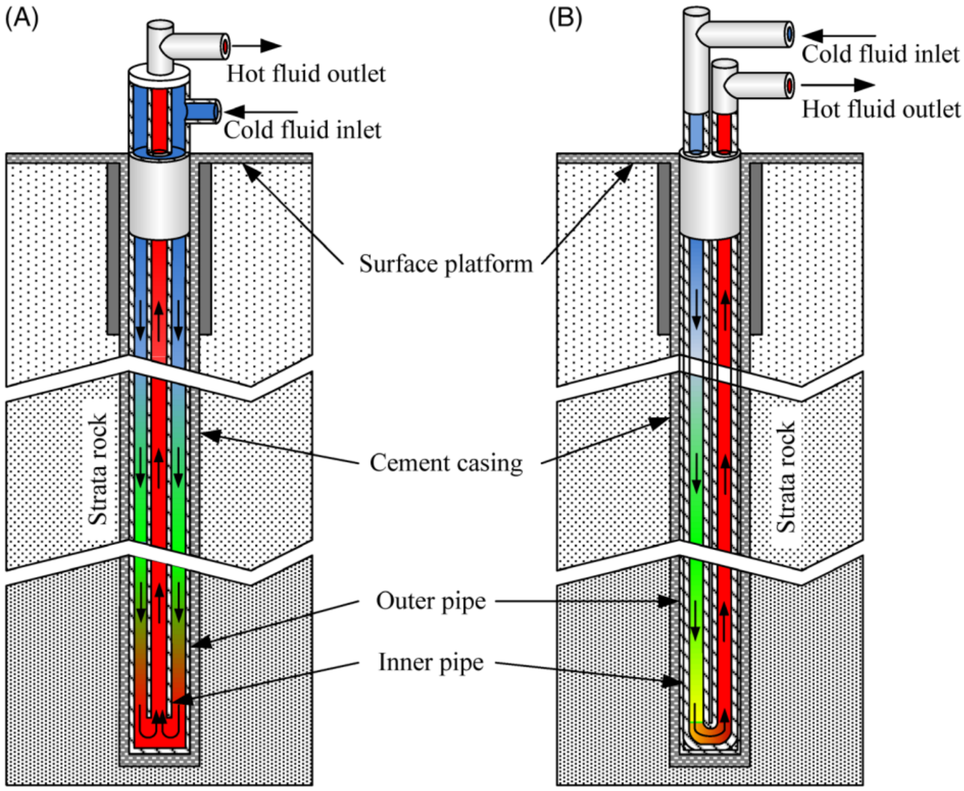

Figure 4. Different types of repurposing abandoned wells to borehole heat exchangers, co-axial (A), and U-tubes (B) (Kurnia et al., 2022).

3.2.3. Combined systems

Because the temperature of conventional co-produced water in the middle east is lower than 100°C and the ambient temperature is high, therefore, the conventional heating systems and electricity generation cycles are not efficient in this region. Therefore, the recovered geothermal energy from co-produced water must be combined with other sources of energy to become as high as suitable for industrial purposes. Along this goal, as shown in figure A1 in Oman, there is a combined cycle that boils the co-produced water with 7 MW power of solar thermal energy to inject steam into the reservoir as the EOR stage to improve the oil production this system produces 50 tons of steam per day (Choi et al., 2017). Also, Javadi and his partners suggested a combined cycle of gas turbine and ORC power plant that use the co-produced water (Figure A2). They designed a process to warm up the co-produced water at a moderate temperature by the exhaust of the gas turbine which is supplied by dissolved gas in high water cut wells. This system could generate net power of 2.2 MW_e, the power of ORC supplied by warmed up geothermal water corresponds to 385 kW_e of the total value. In addition, the system provides heat as a cogeneration process to increase efficiency and reduce carbon dioxide emissions (Javadi, 2021). Related pictures to this section are shown in the appendix.

3.2.3. Further studies

There is another method to extract the stored geothermal energy which is enhanced geothermal systems. The existing oil reservoir and wells (injection, production and abandoned) could be utilized as a closed cycle after their abandonment. Therefore, after capturing the stored heat from hot water, it is injected into the reservoir to warm up again in doublet wells systems. Also, there is a need to increase the permeability between injection and production wells by stimulation methods such as hydraulic or acidizing fracturing. The heat production models are more complex in these systems and they include thermo-hydraulic and mechanic (or chemical) processes. Recently (Sajjadi et al., 2022) offered an analytical equation for heat transfer and showed that regarding preventing a thermal breakthrough in the doublet systems from an economical point of view, well spacing, injection rate and injection temperature must be considered as the main features.

Recently, another novel technology has been investigated for harvesting geothermal energy in oil and gas fields using thermoelectric generators (TEG) which work based on the Seebeck effect. These devices conduct a current when there is a temperature difference across them. Paper (Wu et al., 2022) suggested retrofitted construction for geothermal extraction from both vertical and horizontal aged oil wells which reduces the need for surface facilities. As figure 5 shows the TEG devices which include N and P types are installed on the tubing wall and generate, electricity due to temperature differences by circulating water inside the well.

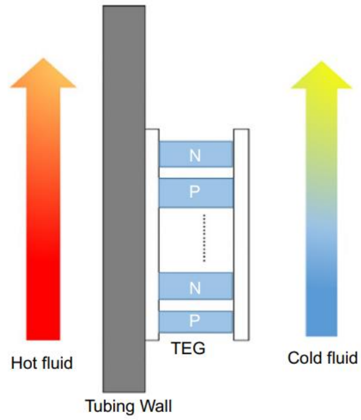

Figure 5. schematic of the installed thermoelectric generator devices on oil wells (Wu et al., 2022)

From another point of view, due to the low efficiency of the geothermal system, the best option for increasing the efficiency of the whole system is cascading design that uses the produced heat in every range of temperature for different applications (Kaczmarczyk et al., 2020, Ambriz-Díaz et al., 2020, Yousefi et al., 2019). For this purpose, Paper (Li et al., 2014) suggested a novel cascading cycle on one of the Chinese oilfields including, ORC, absorption refrigeration, oil gathering heat tracing, oil recovery system and heating directly or indirectly. The oil gathering system only saved about 8163 tons of oil per year, a total saved energy equal to 34,600 tons of oil each year which results in providing heat for 5000 square meters of residential area and hot domestic water for more than 8000 people. Also, the power output of the system experienced growth during both summer and winter because the considered auxiliary cooling system lower the condensing temperature. They concluded the novel system can increase the recoverable reserve and enhance the recovery ratio for oilfields during the high water cut period.

4. RETROFITTING EXAMPLES AND OTHER CONSIDERATIONS

To repurpose the existing wells, a study (Bujakowski et al., 2020) summarized four examples in Poland to extract geothermal energy from disused wells. The process of retrofitting depends on the type and accessibility to the water of existing wells. The instances are discussed as follows.

Mszczonow IG-1 well was decommissioned which was drilled in 1977 to identify the geological condition of subsurface layers and reservoir characteristics with a depth of 4119 m. This well has been retrofitted to restore the appropriate technical condition and evaluate safe geothermal water production. The reconstruction process includes two stages technical work and reservoir studies that have substages as follows:

- Technical work:
  1. Drilling works and securing the well
  2. Making the reservoir accessible
  3. Installation and operation equipment

- Studies and reservoir tests:

  1. Flushing
  2. Measurement pumping (step-drawdown test)
  3. Pre-operation pumping
  4. Hydrodynamic tests
  5. Geophysical studies of absorption zones
  6. Examination of well technical condition
  7. Physico-chemical analysis of waters
  8. Mineralogical and petrographic studies
  9. Isotope analysis of waters

The drilling work consists of drilling cement plugs, flushing the well, testing where the well is not obstructed using a lead impression block, diagnosing and eliminating casing defects. In this case, the final drilling stage was casing perforation at intervals of 1602.5-1645.5 m and 1663.5- 1714.0 m. After some image log surveys, two casing damages were identified at depths of 23m and 59 m which have been repaired by the insertion of a supplementary casing section and milling the casing respectively. The well structure pre and post-retrofitted is shown in figure A3 and the flow characteristics of this case are categorized in table 4.

Table 4. Results of flow test of the Mszczonow IG-1 well (Bujakowski et al., 2020).

Parameters	Values
Production rate (m^3/h)	60
Temperature (°C)	41.5
Mineral content (mg/dm^3)	490
Water type	HCO_3-Cl-Na-Ca
Static water table depth (m b.g.l)	49

There is an abandoned well that has been repurposed for geothermal applications. Poreba Wielka IG-1 well was drilled to a depth of 2002.4 m in 1975 to produce geothermal water but it remained closed after completion and test stages. After 35 years, the owner decided to reuse this well for balneotherapy. This well had two problems, first, the wellhead wasn't sufficient for geothermal water production, secondly, the well was obstructed at depth of 1899 m. Therefore, the well have been cleared by flushing the block to the final borehole end (2000 m) at the beginning, then, the quality of cementation was determined. Finally, they installed a new wellhead to ensure the safety of the geothermal extraction procedure. In this case, the characteristics of geothermal production are listed in table 5.

Table 5. Parameters of geothermal water production of Poreba Wielka IG-1 well (Bujakowski et al., 2020).

Parameters	Values
Production rate (m^3/h)	16.1
Temperature (°C)	42.5
Mineral content (g/dm^3)	23-24
Water type	HCO_3-Cl-Na, I
Static water table depth (m a.s.l)	1060
Artesian pressure (MPa)	5.4

In another case, the Bialy Dunajec PAN-1 well was drilled in 1990 to a depth of 2394 m and was used as an injection well until 2003 when it was found out that the casing was leaking. The leakage problem was eliminated in the first reconstruction phase by running a smaller diameter casing but the results were not sufficient as they predicted because there was an obstructed within the well by a fragment of a drill string (about 240 m). Therefore, they decided to close off the lower section of the borehole and deep the well from the depth of 2136 m to a 2592.8 m TVD by a directional drilling method. After some logging surveys, it was shown that this well is fully suitable for operation in a doublet arrangement with an injection capacity of 375 m^3/h at an injection pressure of 6.3 MPa.

There is Czarny PotT-1 well with a depth of 2853.3 m which was drilled for geological purposes. Unfortunately, this well was categorized as a negative well because of its dry borehole. In Poland, a project was developed to study the feasibility of repurposing the well with a coaxial borehole heat exchanger. They showed that the borehole heat exchanger could have a power of 250-300 kW_{th}.

Figure 6 shows the costs of drilling a new well and its contrast with the retrofitting disused wells for geothermal purposes. It is clear that the costs of reconstruction wells are more than two times lower than drilling new wells. The highest cost is related to the Bialy Dunajec which needed directionally drilling, in contrast, the Proba Wielka required less than $500,000 for reconstruction. There are also details of abandonment processes and costs individually which are listed in table A1 (Kurnia et al., 2022).

The report of (Batir et al., 2022) listed two possible environmental issues for geothermal development in the Wyoming oilfield. The first one is seismicity which is the result of an incorrect injection process by neglecting critical values for injection pressure and temperature. Based on the poroelasticity and thermoelasticity theories, by changing the pressure and temperature of the fluid within the pore, shear stress exceeds a critical value which is the coefficient of rock cohesion, stress normal to the fault plane and friction. Another problem is surface subsidence which is related to the existing imbalance between injection and production fluid or reservoir cooling and caused by the dissolution of evaporative formations. The report said that the subsidence in geothermal fields is more than in oilfields because there are no or fewer injection plans during the beginning years of geothermal water production.

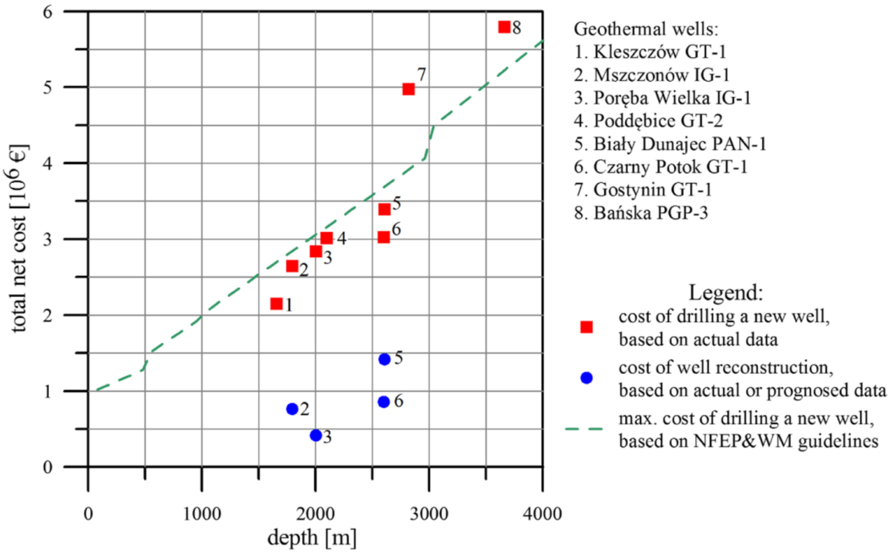

Figure 6. a summary of the actual costs of drilling and reconstructing selected geothermal wells in Poland (Bujakowski et al., 2020).

CONCLUSION

In this study, the production and applications of abundant geothermal energy in oil and gas fields were investigated. Reviewing the papers across the world showed that in addition to continuing revenue for operational companies, harvesting geothermal energy in hydrocarbon fields requires over two times less than developing projects for conventional geothermal resources and it accelerates the geothermal usage, especially in oil producer countries by below reasons:

- Large volume of co-produced water at the surface
- Previous data from exploration, drilling and production stages of reservoirs and fields.
- Existing disused deep wells which have high downhole temperatures or produce water significantly.
- Surface facilities, pipeline and access road which reduce the initial costs of the project.

Also, by studying the installed capacities around the world, geothermal in oil and gas fields are classified as low to intermediate temperature resources which have been utilized directly for heating in crude oil gathering and providing energy for residential areas or even in balneology. In addition, three oilfields around the world have used the available geothermal for significant power generation by installing ORC units. The methods of repurposing the abandoned wells to the downhole heat exchanger have been surveyed and it was clear that the co-axial construction has better performance than installing U-tube heat exchangers. Then, processes of retrofitting the aged wells in Poland which were used for geothermal purposes have been shown and the related cost evaluation showed that the retrofitting processes include lower costs (more than two times) than drilling a new well. Finally, induced seismicity and subsidence as two environmental issues which are related to geothermal production have been investigated. Results showed that geothermal production must regard critical values for injection temperature and pressure to prevent the in situ induced seismicity and a balance between the injection and production must be considered for subsidence problem. This paper could be used for the feasible study of individual projects to find out the optimum methods of harnessing geothermal energy and identify the best application for projects.

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APPENDIX

Figure A1. Combined Solar power and co-produced water unit in Oman (Choi et al., 2017).

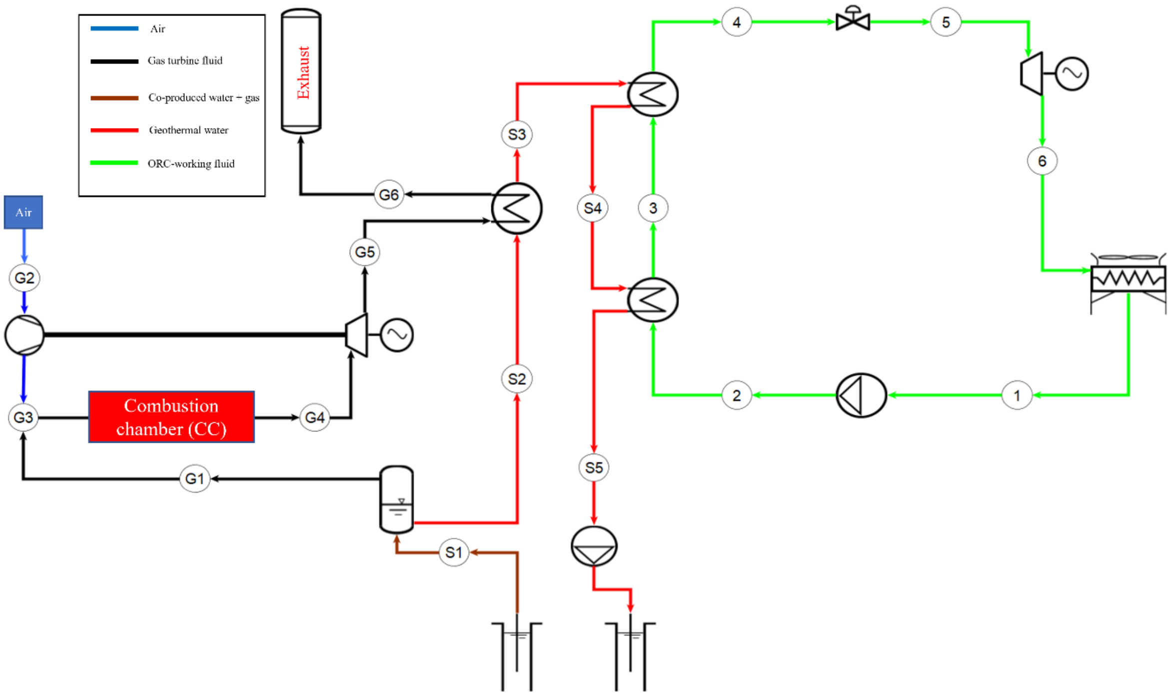

Figure A2. Schematic of combined gas turbine and ORC power plant for high water cut well (Javadi, 2021).

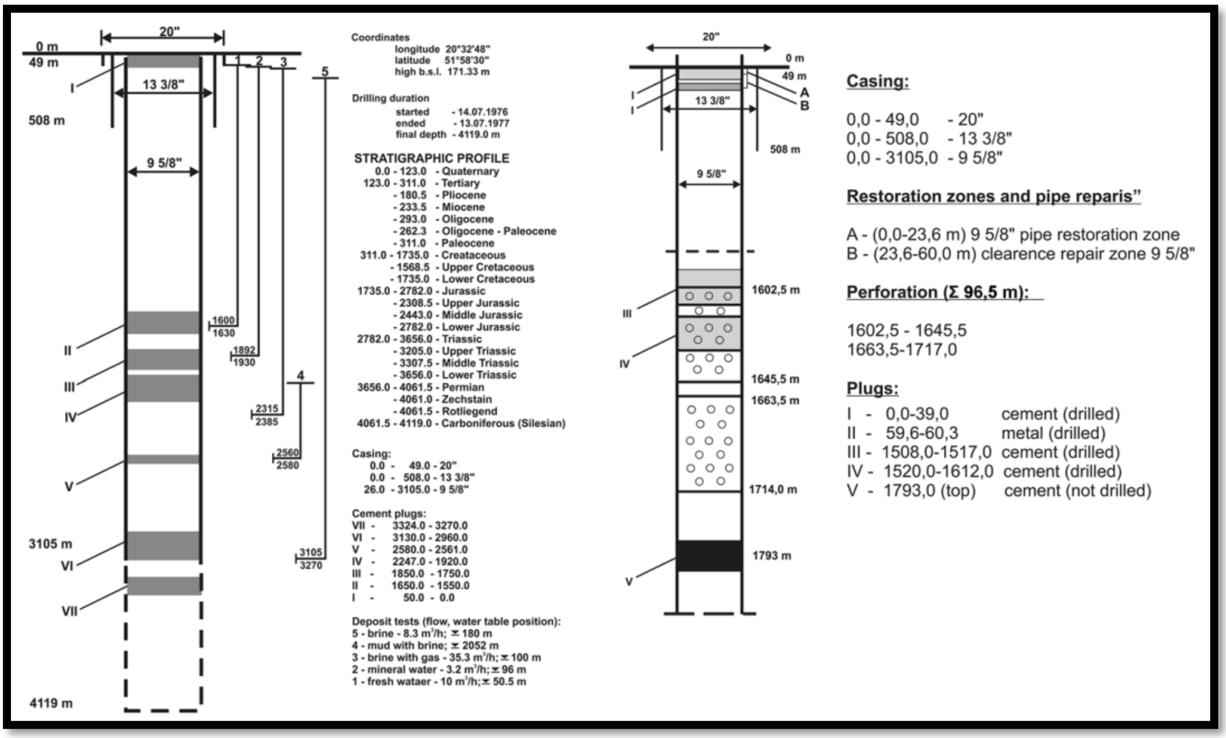

Figure A3. Well pattern of Mszczonow IG-1 (Bujakowski et al., 2020).

Table A1. The average cost of abandoned activities of the Schoonebeek oilfield (onshore) (Kurnia et al., 2022)

Activities	Cost (USD)	Activities	Cost (USD)
Subsurface abandonment		Surface abandonment	
Light drilling rig (per well)	100 000.00	Clean up hardware (per well site)	17 500.00
Heavy drilling rig (per well)	430 000.00	Combination Casing-Kelly (per well)	15 000.00
The second time by leakage of the well (per well)	810 000.00	Cable removal (per meter)	7.50
Environmental investigation (including plan and permit)		Pipeline removal, including inside (per meter)	15.00
Well site	10 000.00	Contaminated soil (light) removal (per ton/metric ton)	17.50
Metering station	175 000.00	Contaminated soil (heavy) removal (per ton/metric ton)	45.00
Crude oil handling	700 000.00	Location road removal (per meter)	4.00
Environmental oversight (per well site)	17 000.00	Recultivation (per well site)	35 000.00
Laboratory analysis (per well site)	3500.00		