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Geothermal energy extraction from abandoned oil and gas wells: potential and limits of extraction and use technologies

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Abstract

Geothermal energy is a renewable and sustainable energy source that can be utilized to generate electricity, heat/cool buildings, and other industrial uses. It has gained increasing attention in recent years due to its multiple benefits such as low environmental effects, constant power outputs, low greenhouse gas emissions, and global availability. All of this contributes to geothermal energy being a substantial contributor to global energy generation in an environmentally acceptable manner. The high investment costs of geothermal wells are a major problem in the exploration of geothermal sources. Therefore, it is essential to deeply comprehend the concept of technologies applied to extract and use geothermal energy from oil wells. Abandoned oil and gas wells (AOGW) with high bottom-hole temperatures provide plentiful geothermal energy that can be adapted to a novel geothermal system for various uses without the need for expensive drilling. Thus, some researchers have recently focused on assessing the performance of thermal energy extraction from AOGW and geothermal power generation employing AOGW with Organic Rankine cycle (ORC) and Wellbore Heat Exchanger (WBHX) systems. This thesis aims to provide information about specific extraction and utilization technologies, as well as, their benefits and drawbacks.

In addition, two case studies that were applied in two countries and described in reference [8] and [12] related to geothermal energy extraction adapting different systems were presented, including all data regarding the methodology and feasibility of studies, results, and discussions of each study were given. Wellbore Heat Exchanger (WBHX) model was applied by reference [8] to the Villafortuna Trecate oilfield in Italy, the model was optimized to increase heat extraction, and different internal diameters for geometrical configuration and two disparate working fluids such as water and diathermic oil were used. ORC plant was established to assess energy conversion. Water at a flowrate of 15 m^3/h produces the best results. The total thermal power is 1.5 MW, with a net electrical power of 134 kW.

Enhanced Geothermal Systems (EGS) and low-temperature deep Borehole Heat Exchanger (BHE) were applied by reference [12] to abandoned wells in three counties Santa Clara, Monterey and Santa Barbara with medium to high crustal heat flows (75-100 MW/m^2) in California,USA.

All in all, the benefits and a few drawbacks of each model were discussed in this thesis work, both methodologies were efficient in geothermal heat extraction. In Italy, in application of WBHX after five years, a pseudo-stationary situation is reached, with a reduction to 45% of the initial power generation. The available electrical output is insufficient to compete with traditional geothermal power plants, which is a shortcoming of the WBHX technology. Instead, the potential usage as thermal power in district heating plants can be evaluated favorably. In USA, abandoned oil/gas wells in California may provide a starting point for well deepening, but in other cases, unplugging and re-casing may be all that is required to separate sandstone formations of interest (EGS) or increase casing contact with adjacent rock (deep coaxial BHE). In all situations, lowering drilling costs results in a 42%- 95% reduction in EGS project costs.

Introduction

One of the main future energy solutions is geothermal energy, which is one of the many energy resources that are currently available and is weather-independent, stable, and environmentally friendly. Future economic and environmental potential could be significant for energy production based on the utilization of deep geothermal energy resources derived from unused or abandoned oil and gas wells in oilfields across continents.Hence,there is a importace of mentioning various geothermal energy utilization technologies and their feautures,which were included in this thesis work.

In the first part of the thesis work,the recent overall energy trends and consumption and production trends of fossil fuels were presented and discussed, as well as correlations and variations related to population growth. The second chapter reports a broad description and detailed review of technologies closely related to extracting and utilizing geothermal energy from abandoned oil and gas wells, considering all the properties, benefits and drawbacks of these systems, regarding all different aspects.

Afterwards, case studies about each country related to geothermal energy were introduced. In Italy, the study described in reference [8] of geothermal energy power generation from a deep oil well in one of the largest oil called Villafortuna Trecate field with wellbore heat exchanger was analysed. The study is centered on optimizing the WBHX to maximize the extracted heat. As a result, a numerical model of a WBHX has been created. The simulations took into account two alternative heat transfer fluids: water and diathermic oil. Different interior sizes of the pipes were also tested in order to optimize the geometrical configuration for the specific case study.

The study proposed by reference [12]about the reuse of abandoned oil and gas wells for geothermal energy production in USA was also reported. An investigation into the suitability of abandoned wells in California for Enhanced Geothermal Systems (EGS) and low temperature deep Borehole Heat Exchanger (BHE) applications is presented in the cited research. Santa Clara, Monterey, and Santa Barbara counties are identified in the study as having a significant number of abandoned wells and adequate sedimentary geology. Alternatively, a mathematical model is used to demonstrate the possibility of deep BHE applications within abandoned oil and gas wells.

A discussion of each specific study and a comparison between two case studies had been presented.

1. Introduction to Global Energy Trends: description of world consumption of fossil fuels and related variations according to population growth

1.1. Summary of the year

The COVID-19 epidemic had a significant impact on energy markets, with primary energy and carbon emissions plummeting at the quickest rates since WWII. Renewable energy, on the other hand, continued to develop, with solar power seeing its highest increase ever.

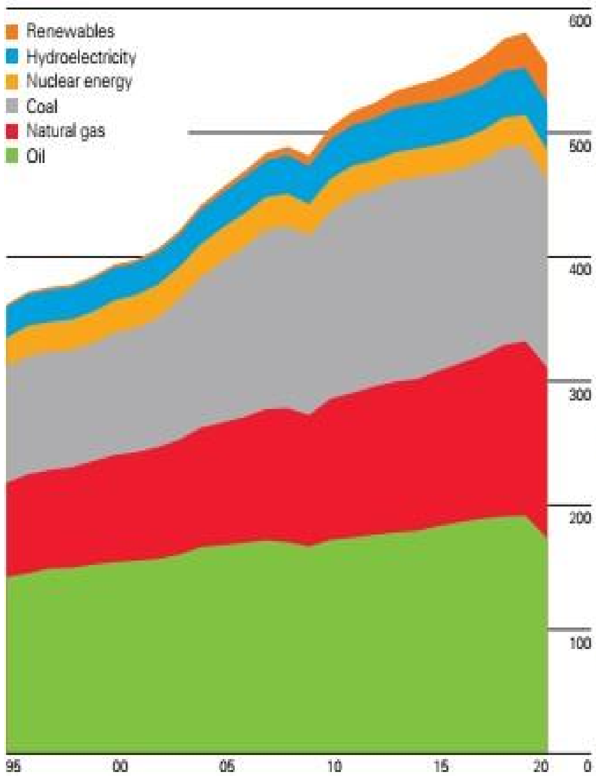
Energy developments indicated below occurred during a year 2020, primary energy usage declined by 4.5 percent, the most since 1945.

Oil was the main driver of the drop in energy use, accounting for about three-quarters of the net decrease, though natural gas and coal also saw large drops,despite a drop in overall energy demand, wind, solar, and hydroelectricity all climbed.

The United States, India, and Russia were the countries with the greatest reductions in energy use. China had the greatest rise (2.1 percent), and was one of only a few countries that had an increase in energy consumption last year [1].

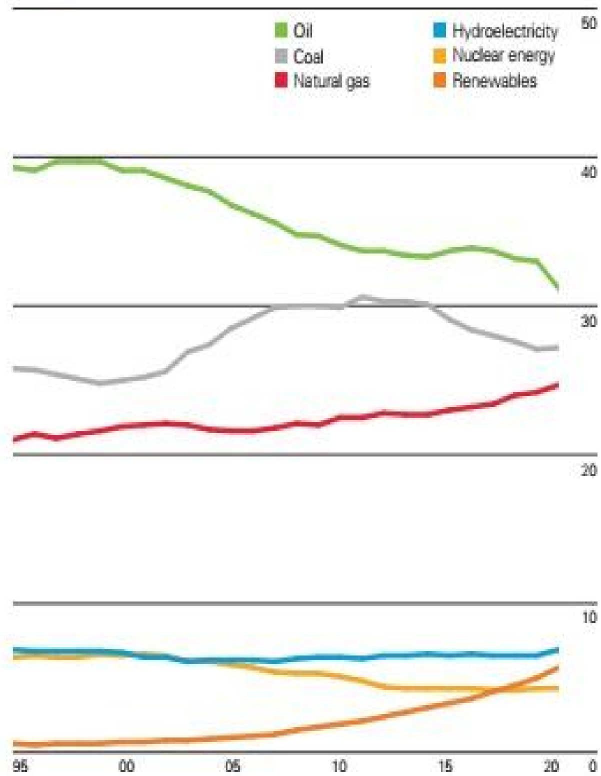
Before delving into the topic of fossil fuel usage, it's important to first define and explain what fossil fuels are. Fossil fuels are hydrocarbons created from the remains of dead plants and animals, primarily coal, fuel oil, or natural gas. The phrase "fossil fuel" is often used to refer to hydrocarbon-containing natural resources that are not generated from animals or plants,arising from geological settings such as anticline trapssalt dome,pinch-out traps,fault traps and so on. Fossil fuels are buried combustible geologic deposits of organic materials generated from dead plants and animals that have been converted to crude oil, coal, natural gas, or heavy oils over hundreds of millions of years by exposure to heat and pressure in the earth's crust. Human combustion of fossil fuels is the leading source of carbon dioxide emissions, which is one of the greenhouse gases that cause radiative forcing and contributes to global warming. Biofuels obtained from atmospheric carbon dioxide make up a minor part of hydrocarbon-based fuels and hence do not add to the net amount of carbon dioxide in the atmosphere [2].

World consumption
Exajoules



Primary energy consumption decreased by 4.5% last year, the first decline in energy consumption since 2009. The decline was driven largely by oil (-9.7%), which accounted for almost three quarters of the decrease. Consumption for all fuels decreased, apart from renewables (+9.7%) and hydro (+1.0%). Consumption fell across all the regions, with the largest declines in North America (-8.0%) and Europe (-7.8%). The lowest decrease was in Asia-Pacific (-1.6%) due to the growth in China (+2.1%), the only major country where energy consumption increased in 2020. In the other regions, the decline in consumption ranged between -7.8% in South and Central America to -3.1% in the Middle East.

Shares of global primary energy
Percentage



Oil continues to hold the largest share of the energy mix (31.2%). Coal is the second largest fuel in 2020, accounting for 27.2% of total primary energy consumption, a slight increase from 27.1% in the previous year. The share of both natural gas and renewables rose to record highs of 24.7% and 5.7% respectively. Renewables has now overtaken nuclear which makes up only 4.3% of the energy mix. Hydro's share of energy increased by 0.4 percentage points last year to 6.9%, the first increase since 2014.

Fig 1.1: Primary global energy comsumption [1]

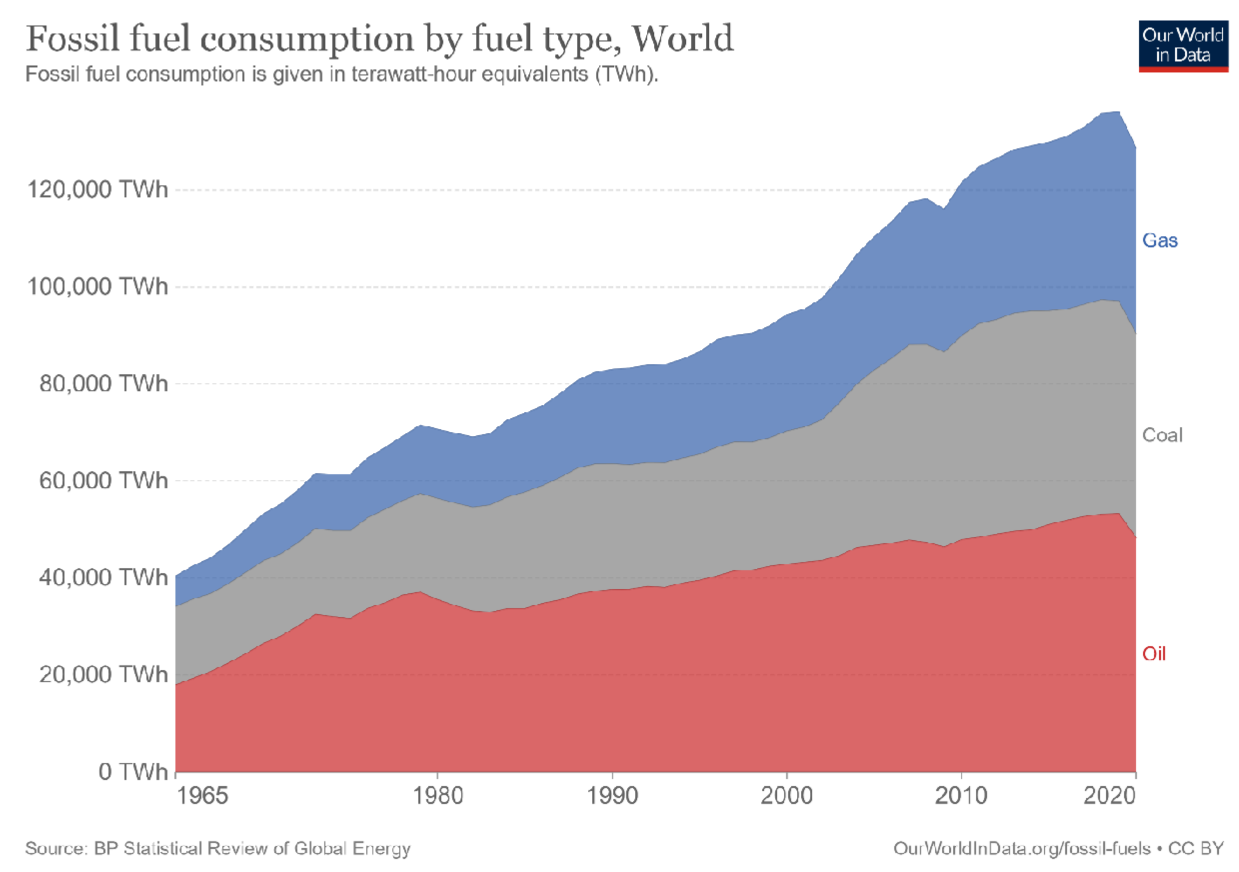


Fig 1.2: Fossil fuel consumption [3]

Fossil fuels (coal, oil, and gas) have long played a significant role in global energy systems, and they continue to do so. Fossil energy was a key driver of the Industrial Revolution, as well as the subsequent technological, social, economic, and development progress. Energy has had a significant positive impact on global transformation. Fossil fuels, on the other hand, have negative consequences, as they are the primary source of local air pollution and a major emitter of carbon dioxide (CO_2) and other greenhouse gases. As a result, the world must strike a balance between energy's role in social and economic development and the need to decarbonize, reduce our dependency on fossil fuels, and shift to lower-carbon energy sources [3].

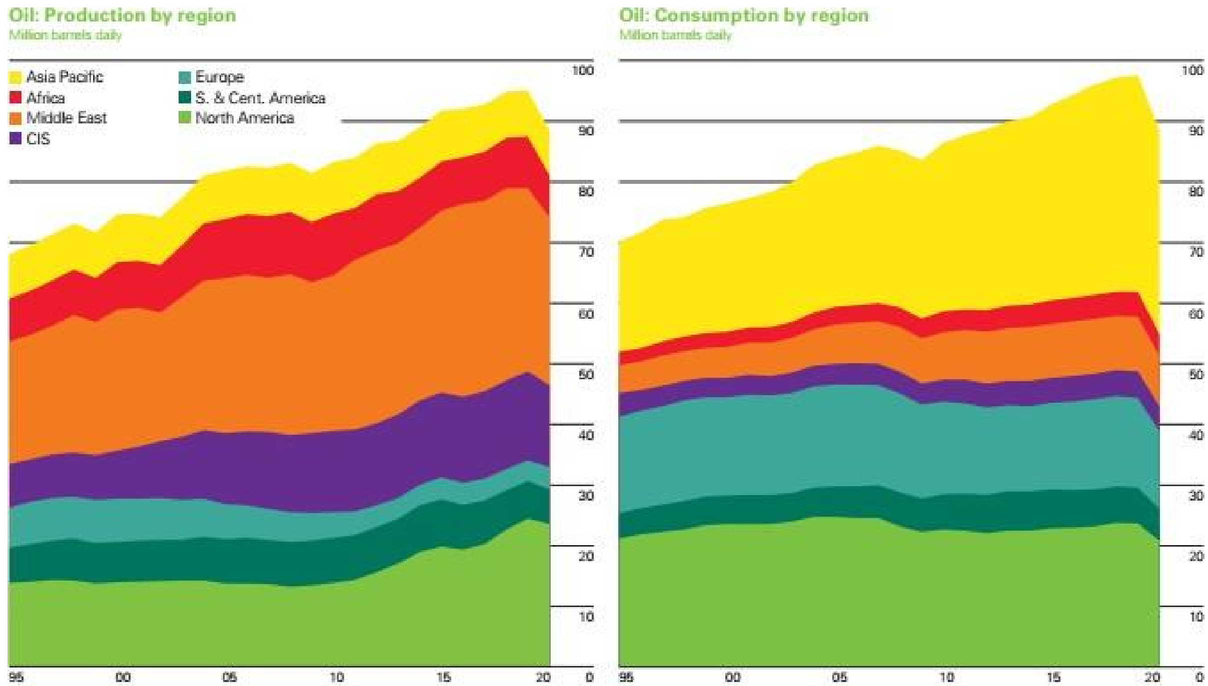
1.2. Oil

Measures to contain the spread of Covid19 and the following recession resulted in a predicted 8.5 mb/d (8.8%) drop in oil demand in 2020, the biggest absolute and relative decline ever. Mobility constraints in 2020 had a significant influence on the transportation industry, which accounts for almost 60% of global oil demand. Demand for jet fuel and kerosene fell by 3.2 million barrels per day (41%), with air passenger travel 66 percent lower than in 2019, while gasoline demand fell by more than 3 million barrels per day (12 percent). Fuel oil demand fell by 0.5 million barrels per day (8%), as bunker fuel demand fell in tandem with international commerce. As petrochemical feedstocks benefited from increasing sales of packaging, hygiene, and medical equipment, demand for gasoil fell to 1.8 mb/d (6 percent), while demand for LPG/ethane and naphtha remained relatively stable.

The better economic situation will sustain a 5.4 million barrels per day (mb/d) increase in global oil demand, or a 6% increase over 2020 levels. Despite the uptick, demand in 2021 is predicted to be 3.2 percent lower than in 2019.

Covid-related mobility restrictions continue to dampen oil demand for transportation in the first half of the year, but to a lesser extent than a year ago. As vaccination campaigns build up and travel returns, demand will gradually climb in the second half of 2021. Nonetheless, oil demand is not forecast to return to pre-crisis levels in the fourth quarter of 2021, with demand expected to be 1.4 million barrels per day lower. The fastest-recovering sector is international aviation, which is predicted to be 20% below 2019 levels by December 2021. Oil demand is likely to return to 2019 levels in the latter months of 2021, excluding international aviation [4].

In 2020, the average oil price (Dated Brent) was $41.84/bbl, the lowest since 2004.Oil consumption dropped by 9.1 million barrels per day (b/d), or 9.3%, to its lowest level since 2011.The US (-2.3 million b/d), the EU (-1.5 million b/d), and India (-480,000 b/d) had the biggest drops in oil demand. China was almost the only country to have a rise in consumption (220,000 b/d). OPEC accounted for two-thirds of the fall in global oil production, which fell by 6.6 million barrels per day. The highest OPEC losses were in Libya (-920,000 b/d) and Saudi Arabia (-790,000 b/d), while non-OPEC reductions were led by Russia (-1.0 million b/d) and the United States (-600,000 b/d).Refinery utilization decreased to 74.1 percent, the lowest level since 1985, by an unprecedented 8.0 percentage points [1].



World oil production fell for the first time since 2009 by 6.6 million b/d in 2020 driven by both OPEC (-4.3 million b/d) and non-OPEC (-2.3 million b/d). Country wise, Russia (-1 million b/d), Libya (-920,000 b/d) and Saudi Arabia (-790,000 b/d). Production only increased in a few countries, mainly Norway (260,000 b/d) and Brazil (150,000 b/d). Oil consumption also dropped for the first time since 2009 by a massive 9.1 million b/d. The decline was in both the OECD (-5.8 million b/d) and the non-OECD (-3.3 million b/d). The US (-2.3 million b/d), the European Union (-1.5 million b/d) and India (-480,000 b/d) reported the largest declines. China was one of the few countries where demand increased in 2020 (220,000 b/d).

Fig 1.3: Regional oil production and comsumption [1]

1.3. Natural Gas

In 2020, global natural gas consumption fell by 75 billion cubic meters (1.9 percent y-o-y). In absolute terms, this is the biggest decline in gas demand ever recorded, but in relative terms, it would be on pace with 2009. The drop was focused in the first half of the year, when global gas consumption fell by almost 4% year over year, owing to unusually mild weather and Covid-19 outbreaks. In 2020, gas demand was significantly less impacted than oil or coal demand, and demand began to rebound in the third quarter as lockdown measures were reduced, while seasonal electricity demand and competitive prices pushed up gas use.

Fuel switching in power generation can account for some of this relative resiliency. The shift was most noticeable in the United States, where gas consumption for electricity generation climbed by roughly 2% year over year despite falling electricity demand, while gas-fired generation in Europe benefited from cheap prices and a rapid rise in carbon prices in the second half of 2020. Gas for power has increased in China, India, and Korea in Asia. With the help of gas despite big drops in Russia and the Middle East, gas use in the power sector remained resilient, accounting for one-quarter of the drop in gas demand in 2020. The biggest other declines came from the buildings and industry sectors, accounting for 30 percent and close to 20 percent of total gas demand decline in 2020, respectively.

In 2021, global gas consumption is predicted to climb 3.2 percent, eliminating losses from 2020 and putting demand 1.3 percent higher than in 2019. Fast-growing markets – particularly in Asia and, to a lesser extent, the Middle East – have fueled the recovery in gas consumption, which has been hampered by concerns about industrial recovery and fuel price competitiveness. The European Union's demand is predicted to recover to levels comparable to 2019. In the United States, growth will be slower, with demand unlikely to rebound to 2019 levels in 2021. Colder-than-average temperatures in the northern hemisphere in the first months of 2021 increased gas demand. Winter storms also caused some acute supply-demand tensions and price surges, first in northeast Asia in January and subsequently in North America in February, particularly in Texas. Rising prices have put pressure on gas's role in power generation, as evidenced by the fact that demand in the first quarter of 2021 was lower than in the first quarter of 2020 in the United States. Higher gas costs are likely to maintain gas demand in the United States near to 2020 levels and roughly 2% below 2019 levels throughout the year. Higher carbon pricing in the European Union help gas compete with coal; early figures for the first quarter suggest an 8% year-over-year growth in gas demand in Europe. The outlook is significantly different in developing Asia, where demand is predicted to rise by 7% over 2020 levels in 2021, putting demand 8.5 percent higher than in 2019. China is leading the charge, with consumption in 2021 expected to be more than 14 percent (or 44 billion cubic meters) greater than in 2019 [4].

Considering all related trends,a summary can be provided. Natural gas prices have fallen to multi-year lows: in 2020, the US Henry Hub averaged $1.99/mmBtu, the lowest since 1995, while Asian LNG prices (Japan Korea Marker) fell to their lowest level ever ($4.39/mmBtu). Natural gas usage has decreased by 81 billion cubic meters (bcm), or 2.3 percent.

Despite this, gas's percentage of primary energy continued to grow, hitting a new high of 24.7 percent.

Russia (-33 bcm) and the United States (-17 bcm) led the declines in gas demand, with China (22 bcm) and Iran (10 bcm) contributing the most rises.

Inter-regional gas trade fell by 5.3 percent, with a 54 billion cubic meters (10.9 percent) decline in pipeline trade accounting for the entire drop. LNG supply increased by 4 billion cubic meters (bcm) or 0.6 percent, significantly below the 10-year average of 6.8% p.a. Although US LNG output increased by 14 billion cubic meters (29 percent), it was partially offset by declines in most other regions, particularly Europe and Africa [1].

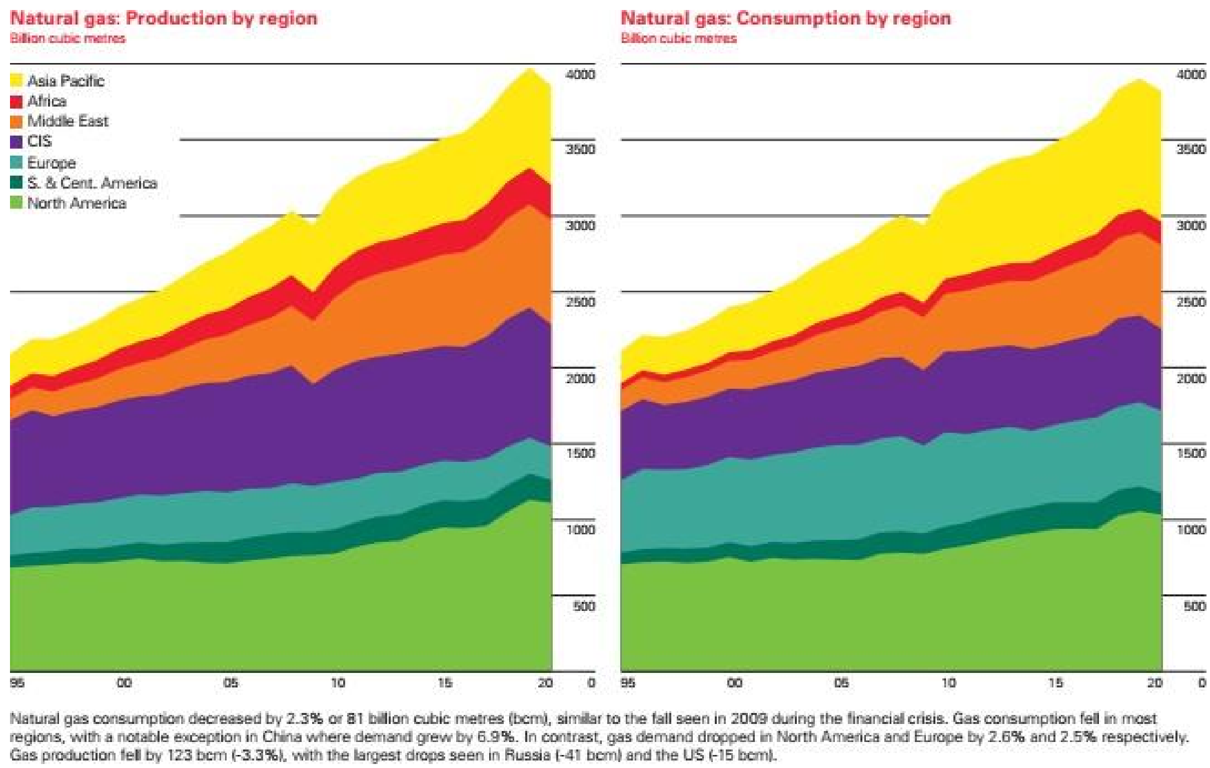


Fig 1.4:Regional gas production and comsumption [1]

1.4. Fossil fuel consumption vs population growth

1.4.1. Oil consumption vs population growth

A new source of energy supplanted coal's supremacy before a coal population ceiling was achieved. The next energy source to be commercialized was oil. Coal is more difficult to handle than oil. It burns cleaner and is less expensive to transport and store, making it an excellent transportation fuel. It was able to boost productivity even further. Oil supplies the energy required to grow and distribute food as well as to boost the nutritional value of agricultural products. Food can be easily distributed thanks to extensive land, air, and marine transportation networks [5].

Oil Population is calculated by subtracting Biomass Population and Coal Population from the total population of the world from 1950 to 2000. Figure 5 shows the oil population together with a fitted logistic curve. Oil today supports almost 2.5 billion people, according to the graph. Figure 1.6 shows the global use of crude oil from 1900 to 2007. The two oil shocks in the 1970s (1973 and 1979) and the implications of the Gulf War in 1991 are reflected in the dips in the oil consumption curve. There will undoubtedly be another downturn as a result of the 2008-09 economic crisis. Alternative future scenarios will be examined in a following section. The oil consumption line is fitted with a logistic curve that estimates a peak yearly consumption of 4 gigatonnes of oil. Based on this anticipated annual peak of 4 Gto, the globe surpassed 97 percent of that amount in 2007. The question of whether oil consumption will continue to rise, allowing the ceiling to rise, is hotly debated. This model assumes that oil consumption is at or near its peak.

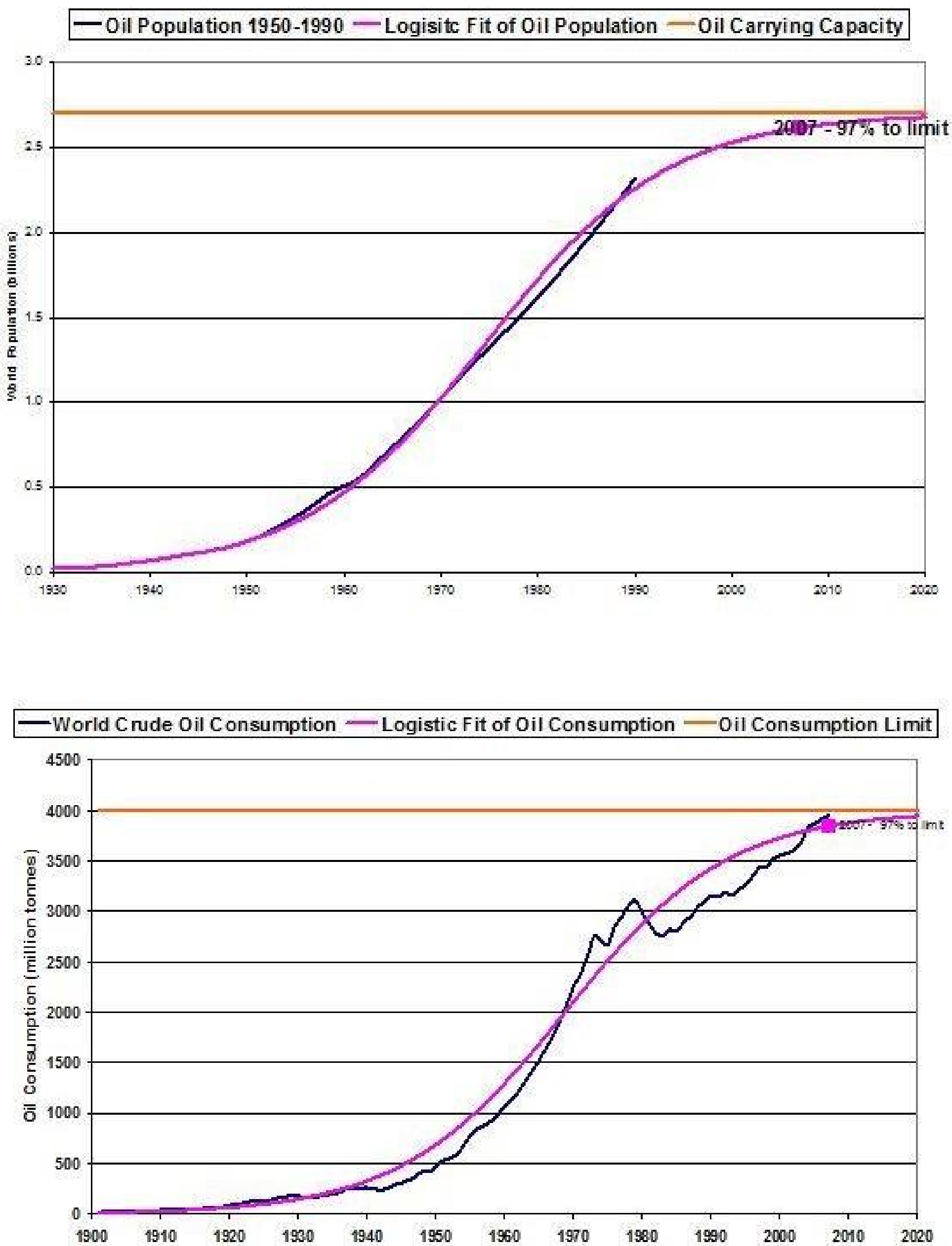


Figure 1.6: Oil consumption 1900-2020 [5]

1.4.2. Gas consumption vs population growth

Despite the fact that natural gas consumption has a recent history and tendencies, the above numbers suggest that Natural Gas Population may boost the population ceiling by another billion people or so (Fig.1.7). This is a significantly lesser increase than the increases caused by coal or oil. Natural gas is primarily a fuel for developing countries. Natural gas accounts for barely 3% of China's energy consumption and only 9% of India's It's possible that gas has less of an influence than oil because oil has already permitted the majority of the mortality improvements. Also, until today, oil has been a far superior transportation fuel. It's also possible that when the quality of energy sources improves, the downward effects on fertility rates outweigh the downward effects on death rates.

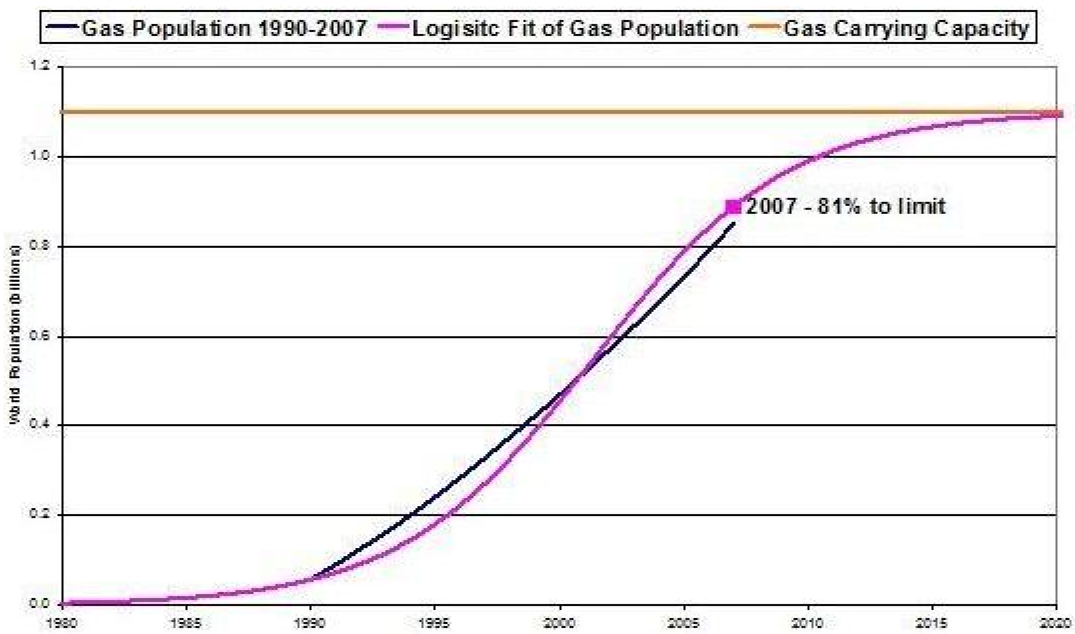


Figure1.7: Natural gas population 1990-2020 [5]

The natural gas consumption line is fitted with a logistic curve once more, this time assuming a peak yearly consumption of 3.2 gigatonnes of oil equivalent (Gtoe). According to this predicted peak consumption level, the globe reached 80% of that level in 2007. If a similar logistic curve could be used to describe Natural Gas Population, as shown in Figure 1.8, Natural Gas Population has achieved 80% of its ceiling, which is around 1.1 billion people [5].

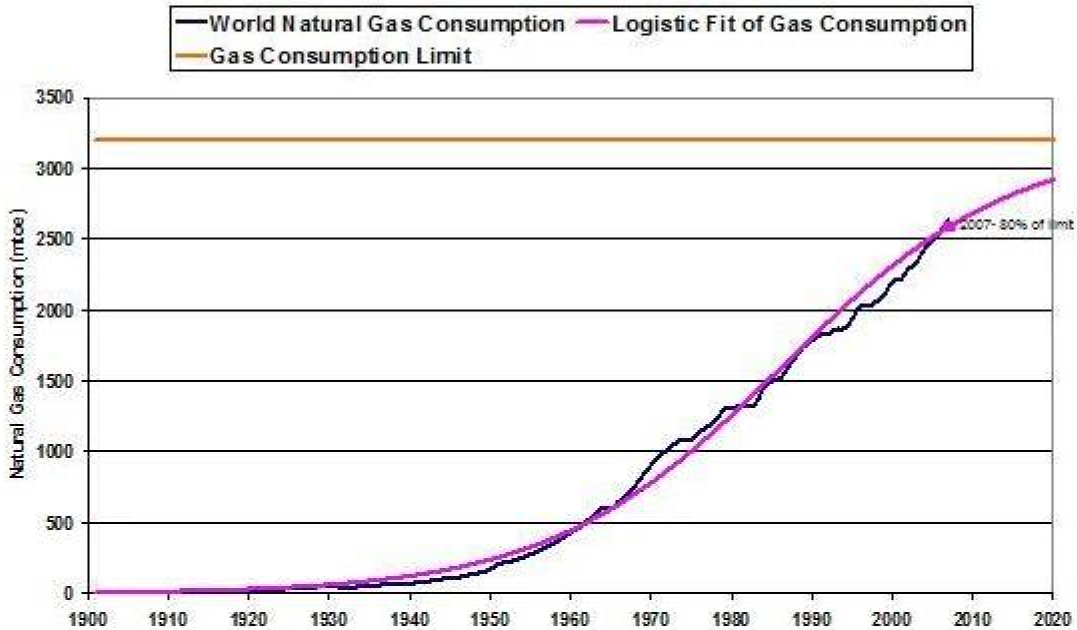


Figure 1.8: World natural gas consumption 1990-2020 [5]

2. Introduction to Geothermal Energy associated to Oil fields and abandoned Oil and Gas wells: advantages, disadvantages and potential

2.1 Introduction to Geothermal Energy

Geothermal energy is regarded as one of the future resources to address the world's growing energy demand due to its dependability, sustainability, abundant supply, and low environmental impact. Using existing assets, data, and technologies to extract geothermal energy from oil wells has substantial advantages over typical geothermal wells, particularly in terms of capital expenditure and operating risk.

Weather independence, stability, operational reliability, and environmental friendliness are all properties of geothermal energy, which is a renewable and sustainable energy source. It has undergone considerable research in order to minimize global warming, reduce air pollution, and meet the world's energy demand. For decades, geothermal energy has been used primarily in areas with a high geothermal gradient and intense volcanic or hydrothermal activity, such as the Geysers in the United States and Iceland in Europe. In addition to such locations, geothermal energy contained in hydrocarbon reservoirs has a lot of potentials, not only because there is a lot of geothermal energy in oil and gas reservoirs, but also because oilfields offer a lot of advantages in developing that geothermal energy.

Oil and gas companies began exploring and utilizing oilfield geothermal energy from existing assets, seeking solutions to reduce operation costs, extend the economic life of aging fields, and achieve environmental and social benefits, as a result of declining reserves, rising operating costs, volatile oil prices, and the green energy trend. Because the geothermal resource reserve in oil and gas reservoirs has been regularly examined, a significant amount of geothermal storage has been observed in oilfields around the world. Furthermore, oilfields have distinct economic and technological advantages when it comes to utilizing connected geothermal resources. With the existing wellbore, surface facilities, and usable data, the oilfield geothermal project may be completed at a lower cost, with less risk, and with greater convenience. In exchange, these effective oilfield geothermal projects help the oilfield by lowering total operating costs, reducing fossil fuel consumption, and extending the economic life. In oilfield applications of space heating, crude oil gathering and transportation, and geothermal power production, field operations have been conducted and significant progress has been made.

Despite some successful oilfield geothermal uses, large-scale development of geothermal resources in oilfields remains a difficulty. Low energy conversion efficiency, limited involvement, inadequate assessment and planning, ineffective policies, and other issues are identified as concerns. Theoretical and experimental research are both being conducted in order to find possible ways to improve oilfield geothermal extraction and usage. Thermoelectric technology is suggested as an alternate geothermal extraction method for recovering geothermal resources with a larger temperature range. The use of horizontal wells and nanotechnology in oilfield geothermal applications has been reported to improve geothermal extractions [6].

2.2. Characteristics of Oilfield Geothermal Resource

2.2.1. Overview of geothermal resource in oilfields

Low, middle, and high temperature resources are the three types of geothermal resources that can be found in general. This classification indicates the availability of various resources that may be used at a specific temperature, such as space heating/cooling, industrial drying, power generation, and other uses. We will utilize the following categories as part of a variety of classification methods. Those are: High temperature resource: above 150°C Intermediate temperature resource: between 90°C to 150°CLow temperature resource: between 30°C to 90°C.

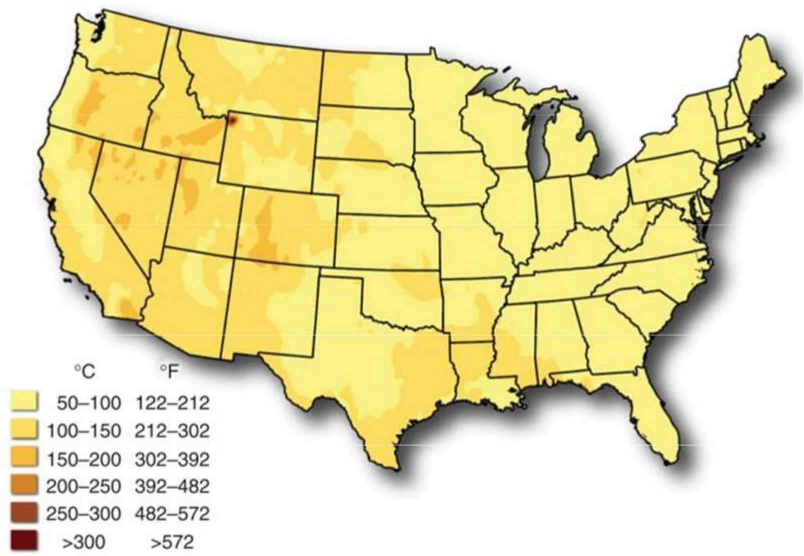


Figure2.1: Temperature map of US lower 48 states at depth of 3500m (Augustine and Falkenstern, 2012) [16]

Given that the produced fluids temperatures range between 65°C and 150°C, oilfield geothermal resources fall into the intermediate to low temperature group as a type of resource that coexists with hydrocarbon in sedimentary basins.The temperature distribution of the lower 48 states of the United States at a depth of 3500 meters (Figure 2.1), revealing moderate to high temperatures in areas with active oil and gas operations, such as Texas, Oklahoma, Louisiana, and North Dakota. Some wells in Texas, Oklahoma, and Louisiana exhibit relatively high temperatures (150°C-200°C) at the bottomhole depth, according to a study in [10]. There are tens of thousands of wells in Texas with bottom hole temperatures of above 121°C, with some reaching 204°C.The entire reserves of recoverable geothermal resource in China's major petroliferous basins, such as Daqing Oilfield, Liaohe Oilfield, and Huabei Oilfield, were reported to be up to 424 EJ (1EJ=1018 J), as indicated in Table1 [6], [16].

Oilfield	Total Geothermal Energy, EJ	Recoverable Geothermal Energy, EJ
Huabei	7099	306
Daqing	2905	89
Liaohe	1008	29
Total	11,012	424

Table 1. Geothermal resource storage in three oilfields in China

Given the above-mentioned widespread dispersion of enormous oilfield geothermal resources, it is vital and useful to understand geothermal resource characteristics in conjunction with oil and gas production, in order to give better design for thermal recovery and utilizations [16].

2.2.2. Features of developing geothermal resources in oilfields

In comparison to traditional geothermal fields, oilfields could offer significant benefits in terms of developing geothermal energy using existing wellbores and facilities at a low cost and with minimal risk. The following are the specifics [6].

2.2.3. Cost-effectiveness

Geothermal energy production from oil and gas wells is a cost-effective method. Because the wellbore has previously been checked for integrity, no or little drilling is required. The drilling cost of a standard geothermal well, on the other hand, might account for up to 50% of the entire cost. Drilling and completion procedures would be far less expensive and risky with the current wellbore. Furthermore, existing oilfield surface infrastructure, such as established wellsite facilities, pipes, and service roads to the wellsite, could reduce the initial outlay even more. Even for those wells or facilities that only require minor upgrades, a small initial investment is required to get the project started [6].

2.2.4. Minimized risk

Enough data has been collected and processed from long-term oil/gas exploration and production. In addition to lowering the risk of drilling and completion, the risk of reservoir uncertainty could be further decreased by utilizing current data for comprehensive reservoir characterization. For example, when estimating thermal resource in geothermal reservoirs, the volumetric resource estimation approach is extensively used.

Fluid saturation is a critical parameter for correct assessment, and it is always considered to be constant based on limited known data. This is obviously not the case in oil and gas reservoirs, where water saturation may increase while oil and gas saturations drop. Errors in geothermal resource assessment in oil and gas reservoirs may be caused by changes in fluid saturations during hydrocarbon production.

The operators can accurately evaluate the geothermal reserves at any point in production history, thanks to the oilfield database, which can provide not only the oil/gas/water saturations, but also the dynamic changes along with the production history, and aid decision-making on the geothermal project [27].

2.2.5. Sufficient candidate wells

Oilfields have a considerable number of candidate wells for geothermal use, particularly in mature oilfields with a substantial number of high water cut wells due to flooding and abandoned wells due to low production. Those wells are losing or have already lost their economic worth, but they may be suitable candidates for geothermal resource utilization. According to the Texas Railroad Commission's database, 10,370 wells were abandoned and plugged in Texas in 2016. There are 164,076 oil and gas wells in China, of which 76,881 have been abandoned. Operators could select high water-cut wells with high bottomhole temperature and large production rate, select abandoned wells with high bottomhole temperature and reliable wellbore integrity, and retrofit for geothermal production, which could produce clean energy, awaken sunken assets, offset operation costs, and extend the economic life of the assets [6].

2.2.6. Abundant market of oilfield geothermal utilization

Oilfields are not only energy producers, but also consumers of energy. In the oilfield, a huge amount of heat is consumed by burning oil, gas, and coal for home heating, thermal recovery of heavy oil, oil gathering, and transportation). Heating, for example, is required for crude oil dehydration and transportation, and heavy oil, in particular, must be heated to reduce viscosity before being transported by pipeline. However, it comes at a great expense in terms of energy consumption and operation; for example, only two crude oil gathering stations in north China might cost up to $503,000 per year in terms of power and gas usage. Oilfield geothermal use has a large market, especially in older oilfields, due to the high demand for thermal energy. Harvesting geothermal energy from oilfields to serve oilfield demand could offset the overall cost of operating [6].

2.2.7. Government and company support

The government's and oil corporations' initiatives have created a favorable atmosphere and a unique chance to increase geothermal utilization. China, for example, is aggressively developing incentive programs and expanding investment in geothermal energy production. Annual geothermal utilization should reach 50 million tons of standard coal equivalent by the end of 2020, according to China's 13th Five-Year Plan, and an integrated technological and industrial system for the development and use of geothermal resources should be in place across the country by that time.

Companies like Continental Resources, Denbury Resources, and Hilcorp Energy, which have done geothermal testing during routine production to recover both hydrocarbon and heat, have seen the potential of geothermal resources and started looking for the opportunity to generate geothermal energy from existing wells.

As previously stated, the built-in advantages of oilfield geothermal resource utilizations to meet thermal energy demand, extend economic life, and offset operation costs indicate a promising future of oilfield geothermal resource utilizations to meet thermal energy demand, extend economic life, and offset operation costs indicate a promising future of oilfield geothermal resource utilizations to meet thermal energy demand, extend economic life, and offset operation costs indicate a promising future of oilfield geothermal resource utilizations to meet thermal energy demand, extend economic life and offset the operation cost [6].

3. Technology of Extraction and Utilization of Geothermal energy from abandoned oil and gas wells.

3.1. Modeling Approach

When a well's oil and natural gas reserves are depleted, the well is deemed worthless. Into a result, existing oil and gas wells can be adapted as geothermal wells rather than being plugged. As seen in Figure 3.1, this can be accomplished by sealing the well's bottom and casing it.

The circulating fluid is injected through the annulus in this example, which is water. Due to a temperature difference between the reservoir rocks and the fluid, water flows downward along the channel and is gradually heated by surrounding rocks. The fluid ascends through the inside channel and flows out to the earth's surface after being reversed at the bottom of the well. When relatively cold water is introduced into the reservoir, a variety of processes occur. Convection (transport of heat and reactants products by bulk motions of fluids), advection (transport of heat and reactants products by bulk motions of fluids), and heat conduction in the low permeable rock matrix, molecular diffusion, hydrodynamic dispersion, and thermo-poro-elastic deformation of pore/fracture/rock are the processes that occur [28]. Figure 3 depicts a schematic diagram of the modeled system:

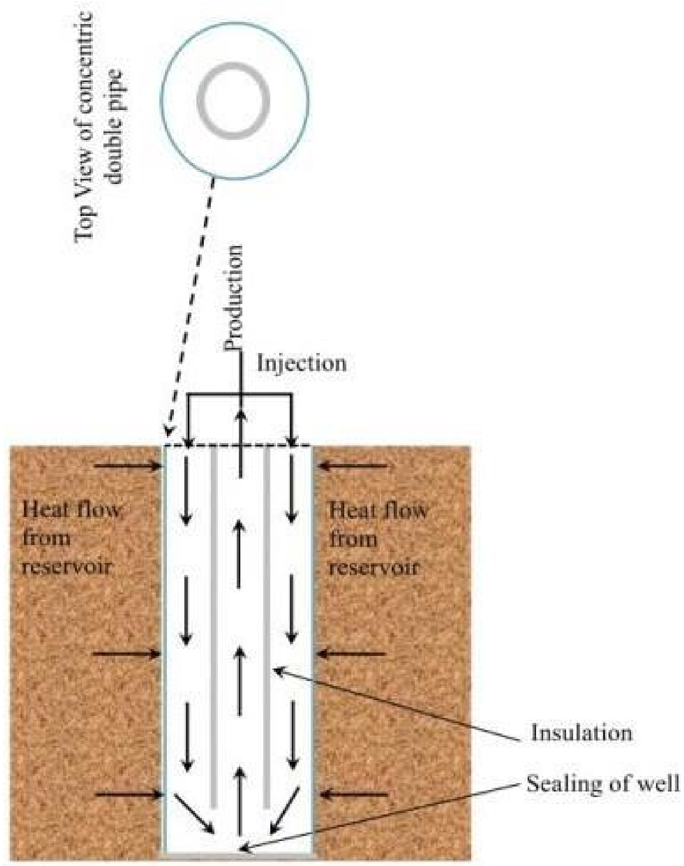


Figure 3.1: Schematic diagram of the modeled system [7]

The distinction between enhanced geothermal systems and traditional geothermal systems is that, unlike a double-pipe heat exchanger, the flowing fluid does not directly contact the rocks in Enhanced Geothermal Systems. As a result, just heat is transferred and no mass is transferred. In traditional geothermal systems, on the other hand, the fluid is retrieved from porous rock or soil. Because the heat exchange surfaces between well walls and rocks are smaller in EGS than in typical geothermal systems, the fluid flow rate necessary to maintain a high temperature is lower. The viability of reusing depleted oil and gas wells as deep borehole heat exchangers is investigated using mathematical modeling of fluid flow using a two-dimensional coaxial deep Borehole Heat Exchanger configuration. Inside a geothermal reservoir, Darcian flow is frequently considered. Non-Darcian flow is used in a few circumstances where the flow transitions from laminar to turbulent.

In the COMSOL Multiphysics software, the numerical solutions to the equations for fluid flow and heat transport are found using the finite element method. The software is used for thermo-hydro-mechanical modeling, and it is typically used for systems with elastic continuum and stress dependent permeability. An envelope of crustal temperature gradients, well depths, and flow rates must be determined. The geothermal gradient is assumed to be linearly increasing at a value of 50C˚/100 m, the study will focus on an abandoned well with a depth of 2 km. The outer and inner diameters of the coaxial BHE arrangement are 200 mm and 120 mm, respectively [28].

3.2. Methods of Extracting Oilfield Geothermal Resource

Oilfield geothermal energy must be retrieved before it can be used since it is stored in a subsurface formation. Oilfield geothermal resource is now extracted mostly through a liquid medium from existing oil wells and used as a hot fluid. The liquid medium could be produced water from a live well or working fluid injected into and circulated out of a sunk well. The following are the two basic methods of geothermal energy extraction [6].

3.2.1 Geothermal extraction by produced water from producing wells

This method uses geothermally heated formation water, a byproduct of oil and gas production. As shown in Figure 3.2, high-temperature water is produced at the surface alongside hydrocarbons, after which the water is separated and sent to processing facilities to capture the heat, which is then distributed or converted to electricity by a power plant, completing the coproduction of hydrocarbon and geothermal energy.

High water production wells are the most common type of producing well used for geothermal extraction and usage. Massive water production has been observed in both mature and unconventional oilfields An average of 25 billion barrels of water are produced annually from oil and gas wells in the United States, with Texas producing 7.4 billion barrels per year, accounting for 30% of the total amount of produced water generated in the country Produced water has traditionally been a nuisance that necessitated expensive disposal; however, it is now being considered as a resource that can be used to generate electricity for field operations or sold to the grid. Coproduced water generates between 2,072 and 9,965 MW of electricity in Oklahoma and Texas. Mining the geothermal energy contained in these high-temperature waters could result in immediate energy savings, reduced greenhouse gas emissions, and a reduction in the cost of water disposal.

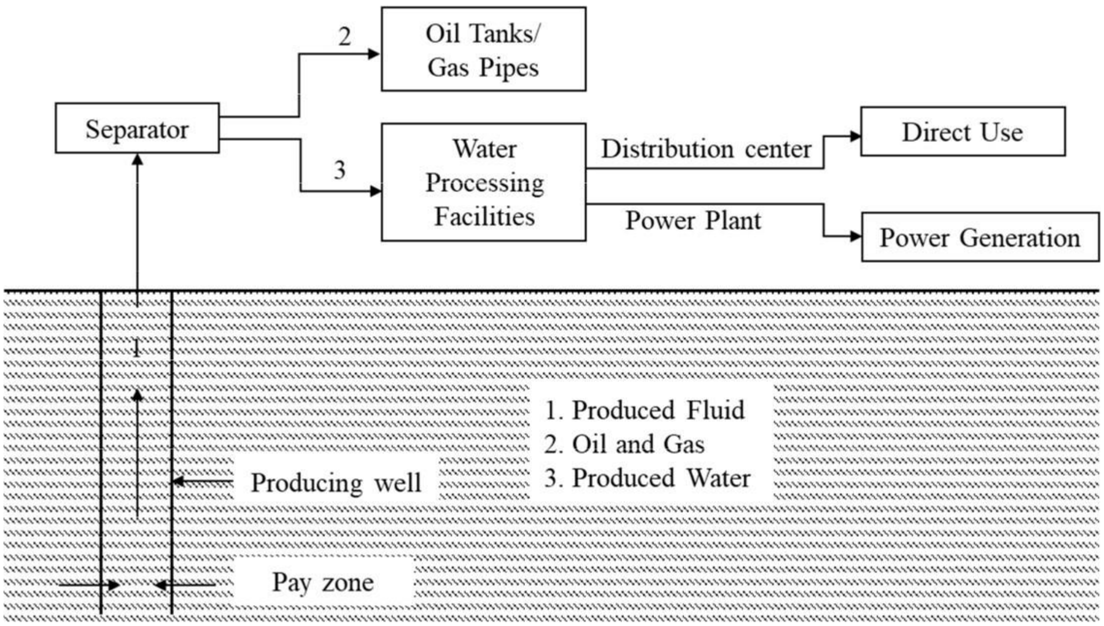


Figure 3.2: The Schematics of produced fluid flow for geothermal extraction from producing wells [6]

However, the performance of this method's geothermal usage is closely linked to oil and gas production operations, and it is heavily dependent on production rate and water temperature. When a well is shut down or production rate is reduced, this dependency will result in a commensurate shutdown or drop in geothermal utilization, especially for geothermal power generation, which has rigorous restrictions on water flow rate and inlet temperature. For efficient and cost-effective power generation, existing available technologies are projected to require at least 15,000 barrels of water per day at a minimum temperature of 101.7C°. Rather than demonstrating the value of thermal recovery, the water rate and temperature threshold values illustrate the limitations of oil well selection for geothermal power generation.

Before pumping produced water to a power plant for electricity generation, the chemistry of the produced water should be considered in addition to the production rate and temperature. As a result of pressure and temperature changes, scaling and corrosion may occur in the heat exchanger system, increasing operating and maintenance costs and reducing economic benefits Although each project of generated water power generation is unique, these issues must be considered, and they place significant constraints on the selection of potential wells for geothermal production [29].

3.2.2. Geothermal extraction by working fluid from abandoned wells

Another option is to recover geothermal resources from decommissioned oil wells. Wells will always be abandoned once hydrocarbon resources have been depleted to the point that they are no longer economically viable. These wells are typically seen as long-term liabilities, resulting in high plug-and-abandon expenses.

However, because an existing wellbore provides access to a subsurface geothermal resource, an abandoned well could be used to extract geothermal heat. The idea behind this technology is to pick a depleted petroleum reservoir and repurpose it as a geothermal reservoir, then collect the heat using a working fluid injected from the surface.

Working fluid must be injected to the intended depth, acting as a heat extractor and heat transporter, because there are no geofluids supplied by the pay zones in abandoned wells. Typically, fluid is injected near the surface, and as it travels down, the fluid is gradually heated by the surrounding formation. The injected fluid changes direction, travels upward, and ascends to the wellhead when it reaches the bottom of the heat exchanger, when it achieves its maximum temperature. At the wellhead, return fluid will be collected, and heat will be gathered and used for various reasons. Before injecting fluids, some wellbore refurbishment may be required to recover heat from abandoned wells. Retrofitting abandoned wells using U-tube and twin pipe heat exchangers is a typical practice[6].

3.2.3. U-tube heat exchangers

To increase heat transfer from the formation to the heat exchanger, a U-tube heat exchanger is installed in the wellbore prior to filling the well with a material with a desired thermal conductivity.

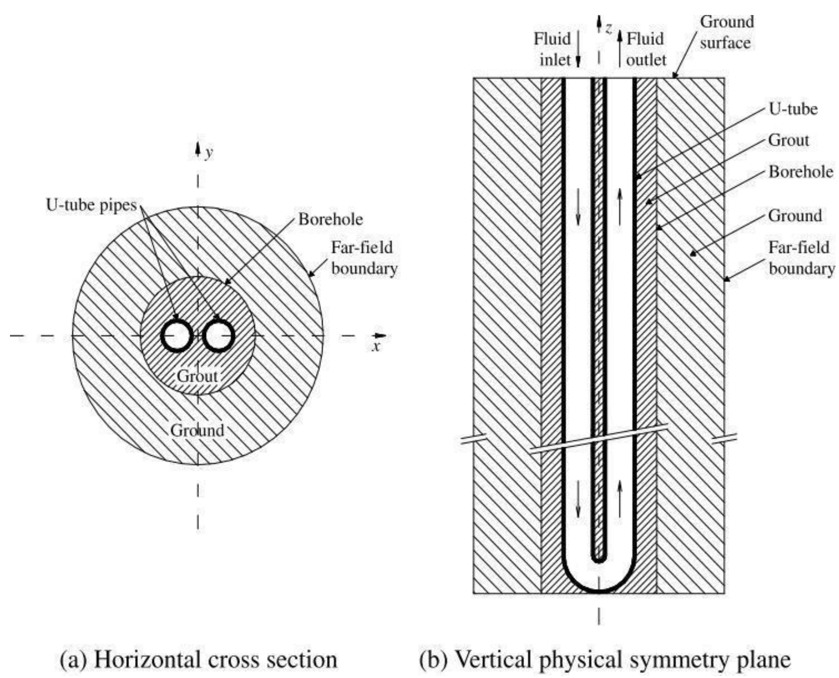


Figure 3.3: Schematic of a U-tube heat exchanger in abandoned well [30]

A working fluid is typically circulated inside the closed loop of a u-tube heat exchanger to extract geothermal heat from the reservoir and return it to the surface (Figure 3.3) [30].

3.2.4. Double-pipe heat exchanger

Another option is to build the wellbore as a coaxial double-pipe heat exchanger, with the casing serving as the outer pipe and the tubing serving as the inner pipe. The working fluid is injected into the annulus between the casing and tubing and then flows down to the desired depth while extracting heat from the formation. The fluid flows upwards through tubing to the wellhead once it reaches the bottom hole. To reduce heat transmission between the fluid in the tubing and the fluid in the annulus, the tubing is always thermally insulated. At the wellhead, return fluid will be collected, and heat will be gathered and used for various reasons. Figure 3.4 depicts the downhole constructions as well as the fluid flow path.

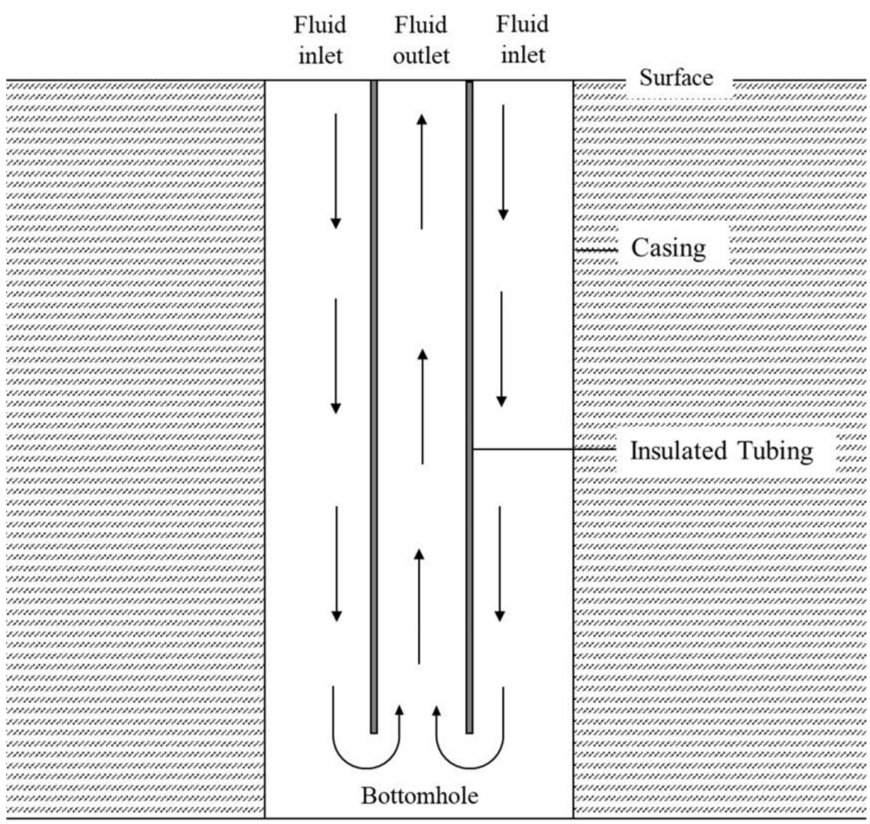


Figure 3.4: Schematic of a double pipe heat exchanger in an abandoned well [30].

In reality, the most frequent type of heat exchanger utilized to extract heat from shallow subsurface for space heating and cooling is the u-tube heat exchanger. Due to the advantages of double pipe heat exchangers in terms of heat exchange efficiency, pumping energy savings, and grout usage, recent research has begun to shift emphasis to them in the literature. When compared to u-tube heat exchangers, double pipe heat exchangers have a bigger surface area for heat exchange and contain a larger volume of fluid through which heat can be exchanged. Fluid flow velocity with double pipe geometry may be lower at the same injection rate, requiring less hydraulic pressure to circulate the fluid, resulting in lower pumping energy consumption. In cased abandoned wells, a double pipe heat exchanger is a better option than a u-tube heat exchanger because the outer pipe (casing) is already existent, saving money and time. Finally, the double pipe heat exchanger's coaxial shape offers the advantage of lowering the thermal resistance between the flowing fluid and the wellbore.

Scholars have used both u-tube and double pipe heat exchanger approaches to analyze the potential of geothermal output from abandoned wells. These studies developed several mathematical models to predict heat extraction, carried out case studies, and demonstrated the geothermal potential in abandoned wells. Although each case was unique, the literature has identified injection fluid temperature, injection rate, insulation type, bottomhole temperature, and fluid selection as important affecting parameters [31], [17].

3.2.5 Review of geothermal extraction methods

Unlike geothermal extraction from producing wells, where the generated water is dominated by oil production, heat extraction from abandoned wells is more manageable, with more flexibility in terms of injection fluid selection, injection rate, and injection fluid temperature. The operator may manage and control the entire geothermal extraction process because of this versatility.

Aside from the difference in manageability, the source of geothermal supply is the most important distinction between the two geothermal extraction processes. The active production well could provide generated water not only at a high temperature, but also at a suitable rate. As a result, the produced water might supply long-term geothermal energy input (in terms of volume and temperature) for power generation, in addition to the continuing oil production. The working fluid pumped into the abandoned well, on the other hand, is only heated during circulation in the wellbore, and while it could be managed to attain a temperature comparable to produced water, the flow rate is far from "competitive" with a producing well. The above distinction will result in comparable variances in geothermal consumption, which will be discussed in the next section [6].

3.3. Methods of Utilizing Oilfield Geothermal Resource

After the geothermal energy has been recovered and transported to the surface, the hot fluid will be sent to processing facilities for various uses depending on the temperature and flow rate. The major ways of oilfield geothermal usage are direct use (no energy conversion procedure) and power generation (thermal to electricity conversion), with an appropriate combined heat and power system also discussed in this topic [6].

3.3.1 Geothermal direct use

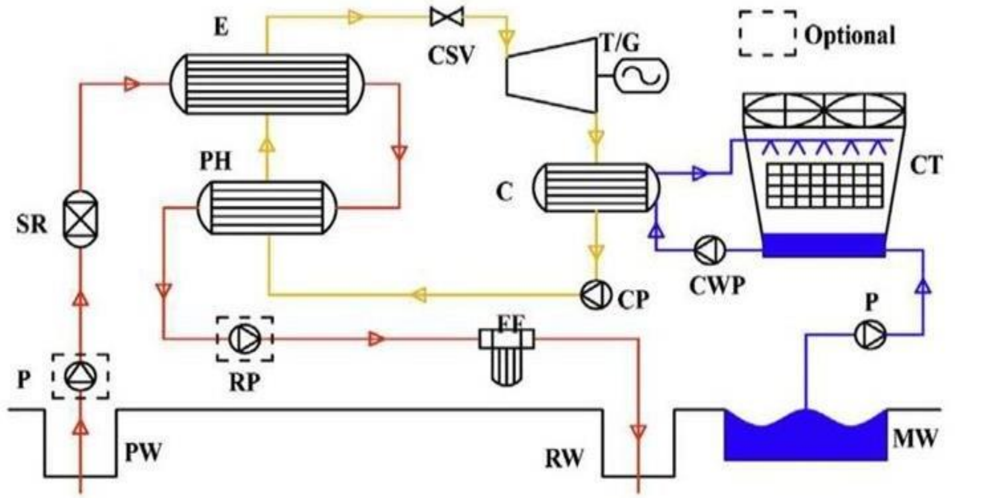
Since it has been widely used in more than 82 nations throughout the world for decades, direct use of geothermal resources is likely the oldest and most diverse utilization. There are two types of direct geothermal energy use in oilfields. One is classic direct-use applications, including as building heating, greenhouse planting, crop drying, and a variety of industrial activities. Special oilfield uses, such as oil collecting heat tracing, crude oil transportation, and geothermal water flooding, are the other options.

Hot fluid circulation is commonly used for crude oil gathering and transportation by burning oil and gas to lower the viscosity of crude oil. Warm fluid might be poured into the pipeline's heat-trace pipe, which would be surrounded by insulation. Produced water could be used for crude oil heat tracing at mature oilfields where enormous amounts of hot water are produced. Geothermally heated water could replace oil/gas-burning heated water, saving a lot of fresh water and lowering crude oil transportation costs.

Flooding using geothermal water is a common oilfield geothermal direct application, particularly for heavy oil increased recovery. Hot water flooding has been shown to reduce oil viscosity and mobility ratio, hence improving final oil recovery. Currently, water is heated by burning oil or using electricity, both of which have substantial operating costs. In comparison to traditional hot water flooding, geothermal water flooding may successfully transport heat from deeper aquifers to shallower oil deposits using the "deep production and shallow injection" approach in the same well. Experimental and statistical studies of geothermal waterflooding revealed a 4 percent -10 percent recovery improvement over conventional water flooding. Furthermore, in order to avoid formation damage when executing geothermal water flooding projects, the injection rate and temperature must be carefully designed, as discussed in the next section. In general, geothermal water flooding is not just a way to harness geothermal energy, but it's also a good way to boost oil recovery [32].

3.3.2. Geothermal power generation

Because oilfield geothermal energy is classified as intermediate to low-temperature geothermal energy, binary cycle Organic Rankine Cycle (ORC) generation is typically employed to generate oilfield geothermal power. The use of low to moderate temperature geothermal fluids in binary power generation is a well-established technology. Figure 3.5 shows how electricity is generated by a binary that transports heat from a hot fluid to a secondary fluid that vaporizes at a lower temperature and higher pressure, and the vapor is then utilized to power a turbine. Due to the closed loop operation, binary power plants could reduce gas emissions while also expanding the spectrum of viable geothermal resources [33] .



PW	Production well	P	Pump	SR	Sand remover
E	Evaporator	PH	Pre-heater	C	Condenser
CP	Condensate pump	RP	Reinjection pump	FF	Final filter
CSV	Control / stop valve	T/G	Turbine / generator	CWP	Cooling water pump
CT	Cooling tower	RW	Reinjection well	MW	Make-up water

Figure 3.5: The schematic of a basic binary geothermal power plant [33]

3.3.3. Adapted Combined heat and power (CHP) systems

Only 10% of the energy from the produced geothermal fluid can be converted to electricity in geothermal power plants,leaving residual thermal energy in the discharged water, which is frequently referred to as waste heat. CHP systems, which combine electricity generation with heat delivery to a neighboring district heating system, are one type of distribution energy system that could offer an effective approach to use waste heat energy from a power plant for building heating.

An adapted CHP system could give an integrity solution of geothermal power generation and direct use for oilfield applications. An oilfield-specific CHP system that includes a binary power plant for power generation and a series of heat recovery units to process discharged water for direct usage. A portion of the generated electricity could be used to meet the system's demand, while the rest is fed back into the grid. The heat recovered from discharged water could be used for local space heating as well as harvesting and transporting crude oil [34].

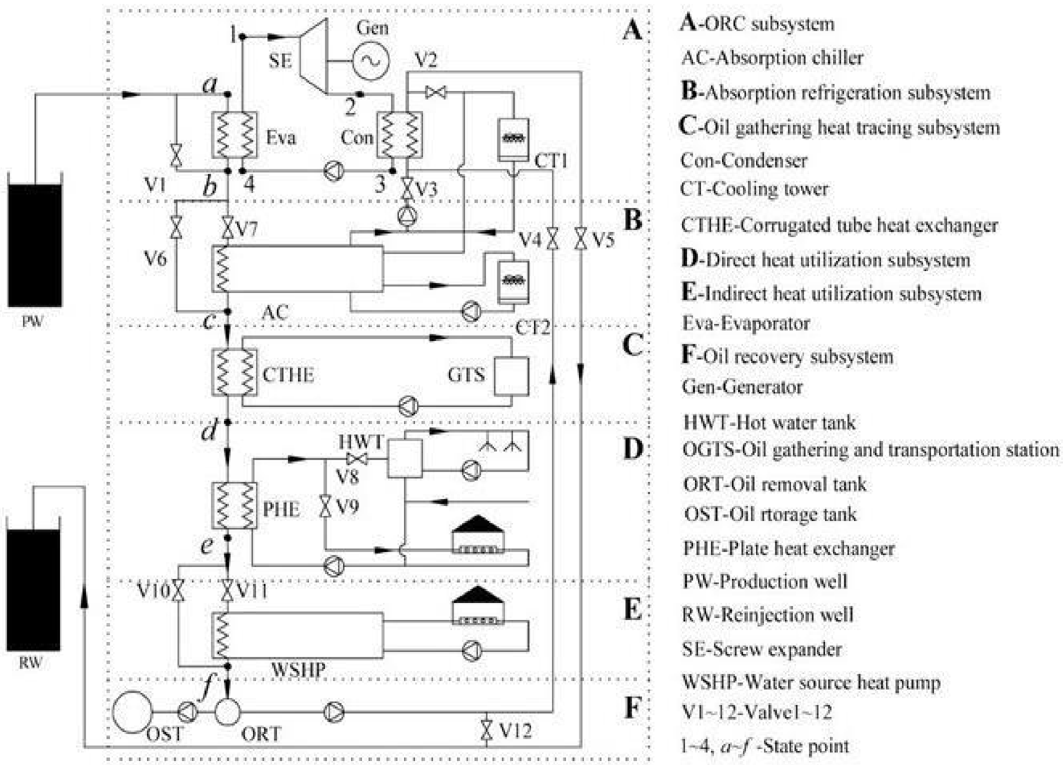


Figure 3.6: Schematic diagram of the adapted CHP system [34]

A case study in a Chinese oilfield to demonstrate the adaptable CHP system's promising potential. The system produced 569kW of net electricity, enough to heat twenty 5000-square-meter residential structures and provide domestic hot water to almost 8000 people. The complete geothermal system's payback time is only about 0.8 years, which is very appealing in engineering applications.

To summarize, linked resource temperature and flow rate are commonly used to identify oilfield geothermal utilizations. In order to meet the demand of energy conversion, power generating always requires a greater temperature as well as a higher flow rate than direct utilizations. However, there is no clear distinction between these two sorts of usages in terms of temperature or flow rate. Direct utilizations may also occur at greater temperatures and at a higher flow rate. Geothermal power generation and direct usage can be coupled by an appropriate CHP system to optimize energy efficiency and maximize thermal recovery [35].

3.4. Current Development of Oilfield Geothermal Utilization

Following a discussion of the enormous reserve, unique advantages, and ways of extracting and utilizing oilfield geothermal resources, notable advancements in global oilfield geothermal utilizations are emphasized [6].

3.4.1. Oilfield geothermal direct utilization

Geothermal energy collected from oilfields is reported from a number of countries in various parts of the world as part of the overall global geothermal direct utilizations. Austria has been using abandoned oil exploration wells to produce thermal waters, which are used in spa resorts, since the 1970s. Albania, likewise, uses its low-temperature geothermal resource (up to 65°C) from abandoned wells to heat greenhouses. In the Algy oilfield in Hungary, geothermal water is used for thermal water flooding for secondary oil production technologies. Another application of geothermal water is the heating of collection pipelines in the heavy oil producing oilfield Sávoly in Hungary's southwest.

Since 2002, a local house heating station supplied by oilfield geothermal water has benefited Furong residential area in Shengli Oilfield, which is located in northeast China. In sum, geothermal heating has saved up to 10.3 EJ energy in this residential area, which is comparable to 3 10 4 t of normal coal and 2 10 4 ton of oil, and has decreased CO2 emissions by 9.8 10 4 ton Geothermal space heating employing moderate formation depths (200–3000 m) accounted for 40 106 m2, or 40% of China's total geothermal heating area, replacing 1.2 106 tons of standard coal per year and reducing 3 106 tons of CO2 emissions.

Geothermal water from oilfields is also used in China for heat-trace oil collecting and crude oil transportation. Two abandoned wells in the Huabei Oilfield have been rebuilt to produce geothermal water at 600m^3/day and 100-110°C for heat-tracing collecting and transportation, saving around 5 tons of oil and 3500 m3 of gas per day.

Table 2 outlines global oilfield geothermal direct utilization projects, and we can see from the table that projects were carried out in both producing and abandoned wells. By utilizing mature geothermal direct use technology and techniques, general direct utilizations of oilfield geothermal resources have been successfully and widely implemented [20].

3.5. Challenges in Oilfield Geothermal Resource Development

Despite the fact that oilfield geothermal resources are garnering more attention and have seen significant development, there are still constraints that limit their rapid and further development. Low energy conversion efficiency, insufficient involvement, inadequate evaluation and planning, rules and regulations, and other issues are recognized as important reasons restricting oilfield geothermal energy exploitation and usage [21].

3.5.1 Low conversion efficiency

The low efficiency of power generation, especially for low to medium temperature geothermal resources, is the most significant technical barrier to geothermal energy utilization. Geothermal power generation will be less competitive than other forms of power generating, such as coal, natural gas, oil, and nuclear power plants, due to its low conversion efficiency.

Oilfield Location	Geothermal Resource	Type of Utilizations	Remarks	Reference
Albania	Abandoned Wells	Greenhouse Heating	Geothermal water (up to 65.5°C) was used for greenhouse heating	Lund and Boyd (2016)
Styria, Austria	Abandoned Wells	Spa Resorts	Geothermal waters that were used at the spa resorts Loipersdorf and Waltersdorf	
Algyő, Hungary	Produced water	Geothermal Water EOR	Geothermal water has been used for thermal waterflooding since 1969	
Sávoly, Hungary	Produced water	Heat-trace Oil Gathering	Geothermal water was used to heat the gathering pipe in Sávoly	
Shengli, China	Abandoned wells	Spacing Heating	Space heating in Furong area saved 3×10^{4} t of standard coal and 2×10^{4} ton of oil from 2002 to 2015	Liu et al., 2015
Daqing, China	Produced water	Spacing Heating Crude Oil Transportation	5 projects replaced 7000-ton standard coal per year	Wang et al., 2016
Liaohe, China	Produced Water	Spacing Heating	12 projects replaced 24400-ton standard coal per year	
Huabei, China	Abandoned Wells	Heat-tracing Oil Gathering	Geothermal oil gathering from 2 abandoned well save about 5 ton of oil and 3500 m3 of gas every day	
Zhongyuan, China	Produced Water	Spacing Heating	One project saved 2537 ton of standard coal per year	

Table 2 Summary of worldwide oilfield geothermal direct utilization projects [6]

Furthermore, as one of the most important methods of oilfield geothermal production, power generation employing coproduced water may pose a risk of worsening power generating performance and economic competitiveness. First, as the field develops, the dynamics of coproduced water rate and temperature may change. Power generating performance will be harmed if coproduced water does not provide enough heat. Second, coproduced water may cause scaling and corrosion issues in heat exchangers, increasing maintenance costs and lowering heat exchanger efficiency, lowering power production and decreasing economic competitiveness [21]

3.5.2 Insufficient involvement, Assessment and Planning

Oilfield geothermal exploitation and utilization has fewer activities than oil and gas exploration and production and typical geothermal field development, slowing the expansion of oilfield geothermal usage. Deepening oilfield geothermal resource exploration, appraisal, and development should be prioritized in scientific and technology research. In exchange, the researchers' advancements in oilfield geothermal development would attract and encourage additional participation, perhaps creating a virtuous circle and boosting the oilfield geothermal business even further.

The geothermal potential of hydrocarbon reservoirs has been well assessed in some areas and oilfields, such as Texas, the Michigan and Illinois Basins in the United States, Daqing Oilfield, and the Bohai Bay Basin in China. However, many locations and oilfields around the world still haven't had their geothermal potential analyzed in a systematic and complete manner. In the meantime, present oilfield geothermal operators are still trying to produce geothermal resources from their own wells. A long-term plan and logical flowchart for developing large-scale geothermal resources are still in the works. Accurate assessment and planning will aid geothermal producers in making the best decisions possible at each stage of the development process, resulting in the most economic and social value. On the contrary, a lack of understanding of geothermal resources severely restricts their exploration, development, and utilization [6]

3.5.3 Laws and regulations

Oilfield geothermal development is cheaper than solar and nuclear, equivalent to wind, but more expensive than coal and natural gas. In essence, the oilfield geothermal sector is a relatively new industry with poor earnings. Although governments have implemented incentive programs, industrial policies, finance and tax policies, and other areas should be more specific, specialized, advantageous, and comprehensive in order to further stimulate and finally support vigorous development.

To be more particular, laws and regulations should be devised that are tailored to the special characteristics of oilfield geothermal resources. Regulations should protect ownership interests in the most cost-effective way possible. Regulations should be put in place to ensure that geothermal resources are extracted in a sustainable manner, both environmentally and socially. A regulation based on these considerations will not only encourage the use and production of geothermal heat, but will also ensure that these resources stay viable and sustainable for a long period [6].

3.5.4. Formation damage induced during geothermal energy extraction

The in-situ thermal-chemical balance is disrupted by lower reservoir temperatures, which also introduces mechanical formation damage processes in the subsurface. To develop oilfield geothermal resources, sufficient high rates of fluid circulation are required to ensure that geothermal systems may be economically exploited. High flowing rates and a wide range of temperature distributions, on the other hand, can cause a large drop in well injectivity and productivity by exaggerating clay particle movement and clogging, as well as permeability impairment.The physic-chemical characteristics of clay particles, fluid pH and salinity, temperature, water film (adsorption water and osmosis water), and fluid flowing rates are the key influencing elements on the migration and clogging of clay particles. As a result, fines migration-induced formation damage must be assessed and quantified as part of the feasibility analysis for oilfield geothermal projects.

Furthermore, temperature-dependent rock properties, such as rock storability, electrical conductivity, seismic properties, and properties of in-situ fractures in reservoirs, have a significant impact on heat recovery in oilfield geothermal development.In geothermal extraction, permeability impairment on inflow performance of oils/gas wells can have major negative consequences. [16]

3.5.5. Other problems

Direct use and power generation may be affected by the location of geothermal production wells and power plants. Long distances from wells to power plant and high demand areas will limit the direct use of geothermal fluid and power generation, with the exception of those wells where geothermal energy is used nearby in the form of heating oil tanks or power wellsite equipment. The majority of wells are found in low-density residential areas with modest demand for heating and electricity. As a result, long-distance transmission could raise operating costs, making geothermal energy less cost-effective. As a result, additional attention should be paid to candidate well selection.

The abandoned wells present another possible hazard. Some wells may have been abandoned for years with a high risk of malfunctioning after being re-engineered for geothermal production, such as failure in double pipe installation, loss of casing integrity, and wellhead malfunction, which could result in increased nonproduction time and geothermal utilization suspension. As a result, before retrofitting selected wells for geothermal production, thorough inspections should be performed, as well as routine maintenance after production [6].

4. Analysis of a case study in Italy.

4.1. Introduction

The physicochemical features of geothermal fluids are incompatible with terrestrial ecosystems. As a result, they should be treated and injected back into the earth. Because these procedures include the drilling and maintenance of additional wells, as well as the treatment and pumping of fluids, they have considerable economic expenses [8].

The WellBore Heat Exchanger, an indirect heat extraction technology, is a feasible alternative (WBHX). This type of well completion allows heat to be extracted by circulating a heat carrier fluid in a closed loop. As a result, no geothermal fluids are produced, and the environmental effect as well as the energy required for reinjection are greatly decreased. Corrosion and scale issues are also kept at bay. The heat recovery efficiency could be reduced, which would be a disadvantage.

The use of oil wells for the application of the WBHX is supported by the reduction of oil field abandonment costs and the improvement of the geothermal plant's economic feasibility by avoiding drilling expenditures (50 percent of total costs of the project).

Based on these factors, the WBHX implementation on one of Europe's largest oil fields-Villafortuna Trecate oilfield has been assessed in reference [8], which has been operational since 1984. The reservoir, which is located between 5800 and 6100 meters deep and has a temperature of around 160-170 degrees Celsius, is classified as a medium enthalpy geothermal resource. Although the Villafortuna-Trecate field continues to produce, it is significantly depleted. Only 8 wells have been drilled and are now producing [9].

Two heat transfer fluids were used in the simulations[8]: water and diathermic oil, which has never been used in this type of application before. It was also changed the internal diameter of the pipes until a configuration was found that ensured better heat extraction efficiency.

Figure 4.1 shows the WBHX's schematic layout as well as a cross-section. In the considered configuration of WBHX, the well's bottom will be sealed, and a dual-shell coaxial tube will be installed. In the annular gap between the well casing and the exterior shell, the heat carrier fluid enters the wellbore heat exchanger. The fluid absorbs heat from the surrounding ground as it flows downward. The fluid is diverted upward at the bottom end and flows into an internal conduit that leads to the wellhead. To limit heat transfer between upward and downward flow, the gap between the two pipes is filled with insulating material.

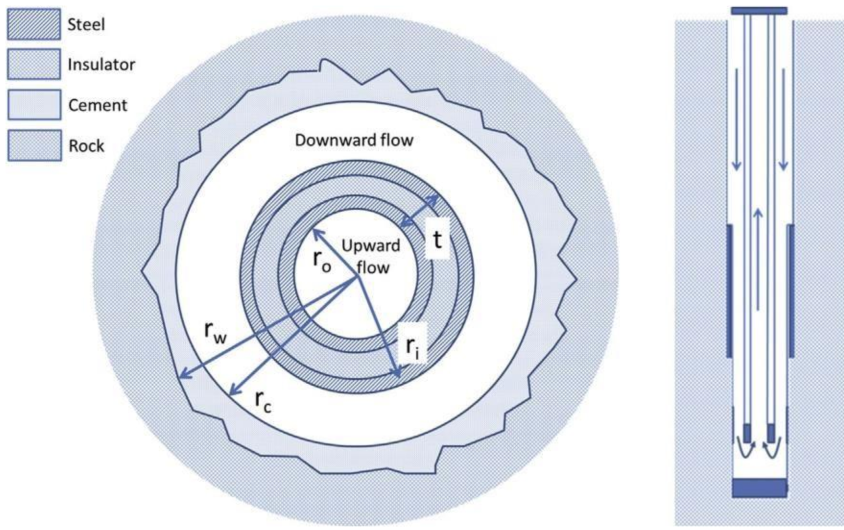


Fig. 4.1: Wellbore heat exchanger. Cross section and schematic [8]

As mentioned in previous research, the produced thermal energy can be employed in district heating plants or transformed into electricity utilizing an Organic Ranking Cycle (ORC) plant) [14]. Besides, other researchers [15] have worked on converting thermal energy into electricity using a direct power generation device.

4.2. Wellbore heat exchanger model

The WBHX model described in reference [8] and reported below is based on the following assumptions: heat is transferred to the reservoir rock through conduction, and heat is transferred to the fluid flowing through the tubes through conduction and convection. The WBHX heat transfer model was established based on the differences in behavior between the downward and upward pipes [8].

4.2.1 Heat transfer in the pipe system

The fluid in the downward pipe comes into direct touch with the borehole wall on the outside. This is made out of steel casing that is anchored to the rock face. The annular space between each pair of casings is filled with a finishing fluid or cement. As a result, it is thought that heat is transferred via conduction from the reservoir rock to the borehole wall, and by convection between the wall and the fluid. Convection into the reservoir rock is not taken into account.

The fluid is in contact with the internal tube on the downward pipe's interior side. Conduction through the pipe and convection between the wall and the fluid are the primary modes of heat transfer between the two pipes.

In the WBHX, the heat flux from the rock to the fluid is given as [8]:

$$Q_{down} = 2\pi r_w k_t (T_w(z) - T_{f,down})\Delta z \quad (1)$$

Where :

- r_w external radius of the borehole
- k_t is the total heat exchange coefficient
- T_w is the rock temperature at depth z
- $T_{f,down}$ is the temperature of the fluid in the outer pipe
- D_z Is the length of the pipe

The sum of heat transfer components yields the total heat exchange coefficient kt. In terms of heat resistance, it is possible to write [8] :

$$R_t = R_a + R_c + R_s \qquad (2)$$

where:

R_a is the thermal resistance due to the heat transfer by convection into the pipe;

R_c is the thermal resistance due to the heat transfer by conduction through the casings of the well completion;

R_s is the thermal resistance due to the heat transfer by conduction the rock and it is a function of time.

In calculating total thermal resistance, the conductive term takes precedence. As a result, the convective transfer coefficient is directly proportional to the heat exchange.

The heat transfer into the rock is modeled using an analytical solution of the Fourier equation of heat transport. The radius of the well's thermal impact grows with time and can be calculated using the relationship [11]

$$r_s = 2\sqrt{a_s(t')} \qquad (3)$$

- t' is the elapsed time since the start
- a_s is the thermal diffusivity of rock equal to $a_s = \lambda/\rho c_p$

4.2.2. Upward pipe

The heated fluid enters the internal pipe at the bottom of the well. Heat is transferred only through the pipe wall as it ascends to the wellhead.

The heat flow is described by the following equation[8]**:**

$$Q_{up} = 2\pi r_o k_o (T_{f,up} - T_{f,down})\Delta z \qquad (4)$$

Where:

- r_o is the radius of the inner tube
- k_o is the overall heat transfer coefficient
- $T_{f,up}$ is the temperature of the fluid in the inner pipe
- $T_{f,down}$ is the temperature of the fluid in the outer pipe
- D_z is the length of the pipe

A conductive component through the composite pipe and two convective components, one on the internal wall and one on the external wall of the WBHX, combine to generate the overall heat flux. The total heat exchange coefficient, ko, is expressed as[8]:

$$\frac{1}{k_o} = \frac{r_o}{r_o + t} \cdot \frac{1}{h_i} + r_o \sum_{i=1}^{n} \ln\left(\frac{r_{i+1}}{r_i}\right) \cdot \frac{1}{\lambda_i} + \frac{1}{h_o} \qquad (5)$$

Where:

- r_o is the radius of the inner tube
- t is the thickness of the pipe exchanger
- h_o is the coefficient of the convective heat transfer to the inner wall
- h_i is the coefficient of the convective heat transfer to the outer wall
- λ_i is the thermal conductivity of the material (air and steel)

4.2.3. Initial conditions

The temperature of the rock at the general depth z is supposed to be influenced by the local geothermal gradient GT in the following way:

$$T_w(z) = T_o + GT \cdot z \qquad (6)$$

where T_o denotes the average temperature at the ground level. [8]

4.3. Discussions

The simulations and, consequently, the results obtained by reference [8] by means the application of the above-described model considered two different heat transfer fluids: water and diathermic oil, which has never been used in this type of application before.

Different configurations were investigated, progressively adjusting the inner and outer pipe widths, in order to determine the more efficient WBHX device design. The fluid's velocity is influenced by its diameter. Because convective exchange is dominant, if the velocity is too low, the heat gained by the fluid in the downhill pipe is lost in the upward pipe. Indeed, if the fluid moves too quickly, there is insufficient time to fulfill the thermal exchange between the rocks and the fluid, resulting in a lower exit temperature.

The ideal arrangement results the one that maximizes the heat flow and reduces the amount of energy required for circulation.According to simulation data, the optimal configuration is attained with a big annulus, increasing the diameter of the well (D_w). Because wellbore already exists, this option cannot be used, and the exterior diameter cannot be altered.

Concerning the inner pipe, the results reveal that a smaller diameter increases heat flow; however, the need for pump energy increases due to larger pressure losses in the pipe. As a result, an optimal geometry of the dual shell tube based on well completion literature data has been defined [8].

4.3.1. WBHX analysis

Based on this design and the assumption that the characteristics of rocks are uniform with depth (λ 2.5 W/m K, ρ_s 2600 kg/m3 and c_p 800 J/kg K) and a heat carrier fluid input temperature of 40 C, the exit temperature as a function of fluid flowrate was estimated [8] .

The first scenario considers fluid properties that are unaffected by temperature. Figure 4.2 depicts the rock temperature vs depth as well as the fluid temperature in the downward and upward tubes. Water is the fluid, and the flowrate is 10 m^3/h. For the first 1000 meters of the downhill pipe, the fluid cools. The temperature rises as it begins to absorb heat. The fluid has low heat losses (less than 20 ˚C) in the upper pipe.

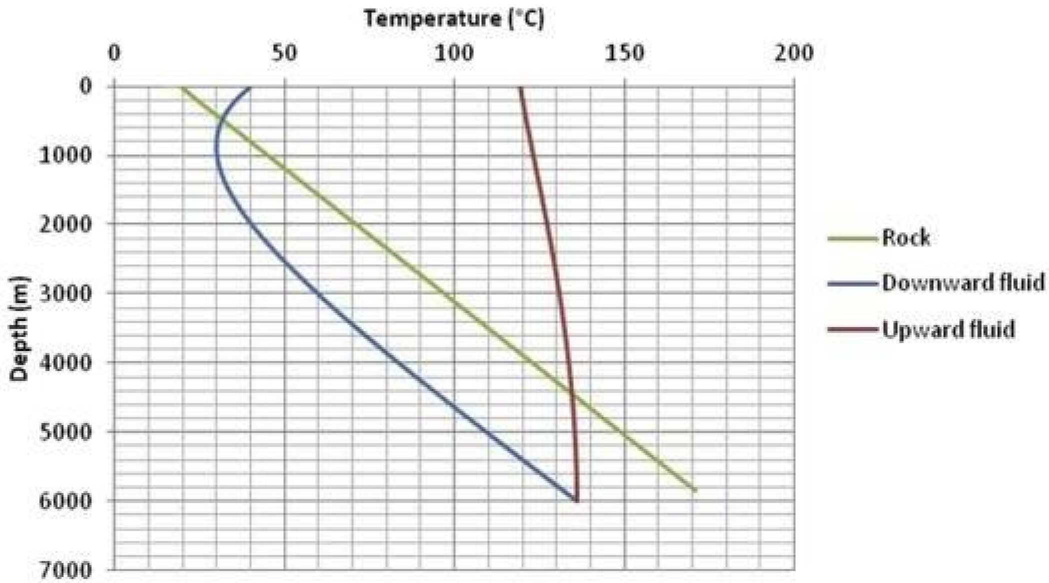


Fig.4.2: Fluid and rock temperature versus depth (flowrate 10 m3/h) (water case) [8]

Figure 4.3 depicts the wellhead temperature vs. flowrate for the two heat carrier fluids. The results for constant characteristics reveal that at a flowrate of 6 m^3/h, the wellhead temperature reaches a maximum of roughly 120 C˚ for water, then drops as the flow rate increases. An extremely low flowrate (1 m^3/h) causes the diathermic oil to cool to 40 C˚. When the flowrate is less than 10 m^3/h, the oil temperature is lower than the water temperature; when the flowrate is greater than 10 m^3/h, the tendency reverses and the oil temperature is higher than the water temperature. The temperature behavior is corroborated for the variable fluid characteristics scenario; the simulation results show a higher temperature for both heat carrier fluids.

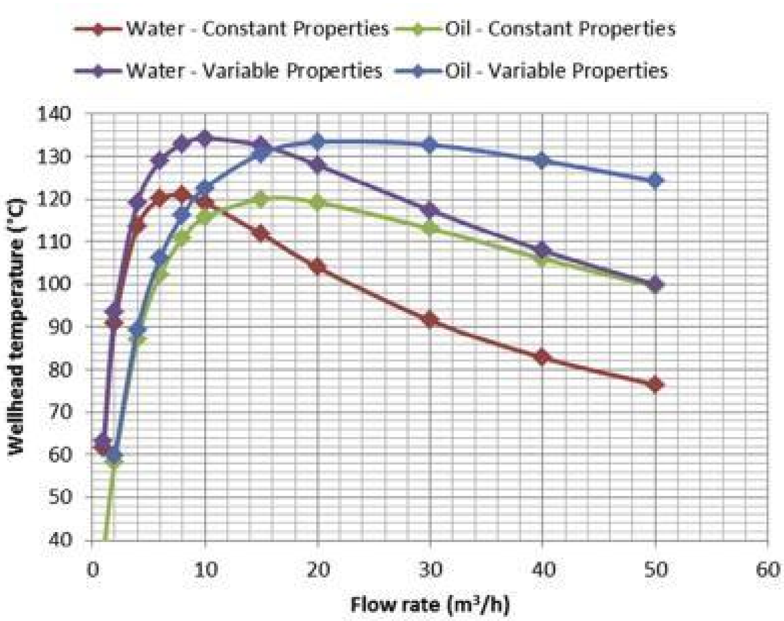


Fig. 4.3: Wellhead temperature vs. flowrate [8]

The heat flux comparison shows that diathermic oil has lower values than water (Fig. 4.4). This behavior is caused by heat flow, which is directly proportional to the volumetric heat capacity value (ρc_p). Water has been demonstrated by the work of Melinder that it has higher thermal conductivity and volumetric heat capacity values than the fluids commonly utilized as secondary working fluids. Until the flowrate reaches 10 m^3/h, the thermal power taken by the water increases fast, reaching 920 kW. The heat flux then gradually but monotonically increases with the flowrate. In terms of power, the heat flux for the variable properties scenario reaches 3 MW [18].

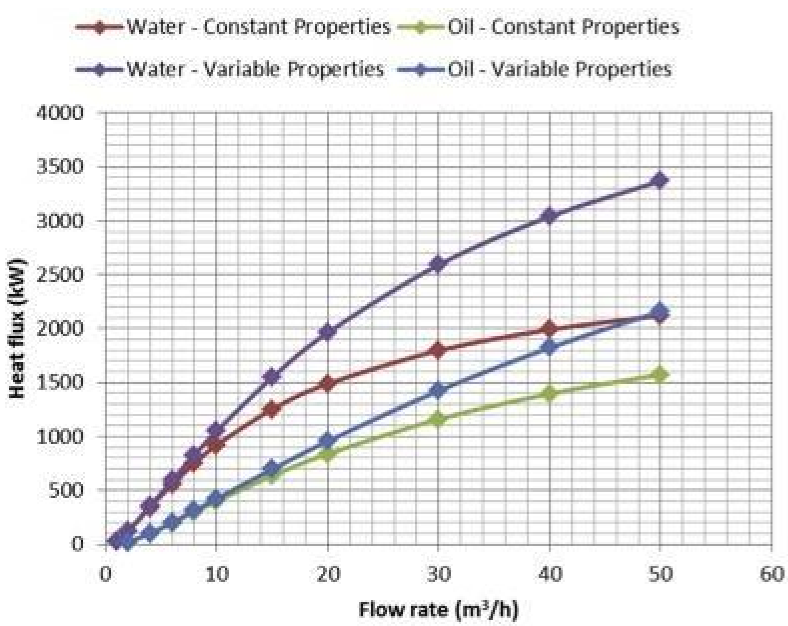


Fig. 4.4. Heat flux vs. flowrate [8]

4.4. Results

By applying Wellbore Heat Exchanger model proposed by [8] it is possible to analyse geothermal heat extraction amount without the production of geothermal fluids possible, then minimizing the energy for reinjection and environmental effect. Problems such as corrosion and scaling are not present, due to no direct contact of fluids with formation: this aspects represents one of the most important advantage of this type of technology.

The heat obtained from this process was used for electrical energy production with ORC plant. Two working fluids were tested: water and diathermic oil. Parameters including heat flow obtained from single well,bottom-well temperature and electrical power were also defined. Water turned out to be more efficient in heat transfer and thermal power production,while diathermic oil was able to reach higher temperature than water.

The authors emphasize the need of taking into account changes in fluid characteristics inside the exchanger, particularly when calculating net electrical power.

The available electrical power is inferior to that of traditional geothermal power plants, which is a flaw in the WBHX technology. Instead, the possibility of using thermal energy in a district heating plant should be preferred. [8]

5.Analysis of a case study in USA.

5.1. Introduction

The focus of the research proposed by [12] is to look into the possibility of capturing geothermal energy from abandoned oil and gas wells in California. According to the California Department of Conservation's Division of Oil and Gas and Geothermal Resources, there are now 147,127 abandoned, plugged, buried, and/or inactive wells. There are 5184 unused wells in Santa Barbara County alone. The majority of the wells were stopped due to a drop in oil and gas production, while others were exploratory. Existing wells in both circumstances give useful subsurface data such as lithology, temperature, and formation porosity. It was demonstrated that by reference [19] in 2003, wells dug to a depth of 5 kilometers cost around $5 million apiece. Given that drilling costs account for 42 percent to 95 percent of the entire cost of an Enhanced Geothermal System (EGS) power plant, pre-drilled and extended abandoned wells could be tremendously valuable.

Traditional geothermal heat extraction has taken place at sites with hydrogeological anomalies, but recent improvements in engineering have allowed for the development of alternative methods such as EGS and borehole heat exchangers (BHE). Both EGS and BHE harvest Earth's heat without the location restrictions that hydrothermal systems have. By increasing in-situ permeability and capturing heat from hot rock geo-reservoirs, EGS generates electrical energy. The injection and permeation of cold fluid through hot rock are used to extract crystalline heat. Heat is transported from the rock to the fluid and then recovered via a production well. Hydraulic fracturing of continuous rock masses or hydroshearing of existing fractures in the rock are used to connect injection and production wells. Fluid flow rate and temperature are the two most critical elements that determine the feasibility of an EGS. Existing EGS have flow rates and temperatures ranging from 15 to 430 l/s and 40 to 250 C, with higher values supporting power generation and lower values supporting direct hot water consumption. Georeservoir permeability stimulation can boost EGS flow rates, but temperatures can only be raised by drilling deeper into the Earth's crust. The temperature in the crust is affected by crustal heat flux, which increases with depth, the existence of insulating rock layers, and the presence of magma chambers. Unlike EGS, BHEs extract geothermal energy without allowing the working fluid to come into touch with the soil or rock. Instead, BHEs circulate working fluid through pipes buried in the subsurface while exchanging heat energy with the earth, using various closed-loop topologies. Shallow BHEs stretch 50-200 m into the soil and are typically used in conjunction with Ground Source Heat Pumps (GSHP) to use the subsurface as a thermal source/sink for residential and business heating and cooling in the winter and summer [20]. Although they operate at depths of 1000–3000 m where rock temperatures can approach 85 C˚ and raw generated fluid temperatures range from 20–55 C˚, deep BHEs use the same concepts as shallow BHEs. The production fluid temperature of a deep BHE is highly dependent on crustal heat flow, much like EGS. In contrast to EGS, the efficiency of deep BHEs depends on the design of the heat exchanger and the thermal characteristics of the host rock rather than hydraulic characteristics like porosity and permeability. In fact, the design and cost of the heat exchanger insulation may determine the viability of a deep BHE project [13].

Prospecting methods, drilling technologies, reservoir technologies, energy prices in the region, resource life, and other factors all affect the economic sustainability of EGS and deep BHEs. Prospecting and drilling risks are reduced by reusing abandoned wells, but the other aspects require further investigation. Because of changes in fluid motion, pore pressures, and cementation/crystallization, fracture network stimulation in a sedimentary reservoir requires different approaches than a similar network design in an igneous reservoir. While the economic viability of EGS is still being researched, deep BHEs are derived from well-known shallow BHE technology [20]. Deep BHEs' economic viability is nearly entirely dependent on comparable regional energy costs without reliance on unreliable fracture networks. The same study found that, in some situations, sealing an abandoned well is more expensive than upgrading it for thermal extraction. Furthermore, because the efficiency of the deep coaxial BHE is dependent on the continuity of the cement in the casing-rock annulus, it can be used as a "kept" plug for abandoned wells [13].

The goal of this research is to define if EGS and deep BHE installations in abandoned wells in California are feasible. Many current wells in California could be deepened beyond 2000 meters to create energy by utilizing >100 C˚ sandstone and shale rock, based on known data regarding crustal heat movement with depth. Lower temperature fluids (20-40 C˚) can also be used directly for recreational, industrial, agricultural, and residential uses. For the range of well depths and crustal thermal gradients encountered in Santa Barbara, Santa Clara, and Monterey, a physics-based mathematical model is developed. The deep BHE model's purpose is to calculate the required abandoned well depths and thermal gradients for 40 C˚ production fluid temperatures [12].

5.2. California abandoned wells characteristics.

A well that has been abandoned is one that has been used indefinitely. Well-plugging is a popular practice that reduces the risks of ground water contamination, ground water comingling, aquifer pressure head loss, and uncontrolled gas migration that come with unplugged abandoned wells.

The amount of formation consolidation, the water table level, and the presence of oil all influence plugging recommendations. Newer plugging standards require shoveling a mixture of sand, clay, and neat cement grouts into the well to make an impermeable plug [22]. California plugging standards call for a 15-meter-long cement plug at the surface, 30-meter-long cement plugs above oil bearing strata, and 15-meter-long cement plugs above and below water bearing strata. Brush, wood, boulders, paper, and other materials may have been used to plug older wells (1850s spud dates) according to informal standards. The cement plugs, whether old or new, can be simply removed by using a particular drill rig to break up and remove the well cement/debris [12].

5.2.1. Crustal heat flow

Numerous studies [24] have documented the crustal heat flow of California, as seen in Fig.5.1. Geothermal anomalies in Imperial County (Salton Sea, >100 mW/m^2), up north in Sonoma (Geysers, 300 mW/m^2), and central east California in Inyo County (Coso, >100 mW/m^2) are connected with the largest crustal heat flows. In the counties of Santa Clara, South Monterey, and North Santa Barbara, crustal heat flows are moderately high (avg 14 84 mW/m^2). In San Bernardino County, Lachenbruch et al. identified dispersed regions of heat fluxes >100 mW/m^2.

Because of the extraordinarily high subsurface temperature gradients and the occurrence of hydrothermal anomalies, many of Imperial County's abandoned wells are focused on geothermal investigation south of the Salton Sea. Thermal gradients of 5.5 to 8.2 C ˚/100 m were recorded by Sass et al. for shallow depths (300 m). According to one abandoned well report, the thermal gradient fluctuated up to 18.2 C ˚/100 m, with a bottom hole temperature of 220 C ˚ at 2440 m. Both the Geysers and Coso geothermal sites, like Imperial County, have temperatures above 200 degrees Celsius. The low number of abandoned oil and gas wells in the Geysers, Coso, and Imperial counties, however, excludes them from the scope of this study; however, any abandoned well (geothermal or oil/gas) in these areas may be equally viable for well reuse if the bottom hole temperature remains above 40 degrees Celsius.

The coastal regions of Santa Clara (and neighboring counties San Mateo and Santa Cruz), South Monterey, and North Santa Barbara are characterized by medium to high heat flows and a plethora of abandoned oil and gas wells. In Santa Clara (Sunnyvale), Sass et al. measured various shallow (300 m) thermal gradients and reported an average thermal gradient of 5.8 C˚/100 m.

Due to insulating lithological phases, the temperature gradient may even reach greater values, but assuming the thermal gradient remains constant at 5.8 C˚ /100 m, a 1220 m deep well in Santa Clara county should meet 70 C˚ rock. The well's depth can be increased by 1000 m, resulting in 130 C˚ rock.

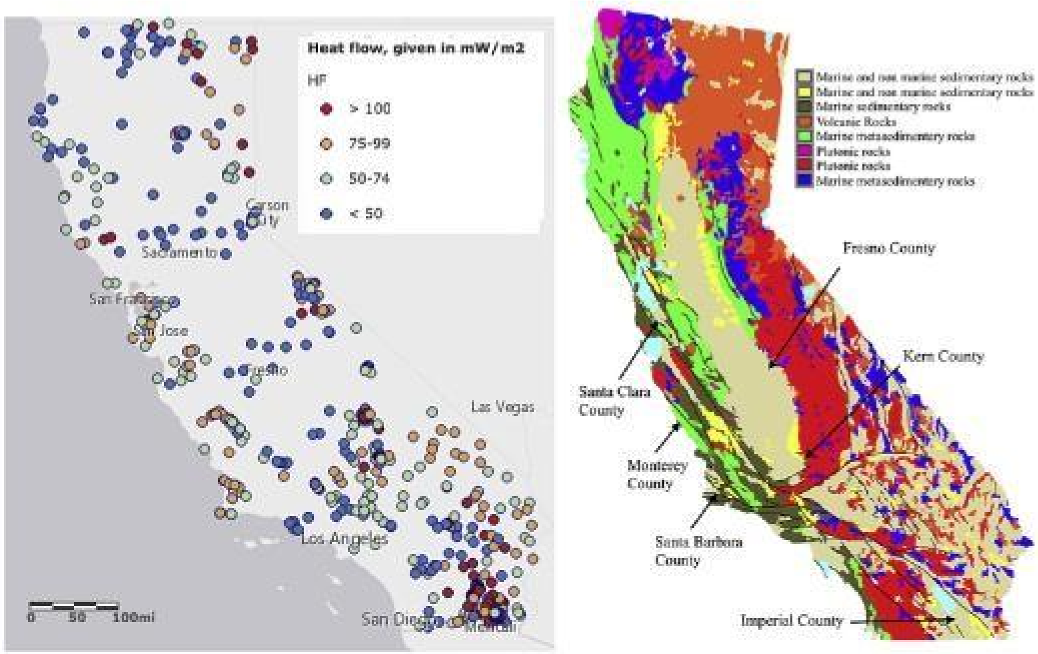


Fig 5.1: Crustal heat flow map of California (created using publically available data and arcgis.com) (left) and California Geology and counties of interest (created using publically available geological map of California) (right) [24]

Despite the fact that available temperature surveys are vulnerable to error due to the range of methods utilized, abandoned wells in any of the coastal counties could provide access to crustal temperatures ranging from 48 to 93 C˚ without the need for further well deepening. Deepening existing wells by 1000 meters will likely provide access to rock temperatures above 100 degrees Celsius, allowing for the production of electrical energy [12].

5.2.2. Geology

The geology of the geo-reservoir is another key feature of EGS. The permeability of the rock must be low enough to prevent fluid loss while yet being high enough for the working fluid to move through the rock quickly enough to sustain required flow rates. Existing pilot EGS sites are aimed at igneous rock formations like granite, where fluid circulation through a heated crystalline rock mass is aided by hydraulic fracturing or shear displacement of an existing fracture network. Although increased permeability prevents sandstone and other sedimentary rocks from supporting the same type of fracture network, certain investigations have shown that sandstone may maintain high flow rates with minimum fluid loss. The presence of natural hydrothermal anomalies in sandstone formations and granitic plutons alike adds to the argument that sandstone is suitable for EGS. As a result, EGS may be suitable for controlling fluid migration in formations made up of sandstone layers with reduced porosities and permeability "caps."

The majority of California's abandoned wells target oil and gas-rich sandstones and shales. As a result, these wells are more likely to bore through and into marine sedimentary strata. Santa Clara County's geology includes moderately to weakly cemented marine and non-marine sedimentary rocks (Fig.5.1). The lithology of abandoned wells (including San Jose) is predominantly silty and sandy shales down to 1000 meters. At 850 meters, a well closer to the coast exposes 460 meters of shale overlying a 90 meters thick stratum of "Costa Sandstone." At these depths, indirect neutron porosity measurements estimate real formation porosity to be around 10% to 25%. Monterey's geology is similar to that of Santa Clara, but with more frequent alternating stages of sandstone, shale, and siltstone. The geology is described by CGS as loosely to moderately consolidated alluviums. These sandstone strata are 15 to 60 meters thick and have porosity levels of 10-15 percent. The occurrence of a granodiorite floor approximately 700 m deep for wells more than 5 km from the San Andreas fault is a distinctive feature of Monterey County geology. The geology in Santa Barbara, south of Monterey County, is described as the same coastal alluvial deposits with low to moderate consolidation (Fig. 5.1). Various wells in the area report alternating 15-60 m thick clay and shale strata. However, as illustrated in Fig.5.2, a significant geological change to sandstone occurs at about 850 m deep. Although many mud log records do not specify rock types beyond 1000 meters, the alternating sequences of sedimentary rock described above can be presumed to continue until basement, which is found at depths of 4 to 10 kilometers. Table 6 illustrates the rock formations encountered at 2000 meters and the maximum depth reached for each county's deepest well.

County	# Unused Wells[d]	Max well depth/ (average) (m)[d]	Temp Gradient (°C/100 m)	Heat Flow[e] (mW/m^2)	Rock type at 2 km (deepest well)[d]	Rock type at max depth (deepest well)[d]
Santa Clara	5184	2000/(550)	5.8 (avg)[a]	75–99	Sandstone poor cons.	Sandstone poor cons.
Monterey	2627	2900/(700)	4.0[b]	75–99	Chert well cons. or granodiorite	Sandstone mod. cons or granodiorite
Santa Barbara	6496	3900/(770)	4.9[c]–7.3[d]	75–99	Claystone mod. cons.	Shale well cons.
Kern	81,000	6600/(720)	2.0[g]–3.6[d]	50–75	Shale mod. cons.	Sandstone mod cons.
Fresno	8435	4900/(1120)	2.5[g]	50–75	Siltstone poor to mod. cons.	Igneous volcanic poor cons.
Los Angeles	2380	4250/(1800)	2.7[d]–5.5[f]	50–75	Shale well cons.	Sandstone well cons.
Ventura	8364	5000/(1580)	2.2[d]–3.5[f]	50–75	Sandstone and shale poor to mod. cons.	Sandstone well cons.

Table 3. Comparison of abandoned well characteristics in California counties[12]

To summarize, California's coastal and inland lithology, particularly the geological context at Monterey, may be suitable for EGS. A similar EGS configuration could be enabled by Monterey's low porosity sandstone formation underlain by a shallow granodiorite basement in combination with a medium to high heat flow. The Zimmermann and Reinicke project used hydraulic fractures extending from a crystalline basement up into the overlying sandstone formation to deliver water to the sandstone formation, where the water permeated the sandstone before reaching a production well [23]. Other counties are also on crystalline basements, although their depths range from 4 to 10 kilometers, requiring further investigation [12].

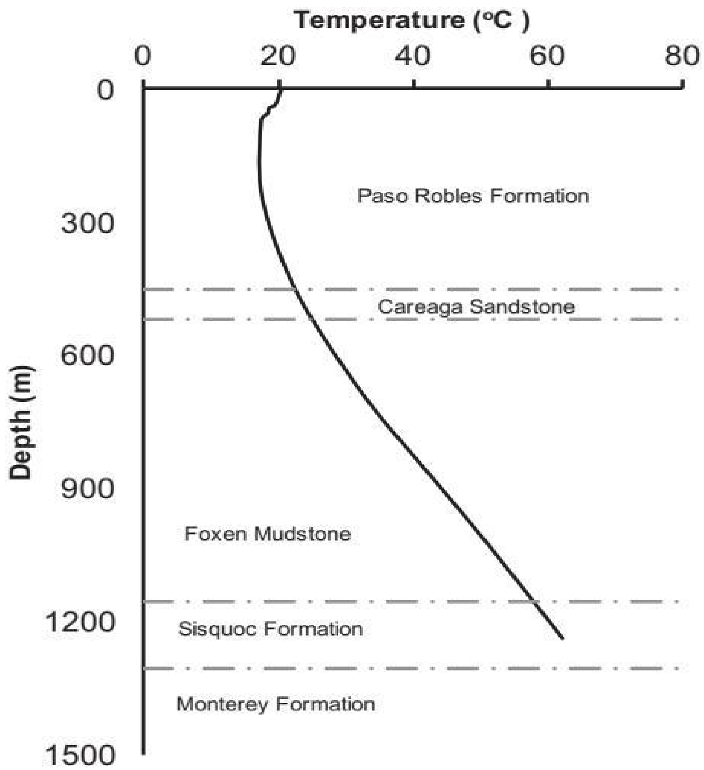


Fig. 5.2: Thermal gradient and lithology for a well located in Santa Maria (North Santa Barbara County) [12]

5.3. Feasibility study of heat extraction by deep BHE.

Fluid flow through a coaxial deep BHE configuration was modelled in reference [12], the feasibility of reusing abandoned oil and gas wells as deep BHEs was obtained. Between the incompressible fluid and the surrounding rock matrix, convective and conductive heat transfer is considered. Parameterizing the deep BHE model according to well and heat flow parameters reported in Santa Barbara, Santa Clara, and Monterey, California, yields an envelope of suitable crustal temperature gradients, well depths, and flow rates.

Figure 5.4 shows the domain geometry and mesh of the well and reservoir models. The domains are discretized in two dimensions, and the result is axisymmetric. The well depths modeled are 1000, 3000, and 5000 meters, which correspond to well depths in Santa Barbara, Santa Clara, and Monterey counties. Convergence analysis determined the domain width of 200 meters to provide a sufficient buffer between the boundary conditions and the well domain (Fig.5.3). The steady state output temperature changes very little beyond 200 m domain width. The dimensions of the coaxial BHE design match those of existing abandoned wells of interest: 180 mm outer and 120 mm inner diameters, respectively. The FEM discretization of the domains is shown in Fig. 5.4, with element sizes ranging from 7.5 mm in the well to 20 m at the domain boundary.

Figure 5.4 depicts the model border and initial circumstances. To replicate the crustal temperature gradient, the model's edge uses a variable-with-depth temperature boundary condition. The edge boundary conditions are set to 4.5 and 7.0 C˚/100 m, which corresponds to the temperature range observed in Santa Barbara, Santa Clara, and Monterey. A constant heat flux of 75 m Wm^{-2} (Nuemann) border condition constrains the domain's bottom, which follows crustal heat flow estimations acquired by multiple geological studies for the counties of interest [24]. The coaxial heat exchanger's inlet mass flow rate is set to 1, 4.4, and 10 kg/s, which corresponds to the heating needs of a single commercial building.A constant pressure boundary condition of 0 Pa was employed for the coaxial heat exchanger's exit. The fluid flow domain (well casing) has a no-slip boundary condition (velocity of fluid at wall is 0 m/s).

In total, 18 parameter combinations were used in this research. Well depths of 1000, 3000, and 5000 m, mass flow rates of 1, 4.4, 10 kg s^{-1}, and edge temperature gradients of 4.5 and 7.0 C˚/100 m were all used.

Figure 5.4 also includes model parameters. The sedimentary geology surrounding abandoned wells in California is represented by the effective thermal conductivity, k. Saturated sandstones with average quartz content and porosities of about 10-15% have effective k values as high as 4.5 $(W(mK)^{-1})$, whereas unsaturated shales have effective k values closer to 1.25 $(W(mK)^{-1})$ [12].As a result, the semisaturated sandstones encountered in the study counties are represented by an average effective k of 2.9 $(W(mK)^{-1})$. The insulating inner pipe in the model has a thermal conductivity of 0.1 $(W(mK)^{-1})$, which equals the installed conductivity of the deep BHE of Weggis, Switzerland's double-walled vacuuming insulating pipe [25].

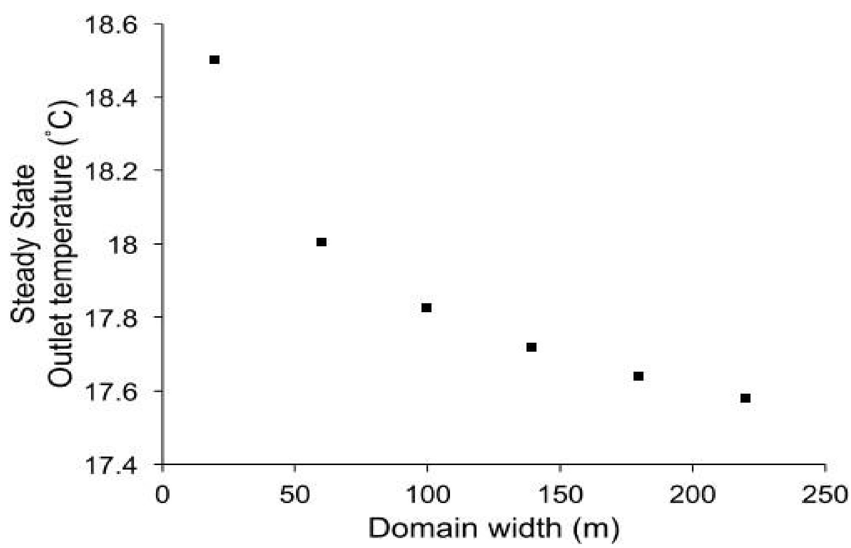


Fig. 5.3: Domain width convergence study. [12]

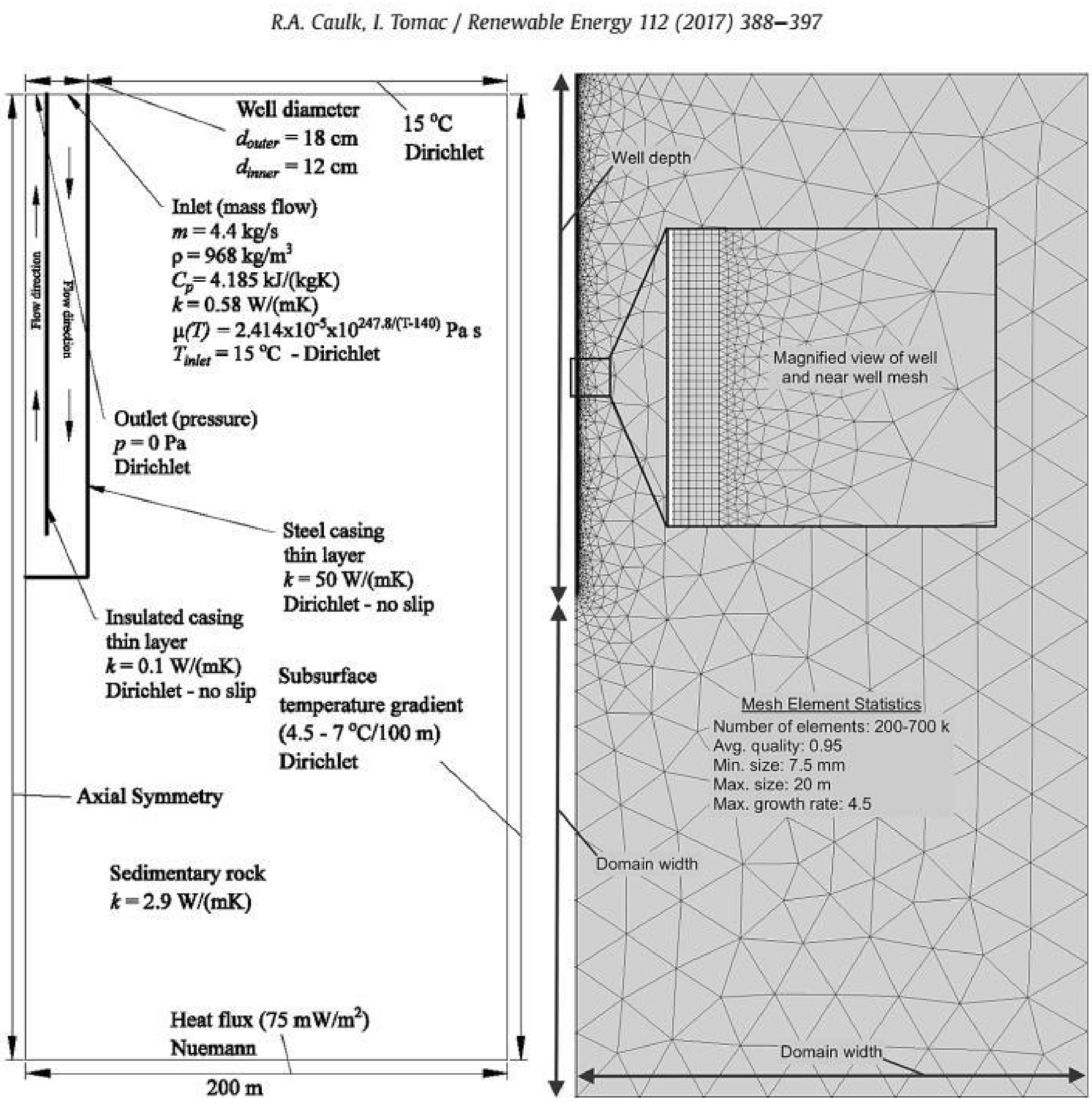


Fig. 5.4: Model geometry and details (not to scale) (left) and domain discretization (right) [12]

5.4. Discussion and Results

The large number of abandoned wells in California provides a potential for low-cost renewable geothermal energy production. The described study found California counties with a high number of abandoned oil and gas wells, medium to high crustal heat flows, and sedimentary geology appropriate for geothermal energy extraction and direct usage via sedimentary EGS and deep BHE. Santa Clara, Monterey, and Santa Barbara counties are among those that could benefit from a local assessment of abandoned wells to learn more about their potential for low-temperature direct usage. District heating, for example, necessitates near proximity to users, whereas industrial applications like greenhouses or aquaculture necessitate a location at the abandoned well site.

In general, abandoned wells in Santa Clara, Monterey, and Santa Barbara counties dip into low to moderately consolidated sandstone rock layers limited by shale layers with similar consolidation characteristics at depths of 900-2000 m.Bottom hole temperatures vary depending on crustal heat flow and well depth, but they typically range from 40 to 70 degrees Celsius, with some wells exceeding 90 degrees Celsius. These depths and temperatures are appropriate for low-temperature EGS applications like as district heating or greenhouse heating.

Although the bottom well temperatures in Santa Clara, Monterey, and Santa Barbara are already acceptable for EGS, predicting hydraulic cracks in loosely to moderately cemented sedimentary rock for various stress regimes is a difficult task. Depending on the intended abandoned well reuse, it may be beneficial to identify locations characterized by reverse faulting regimes. A reverse faulting regime that allows numerous separately triggered horizontal fracture zones to be stacked vertically may benefit a single well EGS more. Within the same well, this setup allows operators to pump water into one zone and produce hot water from another. In other instances, the normal or strike-slip regime might be more appropriate for a twin well system because vertical fractures and vertical wells make it simpler to manage water migration. However, directional drilling allows for well configurations that are regulated by the regime (for example, a well could be directionally drilled to enable a single well EGS within a regime of strike-slip faulting). Despite the flexibility of EGS, further experimental and computational studies are required to comprehend the mechanics of hydraulic fracturing in the particular rock types present in the aforementioned California counties.

Deep coaxial BHE is a practical, low-risk substitute for EGS. Counties with high temperature gradients (7 C˚/100 m) can easily reach desired outlet temperatures of >40 C˚. For moderate to high flow rates, well depth improves the COP while flow rate has a negative impact.The COP is bigger for moderate flow rates (4.4 l/s) and high depths despite high production temperatures at low flow rates (5000 m). Deep BHEs are presently employed for district heating in a variety of buildings around Europe at flow rates between 0.8 and 6.0 l/s.

The study discovered that deep BHE is appropriate for both high and low heat flow counties. High temperature gradients and a large number of deep abandoned wells characterize Santa Barbara.These depths and temperatures could be used in a variety of low-temperature industrial applications, including greenhouses, water desalination, and general space heating. Water temperatures of 40 degrees Celsius can only be reached with well depths of 3000-5000 meters in countries with lower temperature gradients (4.5C˚/100 m). Reduced production temperatures (40 C˚) combined with shallower wells (1000 m) and lower temperature gradients (4.5 C˚/100 m) can be used with a heat pump to provide feasible fluid temperatures for general room heating.

Although a heat pump would diminish efficiency, a solar power connection might offset energy costs and work well with unique direct geothermal usage like greenhouse-water desalination or a reverse osmosis desalination setup [26]. Furthermore, if the thermal loading is cyclic rather than constant, less ideal geological conditions may create remarkable heat output.

Finally, abandoned oil/gas wells in California may serve as a jumping-off point for well deepening, although in certain circumstances, abandoned wells may merely require unplugging and re-casing to separate sandstone formations of interest (EGS) or increase casing contact with adjacent rock (deep coaxial BHE). In all situations, lowering drilling costs results in a 42 percent to 95 percent reduction in EGS project costs [12].

Conclusion

Due to the COVID-19 pandemic impact, prices for oil and natural gas have declined, as well as production and consumption trends of these resources have shown the main decrease in recent years. Global primary energy consumption and carbon emissions dropped by 4.5% and 6.3% respectively.

Geothermal energy is viewed as one of the future resources to meet the world's rising energy demand because of its dependability, sustainability, abundance, and low environmental impact. Geothermal energy from oil wells can be harnessed using existing resources, data, and technologies, which has many advantages over traditional geothermal wells, particularly in terms of lower capital costs and operational risks. This thesis work thoroughly characterized the geothermal resource associated with oilfields, examined current geothermal development in oilfields around the world, identified current challenges, and introduced multidisciplinary technologies as potential solutions to unlock the potential and promote extensive development of geothermal energy from oilfields in order to increase awareness of and encourage discussions on this topic.

According to the presented comprehensive review and analysis of the geothermal resource in the oilfield, unique characteristics in the oilfield utilization, current developments, challenges, and possible solutions, the following conclusions can be drawn:

- Using oilfield geothermal resources to offset oilfield operation costs, reduce CO_2 emissions, and extend the economic life of wells and surface infrastructure is a wise decision, especially in light of low oil prices, aging oilfields, and incremental exploration, operating, and decommissioning costs.
- Geothermal development in oilfields not only removes the most significant barrier of high initial capital expenditures in drilling, but also provides superior conditions to allow geothermal development and help the petroleum industry.
- Significant progress has been made in several nations in both direct use and power generation, which has benefited both the oilfield and society.
- Despite some constraints impeding the development of oilfield geothermal resources, it is projected that geothermal direct consumption and power generation would rise significantly in the future following the breakthrough of revolutionary technologies and research.

The use of an abandoned petroleum well would help the economics of a geothermal energy project. Deep coaxial BHE is a low-cost and low-risk alternative to EGS. Temperatures in the range of 40-52 °C can be expected for the circulation of water as the working fluid in a 2000 m deep well during a 7-year period, which could power a binary cycle power plant. Higher amounts of electricity can be produced by a working fluid that might theoretically collect more heat. At the same time, the pumping system must be efficient in pumping and injecting a specific amount of working fluid under varying injectivity conditions. Potential project returns should be balanced against the feasibility, economic, and environmental considerations of introducing a better-working fluid.

Based on the case study of geothermal energy generation conducted in Italy by [8], the following considerations can be concluded:

- The WellBore Heat Exchanger (WBHX) is a well-completion technology that enables heat extraction without the use of geothermal fluids. Both the environmental effect and the energy required for reinjection are minimized. Because the fluids are not in close touch with the formation, corrosion and scaling problems are avoided.The main disadvantage is that heat recovery efficiency is reduced.
- The current study looked into the feasibility of installing the WellBore Heat eXchanger (WBHX) on one of Europe's largest oil fields, the Villafortuna Trecate oilfield, which has been operational since 1984. With an ORC machine, the extracted heat might be used for both district heating and electrical energy generation. Only the production of electrical energy has been examined in this application.

  Available electrical power is not suitable for conventional geothermal power plants, which is a weak point of WBHX method. In terms of the heating district plant, it is favorable.

The potential of abandoned wells in California for Enhanced Geothermal Systems (EGS) and low temperature deep Borehole Heat Exchanger (BHE) applications have been investigated in this research. Santa Clara, Monterey, and Santa Barbara counties are identified as having a high number of abandoned wells, medium to high crustal heat flows (75-100 mW/m^2), and adequate sedimentary geology. For an average 1000 m deep well, thermal gradients range from 4 to 7.3 C˚/100 m, allowing access to bottom hole temperatures of 40 to 73 C˚. Low-temperature direct use EGS like district heating, greenhouse heating, and aquaculture can all benefit from these rock temperatures. Drilling cost mitigation and documented lithology both lower the risk associated with EGS from an economic standpoint. However, one restriction to the EGS conversion of these abandoned wells is hydraulic fracturing of loosely to moderately consolidated sedimentary rock under transitional stress regimes. A mathematical model is used to demonstrate the possibility of deep BHE applications within abandoned oil and gas wells. In places with temperature gradients >7 C˚/100 m, output fluid temperatures >40 C˚ can be attained for 1000 m deep wells, according to predictions.

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