UTILIZATION OF ABANDONED OIL WELLS IN GEOTHERMAL APPLICATIONS

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ABSTRACT

Abandoned oil wells have several possible applications as geothermal resources. Selecting the most viable application depends on characteristics of individual oil wells and the general condition of the region for the development. In this study, the potential for the possible utilization such as low temperature power production (binary power cycle), desalination of water, pseudo hot-springs and spas, geothermal district heating (GeoDH) and agricultural applications will be reviewed. Moreover, retrofitting abandoned oil wells for geothermal utilizations can reduce the reliance on fossil fuels and also eliminates mining, processing and transportation process for the power production.

According to Geothermal Energy Association (GEA), an economically competitive geothermal power plant can cost as low as 3400US$ per kilowatt installed. While the cost of a new geothermal power plant is higher than that of a comparable natural gas facility, in the long run the two are similar over time (CEC). This is because natural gas construction costs account for only one third of the total price of the facility, while the cost of the fuel at a natural gas facility represents two thirds of the cost. The initial construction costs of a geothermal facility, in contrast, represent two thirds or more of total costs. So, although initial investment is high for geothermal, natural gas and geothermal are still economically comparable over a long term. Considering the drilling costs more than 40% (Carolyn. K) for a geothermal powerplant development, retrofitting high potential abandoned oil wells can make it the cheapest one among all options including renewable energies.

1. INTRODUCTION

Utilization of geothermal energy has been started since Roman times for bathing, spas, cooking and heating buildings by using hot water and steam resources coming from the near surface of the Earth. Water from hot springs is now used worldwide for spas, space heating, agriculture and industries (Dickson and Fenelli, 2004).

In 1892, the first geothermal district heating system began operation in Boise, Idaho (USA). In 1928, Iceland, another pioneer in the utilization of geothermal energy, also began exploiting its geothermal fluids, mainly hot water for domestic heating purposes (Dickson and Fenelli, 2004).

Using geothermal energy for producing electricity is a relatively new industry. The Larderello field in Tuscany, Italy, produced the world's first geothermal electricity in 1904. In the experiment, five light bulbs were lit by electricity produced by hot steam emerging from vents. The success of this experiment clearly indicated the industrial value of geothermal energy and marked the beginning of a form of exploitation that was to develop significantly from then on. Electricity generation at Larderello was a commercial success. Major production at Larderello began in the 1930s; in 1970, the power capacity reached 350 MWe. In 1911, the world's first geothermal power plant was built in Italy's Valle del Diavolo (Devil's Valley), named for the boiling water that rises there.

After the World War geothermal energy started gaining more attention by many countries due to its economic competitiveness with other energies. It does not rely on import and for some countries, it is the only locally available energy source. More recently, extensive direct heat utilization projects have been undertaken in many European countries, and electric power developed extensively in Italy and Iceland. Geothermal heat pumps have been widely used in Austria, Switzerland, Germany and Sweden (Antice and Sanner, 2007).

Geothermal energy utilization is commonly divided into two categories, i.e., electric production and direct application. The utilization method depends on parameters such as local demand for heat or electricity, distance from potential market, resource temperature, and chemistry of the geothermal fluid. These parameters are important to the feasibility of exploitation. The Lindal diagram (Lindal, 1973) emphasizes two important aspects: Feasibility of geothermal projects with cascade and combined uses. Resource temperature controls utilization purposes.

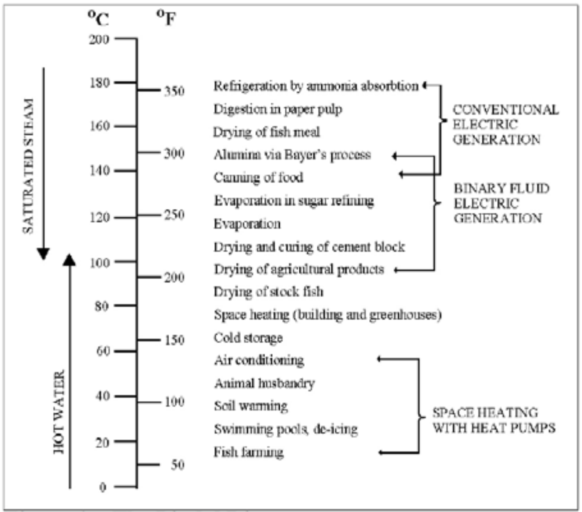


Figure 1: Lindal diagram indicating possible uses of geothermal fluids at different temperatures. Diagram emphasizes cascade and combined uses of application of geothermal sources.

Minimum temperature requirements corresponding to different types of utilizations are shown in Figure 1 (Lindal, 1973). However, the temperature boundaries only serve as guidelines. Conventionally, electric power production only considers fluid with temperatures above 150 °C but considerably lower temperatures could also be used for power generation by using binary systems. The ideal inlet temperature for house space heating with conventional radiators is around 80°C. However, thermal waters with just a few degrees above the ambient temperature can also be used efficiently by applying floor heating radiators, heat pumps or auxiliary boilers (Fridleifsson, 1998).

Due to the limitation of the technology, the available depth for us to exploit by now is only limited to the crust. The geothermal gradient of crust is 25-30℃/km on average. Abandoned oil and gas wells are located in hydrocarbon areas and the thermal gradient ranges from 11℃ to 30℃ on average (Mohammad et, 2019). General depth required for the binary system and single flash are 3.0 km and 6.3 km respectively. The calculation is based on the average thermal gradient of hydrocarbon area and the minimum temperature required for different types of geothermal power plants. Generally, abandoned oil wells can't meet the requirement for single flash powerplant development because most of abandoned wells won't exceed 5000m depth unless they have higher thermal gradient than hydrocarbon area (Moghiar and Antal, 2001).

Specific numbers of oil wells are unknown for many countries. Oil production ranking could be used as a reference for the assumption of active oil well numbers and also as a prediction for abandoned oil well numbers by now and in the future. Table 1 shows the top 10 oil-producing countries of 2017.

Table 1: Top 10 oil-producing countries in the world in 2017 (Oil and Gas, 2019).

bpd: barrel per day

	Countries	Production (bpd) 2017
1	United States	15,647,000
2	Saudi Arabia	12,090,000
3	Russia	11,210,000
4	Canada	4,958,000
5	China	4,779,000
6	Iran	4,695,000
7	Iraq	4,455,000
8	United Arab Emirates	3,721,000
9	Brazil	3,363,000
10	Kuwait	2,825,000

There are oil and gas wells in 35 of the 50 states (70%) in the United States, and 1,673 out of 3,144 (53%) of all county and county equivalent areas. The number of wells per state ranges from 57 in Maryland to 291,996 in Texas. There are 135 counties with a single well, while the highest count is in Kern County, California, host to 77,497 active wells (Fractracker, 2019).

The end-of-life process for Texas wells is initiated when a well becomes inactive. An inactive well is an unplugged well with no reported production for at least one year. As of April 2017, about 27 percent of the wells in Texas were inactive—approximately 118,000 wells. From September 2015 to August 2016, operators plugged 9,296 wells without dipping into the industry-funded Oil and Gas Regulatory and Cleanup Fund (OGRC Fund). Private industry plugs the vast majority of inactive wells without RRC intervention—consistently around 95 percent of all wells plugged.

A delinquent operator's inactive wells are re-classified as orphaned wells. As of April 2017, there were approximately 8,300 orphaned Texas wells. Orphaned wells are often abandoned and become plugging liabilities of the State by insolvent or unlocateable operators.

In the USA abandoned hydrocarbon wells, in regions of high heat flow (>75 mW/m^2) and sufficient water flow such as Texas and Oklahoma, are estimated to have a power generating potential at the gigawatt level. Using the existing wells minimises the initial costs of geothermal power production. The main capital funding input is fitting existing wells with heat exchangers and small power plants. In March 2006, the Southern Methodist University in Texas held the first conference on the potential of harnessing geothermal power from abandoned hydrocarbon wells (GNS Science Report, 2007).

Drilling geothermal wells is a complex process that uses expensive drill rigs and a wide range of drilling experts which requires considerable capital cost. It is also a labour-intensive operation with most of the jobs being performed 24 hours a day, seven days a week, in all weather conditions (Carolyn K., 2015).

The cost of drilling geothermal wells is estimated (Carolyn. K.) to be about 40% of the total investment cost for a new high temperature geothermal plant. This makes geothermal plants more expensive to build than conventional fuel fired power plants, and as a result the cost of the wells becomes a key consideration when determining the economic viability of a geothermal field. Obtaining accurate costs for geothermal wells is, therefore, very important as it quantifies a substantial percentage of the cost of the geothermal project.

The depth of the resource is one of the major parameters influencing the cost of drilling a geothermal well. Along with the rock formation (nature, structure and hardness), which determines the drilling speed, these parameters influence the initial well diameter, the number of casing strings needed and, thereby, the time required to drill the well. According to the variability of these parameters, the drilling of a geothermal well may last from 25 days to more than 90 days, with a reasonable average of 45 days. Deeper wells also require larger and thus more expensive drilling rigs (National Driller, 2019).

Statistical analyses of historical drilling costs data show that the depth of the well is the major parameter explaining its overall cost. It is estimated that 56 percent of the cost variability of geothermal wells is linked to depth. The diameter of the well is another important parameter influencing the cost of drilling.

Though there will be some costs for retrofitting abandoned oil wells for binary power generation, cutting off the drilling cost still makes it the cheapest option among all of the renewable energies (Figure 2) and can save precious time for the project since the drilling is also a time consuming work. Finding a right well with good conditions and high bottom-hole temperature is the key for a successful development.

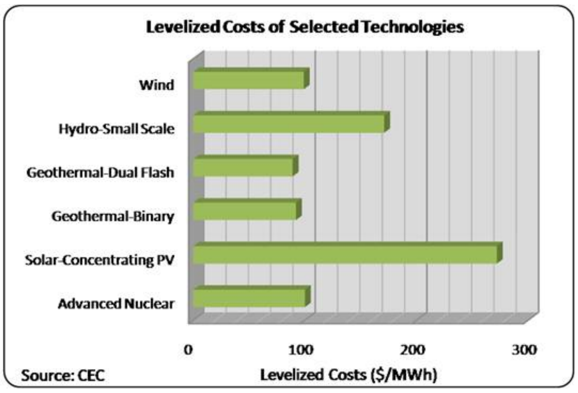


Figure 2: Costs of Selected Technologies (GRC, 2019).

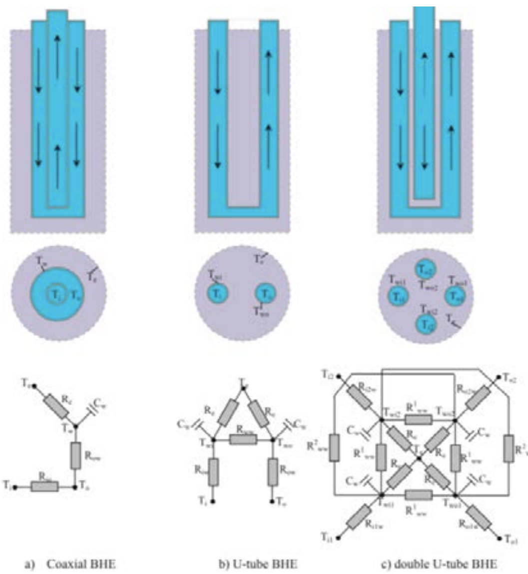
2. CURRENT RESEARCH

Until now, utilization of abandoned oil wells (AOW) are still remaining in the research stage and most of the research is carried out by running simulations with computer software.

2-1. Borehole heat exchanger (BHE)

Generally, the borehole heat exchanger (BHE) mainly includes three types: coaxial BHE, U-pipe BHE and double U-pipe BHE. Each has a different thermal performance. Many researchers have made comparative analysis of heat transfer characteristics of BHEs, and specially focused on modelling of thermal resistance for BHEs. The thermal resistance (R) mainly consists of R between pipes and surrounding rocks, R of each pipes, R of surrounding rocks (Nian and Cheng, 2018). Figure 3 shows the three BHEs with corresponding heat resistances network model. For petroleum wells equipped with a single wellbore including tubing, casing and cement, using U-pipe or double U-pipe BHE to retrofit AOW should reconstruct the wellbore. It is also difficult to build grout in a thousands of meters-depth wellbore. However, it can be the best practicable technology with using coaxial BHE for retrofitting AOW system, therefore all of the studies on abandoned oil well used the coaxial BHE.

Figure 3: Modelling scheme of different types of BHEs with thermal resistance (Nian and Cheng, 2018).



2-2. Thermosiphon

Under 1 atm, the maximum density of water is 0.999975 g/cm^3 at 4 and then it decreases with the increase of temperature. Usually inlet temperature ranges from 20 to 30 and outlet temperature is above 75. Outlet pressure ranges from 3.5 to 5 atm. Slight increase of pressure doesn't have much effect on the T-D diagram (Figure 4) which means inlet water density is always higher than the outlet.

Injected water is heated by surrounding rocks. As shown in Figure 5, fluid temperature depends largely on rock temperature at the given depth. The fluid temperature rose because it was heated by the surrounding rocks as the fluid moved downward. The highest temperature was obtained at the bottom of the well, and then fluid moved upward and the temperature was slightly decreased by 6 (Noorollahi et. al., 2015).

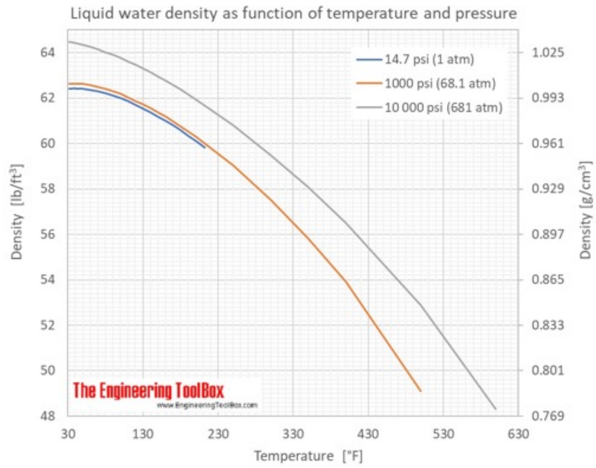


Figure 4: water temperature-density diagram (Engineering ToolBox, 2003).

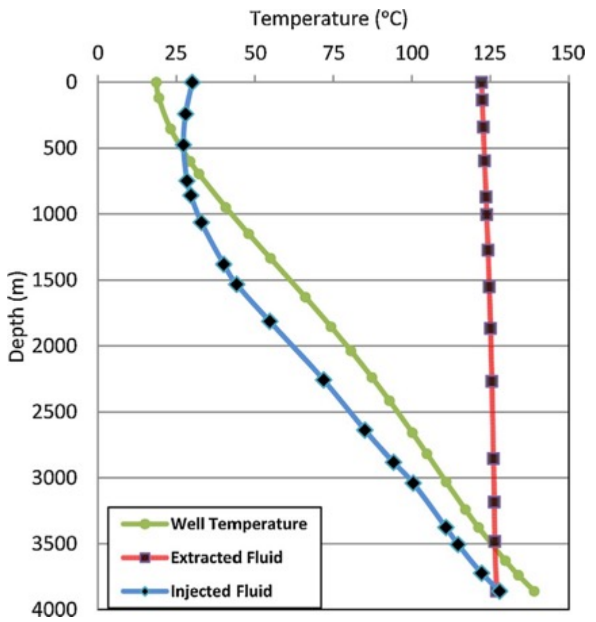


Figure 5: Temperature of injected and extracted fluid (Noorollahi et al., 2015).

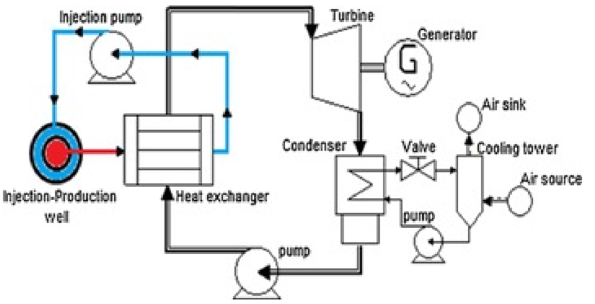


Figure 6: Process flow diagram of geothermal binary cycle.

At the same depth water temperature in the outer pipe is lower than the inner pipe which means water density in the outer pipe is higher than the inner pipe. Cold water in the outer pipe has higher pressure than hot water in the inner pipe. It will cause a thermosiphon effect which can reduce the power consumption of the injection pump (Figure 6).

2-3. Heat exchange.

The output fluid temperature and net heat rate from the borehole heat exchanger increases by increasing the ground layer radius until 20 m and then stabilizes afterwards. With approach to radius of 20 m, the increase of radius has little effect on the increase of heat transfer volume as shown in Figure 7.

It should be noted that the values of the net heat rate of the well, are in fact, the thermal energy of the fluid out of the well, and the amount of thermal energy lost on the way back (extraction pipe) has been removed from the obtained thermal energy of fluid in injection pipe. The result of simulation confirms the previous results and implies that heat extraction is close to optimum value in vicinity of 20 m around the wells (Noorollahi et al., 2015).

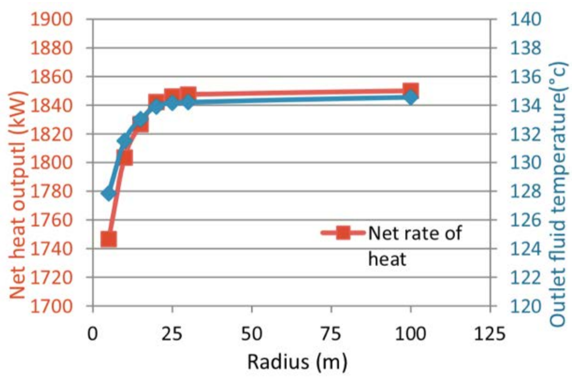


Figure 7: Sensitivity analysis for net rate of heat of fluid obtained from well and output fluid temperature from borehole heat exchanger with the size of ground layer radius.

An oil well is surrounded by different types of geological layers as shown in Figure 8. From top to the bottom it usually follows the order of sand-stone, wet-sand, lime-stone, calcite, marl and dolomite. As shown in Table 2, Thermal conductivity depends on the type of layers. Sandstone and dolomite have relatively high thermal conductivity.

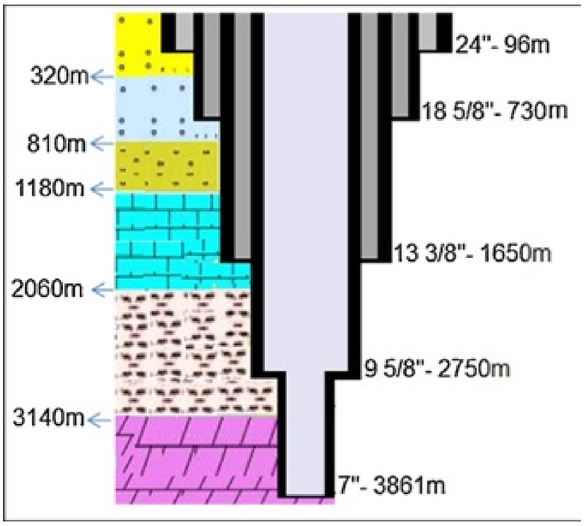


Figure 8: Schematic representation of wells specifications, casings and ground layers (Noorollahi et al., 2015).

Table 2: Thermo-physical properties of the geological layers (Noorollahi et al., 2015).

Thermo-physical properties of the geological layers.

Properties	Density (kg/m^3)	Heat capacity (J/kg K)	Thermal conductivities (W/m K)
Sand-stone	2720	920	3.1
Wet-sand	2600	935	2.3
Lime-stone	2700	908	2.8
Calcite	2730	920	2.8
Marl	2650	880	2.6
Dolomite	2900	911	3.7
Bentonit	2620	650	2.05
Cement coat	2510	840	2.9
Polystyrene	55	1210	0.027
Steel-stainless	8055	480	13.8

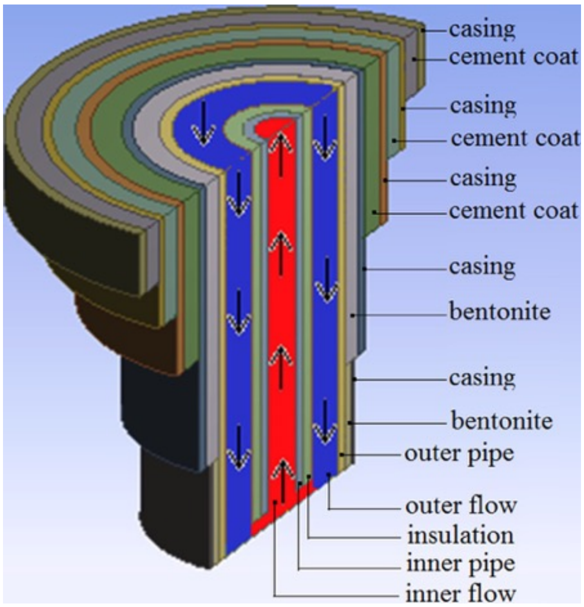
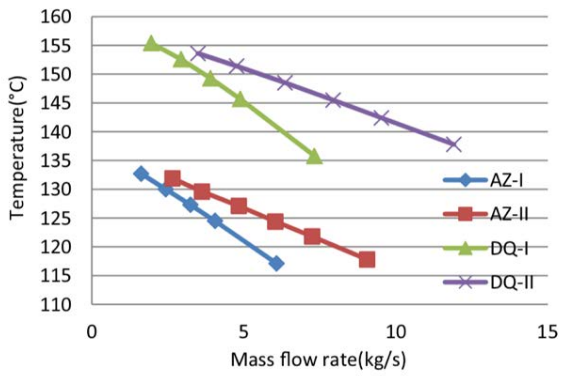


Figure 9: Schematic representation of cross-sectional view of the heat exchanger and well casing (Noorollahi et al., 2015)

The structure of well casings and heat exchangers is quite complicated as shown in Figure 9. Cement is used to fill up the space between casings. Bentonite is used to fill up the space between outer pipe and casing. It has low thermal conductivity and therefore is not an ideal material for heat extraction from surrounding layers.



AZ and DQ are abandoned oil wells modelled in the study, located in Ahwaz province in southern Iran.

Figure 10: Bottom-hole fluid temperature variation with mass flow rate (Noorollahi et al., 2015).

AZ-I and DQ-I have a thicker bentonite layer compared with AZ-II and DQ-II which caused bottom hole fluid temperature of AZ-II and DQ-II higher than AZ-I and DQ-I. Figure 10 also shows that the increase of mass flow rate will lower the bottom hole temperature.

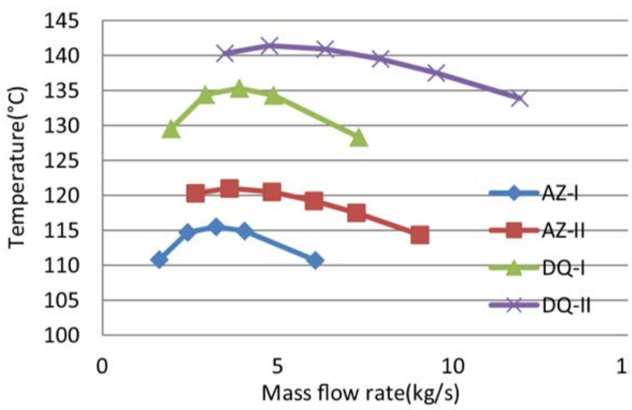


Figure 11: Outlet temperature changes with mass flow rate (Noorollahi et al., 2015)

In addition to the difference of bentonite thickness, AZ-II and DQ-II have thicker insulation layer comparing with AZ-I and DQ-I. It causes outlet fluid temperature of AZ-II and DQ-II higher than AZ-I and DQ-I as shown in Figure 11. Unlike bottom-hole fluid temperature, outlet temperature has an optimal value corresponding to the mass flow rate.

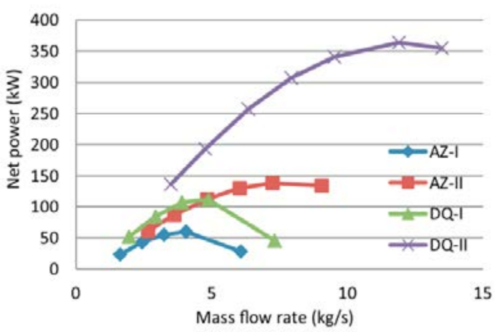


Figure 12: Net power output with different mass flow rates for both models of Wells AZ and DQ (Noorollahi et al., 2015)

Figure 12 shows higher injection pressure in AZ-I and DQ-I caused less net power output compared with AZ-II and DQ-II. For AZ-II and DQ-II, high mass flow rate corresponds to high net power production.

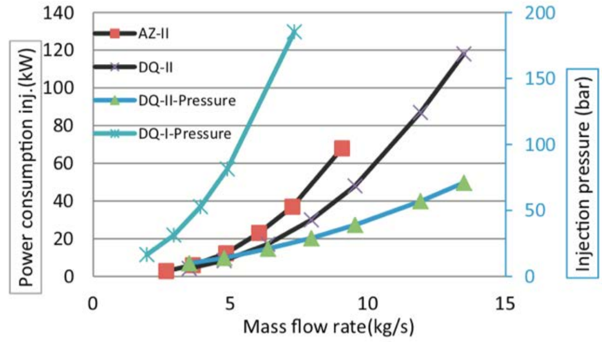


Figure 13: Power consumption and injection pressure changes with mass flow rate.

AZ-II and DQ-II have bigger inner pipe diameter compared with AZ-I and DQ-I and it caused high injection pressure for AZ-I and DQ-I compared with AZ-II and DQ-II as shown in Figure 13. High injection pressure also causes high power consumption. Injection power consumption increases along with the increase of the mass flow rate.

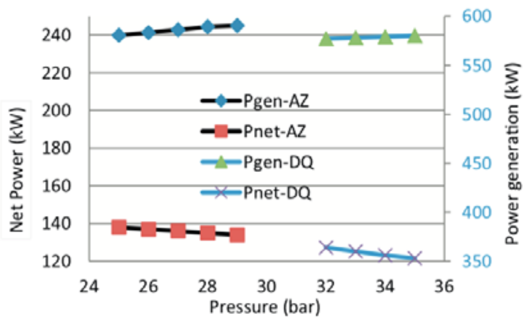


Figure 14: Power generation and net power variation with isobutene pressure (Noorollahi et al., 2015).

Though high working fluid pressure can generate more electric-power it also causes high in-house power consumption and low net power output as shown in Figure 14. Working fluid pressure should be minimized in a binary cycle.

Table 3: Thermal conductivity of different materials.

	Thermal conductivity (W/mK)			
	Temperature (℃)			
Material	25	125	225	
Polystyrene	0.0300			Currently used
Air, atmosphere (gas)	0.0262	0.0333	0.0398	Only suitable for the room temperature
Argon (gas)	0.0160			Expensive
Krypton (gas)	0.0088			More Expensive
Xenon (gas)	0.0051			Very Expensive
Radon (gas)	0.0033			Too Expensive and radioactive
Carbon dioxide (gas)	0.0146			Could be considered

Air is a better insulator at room temperature compared with polystyrene but the thermal conductivity increases along with the increase of the temperature as shown in Table 3. Inert Argon, Krypton, Xenon and Radon are all good insulators but the price is also high and Radon is radioactive. Carbon dioxide could be considered as a new insulator due to its abundancy and low price. Density of carbon dioxide is 1.6 times more than the air. Therefore, once it is injected into the underground it will have little chance to escape from insulation layers to the atmosphere.

3. APPLICATION

3.1 Introduction to the application of abandoned oil wells for geothermal energy

The usage of abandoned oil wells for geothermal energy at present is rather hypothetical and doesn't go far beyond simulations and the use of hydrothermal water in Spas (Reyes, 2007).

However, there are several possible applications of geothermal energy from abandoned oil wells. What kind of application is most viable will depend on the individual oil well, and general conditions in the region. In this section, some possible applications that have already been suggested by previous researchers will be introduced, as well as some applications that so far have not been introduced but still may be viable.

3.2 Possible application for geothermal energy from abandoned oil wells

3.2.1 Desalination of water

Recently, newer technologies that utilize low-temperature heat have been developed: Membrane Distillation (MD) which combines thermal and membrane distillation processes, and Adsorption Desalination (AD) which can provide potable water and cooling energy at the same time. Such technologies provide the opportunity to use low temperature heat sources supplied by renewable sources to treat produced water with high TDS levels. Currently, using solar energy to power such desalination units is the most common technology. Meindertsma et al. reported solar energy as the most reliable and available renewable energy source for desalination in Israel. Ghaffour et al. developed a solar-powered AD facility to treat seawater. However, geothermal energy output is more stable compared to other renewable energy sources such as solar and wind energy and, as noted by Sablani et al., does not require thermal storage. Geothermal resources above 150 °C are typically used for electric power generation, however, resources with lower temperatures can be used to power desalination units (such as AD and/or MD), representing a new application of this resource. Geothermal energy can be used to directly heat produced water in thermal based desalination units, or to generate electricity for operating Reverse Osmosis (RO) units. Missimer et al. and Ghaffour et al. combined solar energy with geothermal energy and developed a hybrid approach to desalinate seawater. Missimer et al. demonstrated two successful strategies to desalinate seawater using geothermal energy. They used the latent heat from their geothermal electricity generation site to power a coupled Multiple Effect Distillation (MED)-AD system, and diverted some of the generated electricity to power an RO system.

Pseudo hot-springs and spas

A. G. Reyes (2007) proposed that abandoned oil and gas wells could be used to produce hot water for pseudo hot-springs and spas. In fact, there already is a pseudo hot spring in New Zealand that originated from an abandoned oil well. There also is a spa which uses water that is emitted from the 910 m deep Benithon-1 abandoned oil well. However, the emitted water has a temperature of 27°C and therefore must be further heated to enjoyable bathing temperatures.

3.2.2 Geothermal district heating (GeoDH)

Geothermal district heating (GeoDH) makes use of geothermal energy for space and water-heating. According to the EU-sponsored website geodh.eu most wells for geothermal district heating have a depth between 2000 m and 3500 m. Modern oil and gas wells reach this depth and abandoned oil wells could potentially be used for GeoDH. A problem though might be the exact location of wells. The wells for GeoDH are normally inside or very close to the district that the heat is used for. Most abandoned oil wells are located away from cities, increasing the distance either the working fluid or the heated water would have to travel on the surface. During this travel time, heat might be lost to the environment, rendering this method unpractical.

3.2.3 Agricultural applications

Greenhouses are an important factor in today's agriculture since they make it possible to grow crops outside of their season or climate zone. Greenhouses, for example, make it possible for the Netherlands to supply central and northern Europe with tomatoes. In principle greenhouses make use of the "greenhouse effect" where solar energy is trapped as heat. In some colder countries, however, or in locations that have only very little direct sunlight, this is not enough.

The simplest kind of geothermal greenhouse uses mere "air-tubes" which are buried some decimeters to meters into the soil. Air is cycled through these tubes and heated by the soil around it. This is used in areas that have distinct seasons and soil temperature in winter is significantly higher than outside temperature. The most common type of geothermal greenhouse, however, makes use of a fluid system and heat pumps. It might be possible to develop a system like this that makes use of an abandoned oil well. The advantage in comparison to GeoDH would be that the distance between oil wells and cities is not a problem. Many oil wells are located in sedimentary basins which are often already used for agriculture.

3.3 The type and the risk of abandoned oil wells

Basically, there are two types of abandoned oil wells:

1. Properly plugged or capped oil wells

2. "Orphaned" oil wells

Let's take a look at the properly plugged oil wells first: Most abandoned oil wells are plugged by filling them with concrete. This is done to different degrees. Most online sources and reports simply state that upon abandoning, oil and gas wells will be filled with concrete (Reyes, 2007). To what degree this happens is often not stated. However, it is stated that in some cases wells plugged intentionally in a way that makes it hard, if not impossible, to re-open them. In the same source it is also claimed that in Alberta wells are plugged in a way that makes it easy to re-open them.

Orphaned oil wells are ones that are not properly plugged. This happens when an oil company becomes bankrupt, for example, and cannot afford to properly plug a well. Infrastructure will be left on top of the well to varying degrees. Generally, pump-jacks can be turned into money, but sometimes even those are left.

When reopening a well, several factors have to be considered:

In the case of properly plugged wells:

Re-opening might be easy, if the plug is not too deep or the well has been designed in a way that it is easy to re-open it. If the whole well is filled by concrete, re-opening it might not be economical. In cases where the situation is not known, the risk might be too high for investors. Re-opening would mostly be done by drilling into the concrete.

In case of orphaned oil wells:

Orphaned oil wells will not have a concrete plug, making drilling upon re-opening unnecessary. However, there are still unknowns that must be addressed. It is possible that even though there is no plug, the well is still in an unfavorable condition.

And abandoned oil wells cause various problems.

For example, in some country abandoned oil and gas wells are leaking methane, in some cases at levels that create the risk of health damage and explosions.

Risks for abandoned oil wells include: Methane, explosion risk, and contamination.

Methane leaks from abandoned oil and gas wells pose a serious threat to the environment and public safety. The highly flammable gas can contaminate groundwater, accumulate in buildings and pose an explosion risk, and contribute to greenhouse gas emissions. Contamination is an important issue. Abandoned oil wells may have degraded well casing or cement that can allow oil, gas, or salty water to leak into freshwater aquifers.

CONCLUSION

Although use of abandoned oil and gas wells looks promising according to the research based on the simulation, it also faces some challenges. Because most of the wells have history over 30 years, the casings could already have corrosions and also the trace of the surface mark for the wells will be difficult to find. By far, the only utilization for abandoned wells is a pseudo-warm spring in New Zealand with the temperature 21. However, New Zealand has high potential abandoned wells with high bottom hole temperature in Taranaki area. If one of those wells put into practice and generate substantial electricity, then it will set a good example for other countries who have uncountable number of abandoned wells. This research can also provide a reference for drilling new oil and gas wells in newly discovered reservoirs. Investors could consider drilling bigger diameter wells and reducing the thickness of bentonite layers for the future geothermal power generation after the reservoir is depleted.

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