GEOTHERMAL ENERGY FROM PETROLEUM WELLS IN NEW ZEALAND: BENEFITS AND HURDLES

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ABSTRACT

Deriving geothermal energy from petroleum wells in New Zealand is in line with the government's initiative to reduce greenhouse gas emissions by 2030 and attain carbon neutrality by 2050. It is also a pragmatic progression for coping with the depletion of petroleum reserves in Taranaki. Onshore Taranaki contains 40% of petroleum wells in New Zealand, where deep wells can access temperatures as high as 150ºC ± 20ºC, based on estimated bottom hole temperatures (BHT), and 175-200ºC based on solute chemistry. More than 20 countries have studied and considered petroleum wells as sources of geothermal energy and more countries are setting-up installations for direct heat use or power generation. The technical and economic hurdles, as well as different approaches to reservoir modelling should be considered for any petroleum to geothermal conversion. Some of the primary differences include the role of water in the reservoir; physical and geological properties including temperature, permeability, flowrates, and heat sources; surface installations; production time frames; fluid characteristics; and environmental impact. Harnessing geothermal energy from petroleum wells is at the nexus of two mature energy-related industries in New Zealand, with the requisite local expertise and international connections, so there is a high likelihood that such initiatives can progress in Taranaki from concept to working reality in a few years.

1. INTRODUCTION

1.1 Word-wide Interest

Since about 1982, there has been interest in harnessing abandoned petroleum wells for geothermal energy in the USA (e.g., Bebout et al, 1982). There are at least 20 countries actively doing research on converting petroleum wells for geothermal energy (e.g., Gerard et al, 2006; Reyes, 2007, 2015 and 2018; Zhang et al, 2008; Blackwell et al, 2010; Sanyal and Butler, 2010; Kurevija and Vulin, 2011; Angalwa, 2014; Marowicz and Moore, 2014; Noorollahi et al, 2015; Kolbah et al, 2015; Wang et al, 2016; Caulk and Tomac, 2017; Roksland et al, 2017). Although geothermal pilot plants have been installed in petroleum-producing sedimentary basins as early as 1987 in Soultz-sous-Forets in France (Gerard et al, 2006) and 1989-1991 in Pleasant Bayou Texas (Blackwell et al, 2010), the wells used were specifically drilled for testing. It is only in the 2000s that petroleum wells are being actively exploited for co-production (Xin et al, 2012; Wang et al, 2016) or solely as a source of geothermal energy for power production and direct heat applications. Examples include China since 2011, North Dakota USA since 2016 (Wang et al, 2016) and recently, Croatia (www.turboden.com) although more countries are expected to be retrofitting petroleum wells for geothermal use in the near future.

1.2 New Zealand Incentives to Generate Geothermal Energy from Petroleum Wells

Since the initial studies on the extraction of geothermal energy from unused petroleum wells in onshore New Zealand (Reyes, 2007; Angalwa, 2014; Reyes, 2015 and 2018) there has been recent encouragement from the government to develop this idea. These aforesaid initial studies have selected Taranaki as the region to focus on. The interest in Taranaki as a source of geothermal energy has been spurred on by (1) the government's initiative, under the Paris Agreement, to reduce greenhouse gas emissions by 30% below 2005 levels by 2030 and to attain carbon neutrality by 2050 (www.mfe.govt.nz) and (2) the depletion of reserves in the region. Taranaki is the only oil, gas and condensate producing region in the country (www.mbie.govt.nz) where more than 175 presently-unused wells are extant and another 75 available when petroleum production ceases. The success in converting petroleum wells for district-wide direct heat use and low-enthalpy geothermal power production in other countries (e.g., Wang et al, 2016) encourages similar development, although, the long-term success (20-25 years) of this source of geothermal energy is still unknown. The term "unused wells" in this paper are based on plugged and abandoned petroleum well data (https://www.nzpam.govt.nz).

1.3 Objectives of this Study

The objectives of this short paper are to evaluate the potential geothermal resource in petroleum wells in New Zealand.

2. UNUSED PETROLEUM WELLS IN NEW ZEALAND

2.1 Distribution of Unused Petroleum Wells in Onshore New Zealand

There are more than 500 onshore unused petroleum wells (Figure 1) drilled from 1865 to recent (https://www.pepanz.com). Of the unused wells with known drilling dates, nearly 35% were drilled post-1980 (Reyes, 2007). Vertical depths of unused wells range from 17 to 5065m with the majority drilled below 3000m. Stabilized downhole temperatures are rarely measured in petroleum wells although temperatures during or just a few hours after drilling are available. In the absence of stable downhole temperatures, in this paper, bottom hole temperatures (BHT) are roughly estimated using surface conductive heat flow data (Funnell et al, 1996; King and Thrasher, 1996; Funnell and Allis, 1997; Field et al, 1997; Allis et al, 1998; Cook et al, 1999) converted to thermal gradient (Funnell et al, 1996) and an average surface temperature of 12ºC for the South Island and 15ºC for the North Island. A comparison of a few BHT with measured downhole temperatures, aqueous solution chemical geothermometry and homogenization temperatures of the latest aqueous fluid inclusions in Taranaki wells (Reyes, 2015) suggest that BHT values are within ±20ºC of stable well conditions.

Most wells are abandoned because of the lack of strong hydrocarbon indications. The reservoirs in such "dry" wells

will be saturated with fresh or saline aqueous solutions. Oil companies often cement-plug and recover casings prior to well abandonment and it is expected that many pre-1980 wells will not be able to be located (see Section 5.2; Reyes, 2007).

Figure 1 shows the distribution of unused petroleum wells (https://www.nzpam.govt.nz). The estimated bottom hole temperatures (BHT) of abandoned wells vary from near ambient to 150º ± 20ºC with the highest estimates found in Taranaki. Most unused petroleum wells in the country have thermal gradients of 25º-45ºC/km with Rotokautuku-1 in the East Coast at 90ºC/km (Reyes, 2018) and the DFDP (Deep Fault Drilling Project) well in region 14, along the Alpine Fault in the South Island, at 125ºC/km (Sutherland et al, 2017).

About 22% of the wells have BHT>95ºC (Figure 1) that could be considered suitable for power generation using a binary cycle or hybrid system (Reyes, 2007) and the rest could be used for direct heat applications. Nearly 80% of wells with BHT>95ºC are located in Taranaki. The rest occur in the Hikurangi Accretionary Prism (region 1), Northland (region 9), Whanganui-Taumarunui (region 10) and the West Coast (region 12).

Estimated subsurface temperatures (coloured panels in Figure 1) are based on Na-K geothermometry from chemical analyses of aqueous fluid discharges (Reyes et al, 2010; Reyes, 2015 and 2017) and broadly indicate maximum possible temperatures of subsurface fluids in each region. Aside from springs, only well discharges with no more drilling contaminants detectable from fluid chemistry and have no chemical evidence of recent seawater incursion have been used in the temperature estimates. Thus, the aforementioned regions with well BHT>95ºC may intersect the following subsurface temperatures based on solute chemistry: 175-200ºC in Taranaki, 140-160ºC in the Hikurangi Accretionary Prism (region 1) and the West Coast (region 12) and 100-140ºC in the West Coast and at Northland (region 9) outside Ngawha.

Figure 1 also indicates 200-250ºC subsurface temperatures in the Coromandel Peninsula (region 5), Auckland (region 8) and the Alpine Fault (region 14). However, any drilling in these regions will require geothermal geoscientific exploration studies.

2.2 Accessing heat energy through petroleum wells

As mentioned above, one of the ways to access the heat energy locked in the subsurface down to >5000m is to drill new wells or convert some of the hundreds of unused petroleum wells in the country to harness their geothermal energy (Reyes, 2007).

Existing petroleum wells can be viewed as man-made fractures or traps that can hold heated fluids, act as a focus for advecting hot aqueous solutions from depth or, in the absence of viable fluid flow, act as ready-made pipes for Enhanced/ Engineered Geothermal System (EGS) technology including deep Borehole Heat Exchangers (BHE; Templeton et al, 2014; Sui et al, 2019).

Given the cost of drilling new deep wells, using unused petroleum wells can cut geothermal development costs by as much as 50% (e.g., Templeton et al, 2014). There is significant amount of published (e.g., King and Thrasher, 1996; Funnell et al, 1996; Field et al, 1997; Cook et al, 1999) and publicly-available geoscientific and geotechnical data for petroleum systems and individual wells in New Zealand that can further reduce geothermal development costs. Publicly-available information include seismic surveys of the regions and subsurface data from well drilling e.g., geology including lithology, stratigraphy and structures; formation properties such as porosity and permeability; reservoir pressures; fluid salinity and gas compositions; gas and water flow rates; well temperatures during drilling and BHT; and drilling history including mud losses and the state of the well (www.nzpam.govt.nz). Cuttings and sidewall cores from wells are also available for study.

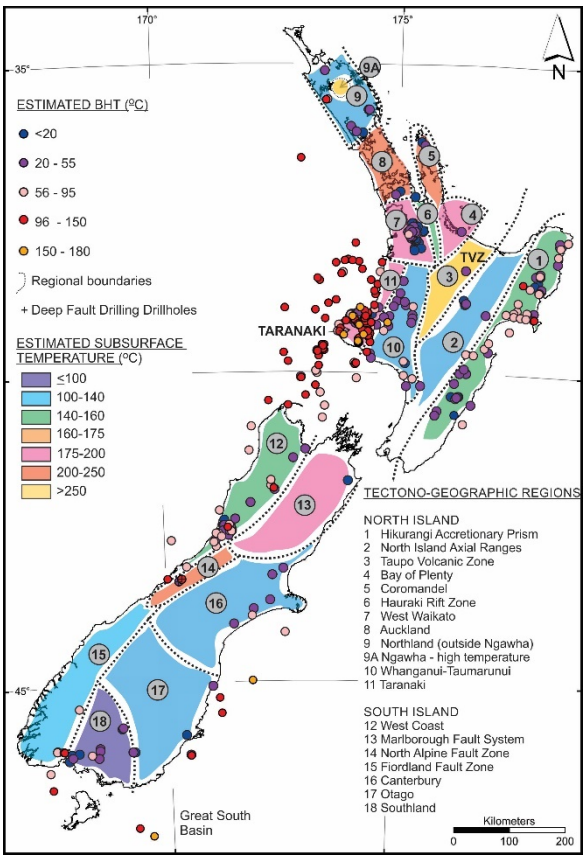

Figure 1: Distribution of abandoned wells and general BHT (estimated bottom hole temperature) in New Zealand (Reyes, 2007) with broad regional estimated subsurface temperatures based on Na-K geothermometry of surface discharges (adapted from Reyes, 2017).

3. FOCUSSING ON TARANAKI

Surprisingly, New Zealand has been harnessing geothermal energy from an abandoned petroleum well in Taranaki since 1936 when 27ºC water from the 915m deep "dry" well, Bonithon-1 (Clarke, 1912) was tapped for the Tarawhata Tepid Baths (Auckland Star, 1936). Although fluid compositions have changed (Reyes et al, 2010), the warm baths are still extant and now called Pure One (http://www.pureone.co.nz).

About 40% of all unused petroleum wells in onshore New Zealand occur in Taranaki (Reyes, 2007). These are located within or near populated areas where access to geothermal energy (or cogeneration of geothermal and gas), for power and direct heat use, would not only benefit existing energy-intensive dairy, food-processing and horticultural industries in the region but can also hold the potential to catalyze the creation of new industries.

A plot of vertical well depths vs temperatures of active and unused petroleum wells in Taranaki (Figure 2) shows a BHT range from near ambient at shallow depths up to a maximum of 175ºC, although most temperatures are <150ºC. Most wells lie along thermal gradients of 25ºC/km to 35ºC/km, assuming an average annual ambient air temperature of 15ºC.

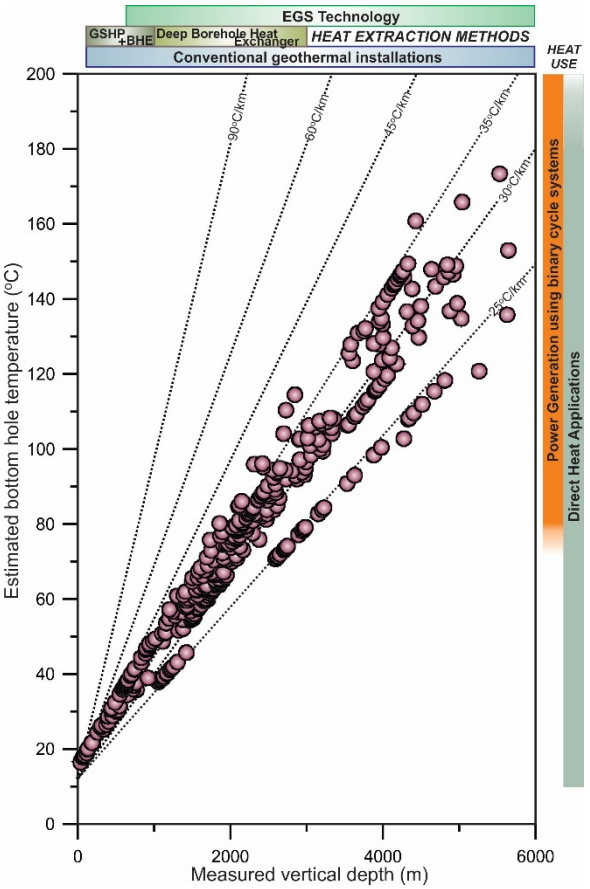

Figure 2: Vertical depth vs bottom hole temperature (BHT) of Taranaki petroleum wells and corresponding thermal gradients. On top are general heat extraction methods based on depth and temperature; on the right are general heat energy uses based on temperature. EGS: Engineered/Enhanced Geothermal System; GSHP: Ground Source Heat Pump; BHE: Borehole Heat Exchanger

The top of Figure 2 shows methods to extract heat from the wells, whether using conventional geothermal installations or less conventional wellhead arrays involving a combination of ground source heat pumps and borehole heat exchangers for use at <1000m and deep borehole heat exchangers at deeper depths (e.g., Templeton et al, 2014).

Although in some cases artesian conditions do exist in Taranaki (King and Thrasher, 1996) with well drilling and completion tests indicating the presence of formation permeability, water flow rates in Taranaki are in general not as high as in most producing high-temperature geothermal systems in the circum-Pacific. Various methods such as EGS (Enhanced/Engineered Geothermal Systems) might be employed, allowing heat energy to be economically extracted without the limitations of in-situ permeability or high natural fluid flow rates.

On the right of Figure 2 are the possible general uses of heat energy and how this can be harnessed. There is a wide range of direct heat applications for wells with temperatures from near-ambient to as high as 180ºC (e.g., Lindal, 1970 and 1992). Using suitable heat extraction methods, heat energy from the wells can be transformed to mechanical energy and thence to electricity using a binary cycle system that uses organic fluids (Organic Rankine Cycle) or a mixture of pure fluids such as ammonia-water (Kalina Cycle) or a system using working fluids with very low critical temperatures such as CO_2 (e.g., Khennich and Galanis, 2012). Theoretically the hot water supply temperature can be as low as 30ºC using ORC (Oyewunmi et al, 2017) but then higher inlet temperatures assure higher power output (Herfurth et al, 2015). However, the optimum inlet temperatures used for most ORC systems is 80º-350ºC (e.g., http://www.exergy-orc.com). There is a narrow range of inlet temperatures from the Taranaki petroleum wells that can be harnessed for electricity using binary cycle systems with varying working fluids. A hybrid system could be installed for cogeneration of oil/gas and geothermal to optimize the use of energy resources in the region (Reyes, 2007; Darby, pers. comm., 2007) as has been previously attempted in Pleasant Bayou, USA (Campbell and Hattar, 1990), for example.

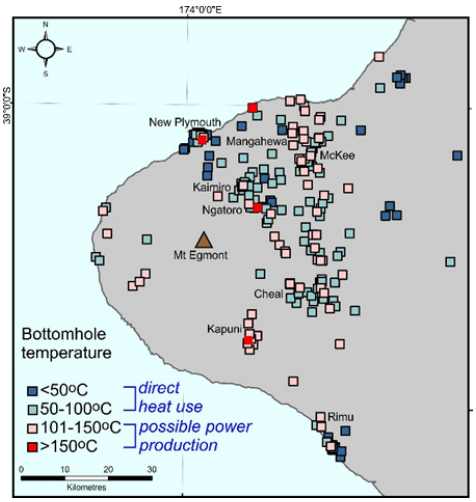

Figure 3: Well locations (https://www.nzpam.govt.nz) and estimated bottom hole temperatures.

Figure 3 shows the distribution of some Taranaki wells and estimated BHTs. As mentioned before, most well BHTs are ≤150ºC and only four wells have estimated temperatures >150ºC at Kapuni (153ºC at 5664m depth), New Plymouth (160ºC at 4450m), Inglewood (166ºC at 5059m) and Waimanu NE of New Plymouth (174ºC at 5550m). Wells with the potential for power production are evenly distributed throughout the peninsula. However, as pointed out by Angalwa (2014) other considerations need to be considered before geothermal energy can be extracted from these wells. Important factors are permeability and the presence of aqueous fluids with viable and sustainable water flowrates. As indicated by studies by Greymouth Petroleum Ltd. (2018 a and b), Irrgang (2002), and Shell Todd (2012), for example, copious water discharges occur in petroleum wells in Taranaki.

4. A COMPARISON BETWEEN GEOTHERMAL AND PETROLEUM MINDSETS

Converting petroleum wells for geothermal energy requires the collaboration of two mature industry knowledge bases that have not fully interacted before in New Zealand. The major

characteristics of New Zealand geothermal vs petroleum systems and how they are developed are vastly different in terms of (1) the role of fluids in the reservoir including hot water (essential in geothermal vs nuisance in petroleum) or petroleum-rich fluids (causes complications in geothermal production but essential in petroleum); (2) physical and geological properties including temperatures (at least 80ºC-120ºC for geothermal electricity production vs elevated temperatures not a consideration in petroleum systems), water flowrates (100's of kg/s in geothermal, 10's of kg/s in petroleum), heat sources (external volcanic heat for high-temperature systems vs natural thermal gradient), major source of permeability (fault-dominated vs stratigraphically- and lithologically-dominated), and major gas component (CO_2 in high-temperature geothermal systems vs wide range of hydrocarbons in petroleum systems); (3) well and surface installations (slotted liners vs liner tubings); (4) production time frame (>25 years of steady geothermal production vs steady depletion of petroleum resources with time) and (5) environmental effects of production (generally clean and green vs high greenhouse gas emissions).

Furthermore, petroleum wells are often deeper than geothermal counterparts (Reyes, 2007), and there are no detailed assessments of heat transport in petroleum reservoirs and wells (J. Burnell, pers. comm.). Equally, the fouling tendencies of petroleum (liquid and gas)-charged formation fluids on surface and subsurface installations and reservoir rock formations have not been considered especially when variations in pressures and temperatures, and fluid mixing accompany the shift from petroleum to geothermal heat production.

The dissimilarities between the two industries has engendered different technical and scientific approaches to reservoir assessment and exploitation that could be bridged by transferring activities that are standard in the geothermal sector to a petroleum environment. For example, geothermal research is mostly focussed on elevated heat flows and heating of cooler recharge fluids over kilometre scales. In the petroleum sector, temperature is a secondary consideration with the main focus being on changes in fluid properties within multi-layered reservoirs of varying petrophysical properties. The exchange of knowledge and capabilities between the geothermal and petroleum sectors will enable the development of an innovative green industry at the nexus of two mature energy-based industries. The results of a Taranaki study can be used as a template for other regions in the country.

5. BENEFITS AND HURDLES

5.1 Benefits

From a socio-economic point of view the use of unused petroleum wells in onshore Taranaki including some of the existing pipelines is a pragmatic decision for coping with the depletion of petroleum reserves in onshore Taranaki. A geothermal industry in Taranaki might not only serve the dairy, food-processing and horticultural industries in the region but also catalyze the creation of new industries and offset some of the projected job losses and regional income caused by the closure of offshore petroleum exploration and exploitation (NZIER, 2019).

The partial shift to geothermal energy production of a petroleum-producing system such as Taranaki may slightly decrease New Zealand's contribution to the global greenhouse gas emissions. At present. New Zealand produces only 0.15% of the global greenhouse gas emissions (GHG; www.mfe.govt.nz/climate-change) at 80.9 Mt CO_2-e (CO_2-equivalent) vs a global emission of 53.5 Gt CO_2-e for 2017 (UNEP, 2017) but any decrease in GHG emissions is essential to the well-being of the earth's atmosphere.

By using unused petroleum wells about half the capital costs in the development of a geothermal system is eliminated because drilling new wells is a costly undertaking (e.g., Templeton et al., 2014).

Geothermal retrofitting of petroleum wells, instead of decommissioning and moth-balling (http://taxpolicy.ird.govt.nz), will not only optimise the economic returns of an expensive investment and infrastructure but also introduce a cleaner source of energy.

5.2. Hurdles

It has taken about 30 years since the publication of Bebout et al (1982), for the idea of retrofitting unused petroleum wells to become mainstream enough that more countries are studying their petroleum resources for future geothermal use and for an upsurge in the installation of district-wide geothermal installations using petroleum wells (e.g., Wang et al, 2016). However, there are scientific technical, social and economic factors that each country must contend with to successfully develop their petroleum wells for geothermal energy. In New Zealand, the transition from petroleum to geothermal generation in Taranaki requires the development of a geoscientific model of geothermal systems in a sedimentary basin that includes (1) an understanding of stress regimes and stratigraphy related to permeability, fluid flow paths and fluid flow rates; (2) fluid chemical compositions related to source temperatures, gas contents and the propensity of fluids for causing corrosion, mineral deposition and fouling on subsurface and surface installations; (3) lithology and physical rock properties related to heat flow regimes, subsurface conductive heating, thermal decay and the life of the geothermal system; and (4) the role of groundwater flow and depths to geothermal energy accessibility.

Aside from the difficulty of locating some old wells due to burial/removal of wellheads and cellars (Reyes, 2007), there are other factors that cause abandoned wells to be unusable without expensive remediation. e.g., (1) unknown state of the casing, such as corrosion, and unsatisfactory grouting jobs especially of wells drilled before 1980 (65% of wells), (2) practice of filling and plugging abandoned wells will require drilling-out plugs before use, (3) liner tubings, normally used for petroleum wells will need to be converted to slotted liners or the tubings perforated, (4) absence of liners in some wells may cause formation cave-ins, (5) fluids may cause fouling (e.g., oil entrainment, deposition of solid hydrocarbons with temperature and pressure changes), mineral scaling (e.g., carbonates) and/or corrosion of geothermal installations. In addition, land access to the wells may continue to be an issue.

Because the geothermal system in Taranaki is comparably lower grade than in the Taupo Volcanic Zone then it is likely that geothermal development would require unconventional and possibly costlier EGS technology (Reyes, 2018).

At present there are no precedents in New Zealand for reusing petroleum wells for power generation but the countries with experience in converting petroleum wells for geothermal use e.g., China, Croatia and the USA may be future sources of practical and on-site information.

6. CONCLUSIONS

Subsurface temperatures necessary for geothermal energy development are present in all regions in New Zealand with unused petroleum wells. The end-of-life of gas and oil systems is an opportunity to develop Taranaki as a region where hot fluids from depth can be harnessed to generate renewable geothermal energy for direct use and possibly base load power production with some possibly obtained from cogenerated oil/gas, using existing wells. The Taranaki studies will provide a template for the exploitation of geothermal energy in the many unused petroleum wells located throughout the country and will aid in providing an alternate energy source especially in regions such as Northland and the north of the East Coast.

There are technical and economic hurdles to conversion, as well as different mindsets between the geothermal and petroleum industries that need to be addressed. However, these two mature energy-related industries in New Zealand have the requisite local expertise and international connections that can move this initiative from conceptual to working reality in a few years.

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