ASSESSING THE VIABILITY OF GEOTHERMAL PROJECTS USING PUMPED WELLS

Greg Ussher[1], Jane Brotheridge[1]

[1]Jacobs, 12-16 Nicholls Lane, Parnell, Auckland 1010, New Zealand

gregory.ussher@jacobs.com

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ABSTRACT

The common assumption within the world of high-temperature geothermal development has been that the economics of geothermal projects producing from resources below 200 ºC are so poor that such resources are generally not considered viable for power production and given a low priority for attention. While a very high tariff in selected locations such as Germany has enabled some deep, low-temperature power projects to be built in the last decade, these projects indeed are high cost mainly due to the depth of wells required to produce from warm aquifer sources in deep sedimentary basins for power. However, a substantial number of projects tapping resources in the 145 to 160 ºC range have been developed in the USA in the last eight years in a relatively low tariff environment and an absence of major subsidies.

Through Jacobs' work assisting with inventory studies for the government agencies in Indonesia, we have had to look closely at lower temperature systems that surprisingly form the bulk of the new systems now being identified in Indonesia. The accessible, high-temperature systems have primarily been identified and claimed, and these lower temperature systems comprise much of the future pipeline for geothermal exploration. We have had to apply global experience from the low-temperature sector of our industry to analyse the well pumping technology required to achieve economic well production and other key factors that may make these projects surprisingly viable. We share these learnings, and we also suggest some opportunities for the New Zealand geothermal industry to evaluate and possibly adopt this technology.

1. INTRODUCTION

1.1 Objective

This paper is primarily addressing the New Zealand geothermal community, where we have been blessed with some excellent geothermal resources and where much of the original technology for developing the globally common "wet" geothermal systems was developed over the last 50 years. From this background, the New Zealand industry has a strong focus on high-temperature systems with wells that abundantly self-flow due to flashing in the wellbore that provides the lift necessary to deliver 2-phase fluids to surface facilities. We are rightly proud of our 2-phase fluid transmission and steam-water separation technologies and power plant that optimise the energy often now using multiple stages of flash, combined steam turbines and binary, or 2-phase binary plant.

In New Zealand, we know that well productivity is in general related to resource temperature and our usual reservoir energy assessment methodologies assume wells fail to be useful somewhere below 200 °C and that any reservoir below that temperature is "effectively useless" for power production. We also generally know that binary plants can be used on lower temperature resources. But if well productivity reduces with temperature (as does binary plant efficiency), and we "know" that binary plants are more expensive than a steam plant, then we have to conclude that lower temperature projects must have a higher cost than higher temperature projects which are often marginal in themselves, and so could not be economical in most settings without subsidies or high feed-in tariffs.

While we have reported on the potential for lower temperature pumped systems in New Zealand previously based on what we have seen internationally (Hochwimmer et al. 2015 and Yearsley, 2019), and Patrick Walsh of Ormat gave a keynote address sharing the important features of pumped geothermal systems (Walsh, 2019), there is still limited recognition of this technology in Aotearoa (New Zealand). We want to provide this summary update for the New Zealand industry because there will be increased demand for geothermal baseload energy in Aotearoa, and we are seeing lower temperature projects needing to be considered in our traditional service geothermal markets such as Indonesia.

1.2 Our Earlier Work in Lower Temperature

To give some context for Jacobs' standing to comment on this sector and its technology, it may be useful to outline our experience with lower temperature systems. While one of the authors was involved in reservoir evaluation and modelling of one of the earliest pumped geothermal projects at East Mesa in the USA 20 years ago, Jacobs was initially engaged with conducting due diligence of these systems in Germany around 2008.

Germany was embarking on a substantial geothermal program based around a high feed-in tariff that was stimulating investigations in the Rhine Graben in the north and the Molasse Basin near Munich in the south. Jacobs' involvement was mainly with a few projects in the Molasse Basin where due diligence and investor advisory services for equity investors extended over several years, including initial evaluation, monitoring of exploration, visiting reference projects and working closely with local technical teams. In this period we developed tools for modelling pumped well performance and understanding of pump technologies and behaviour of sedimentary warm-water aquifers.

Following that work in Germany, we supported several companies to evaluate the potential of sedimentary aquifers in Australia, including a very substantial evaluation and modelling of possible configurations within parts of the Great Artesian Basin and several other plays. This highlighted the importance of permeability at depth and enabled us to develop integrated models of the entire production system from reservoir, wells and plant, back into the reservoir.

We have conducted evaluations and been lender's technical advisor on some pumped well projects in Nevada and Utah and retain an annual review role on one of these. This work gave us exposure to the challenges of balancing pump parasitic power with plant generation, particularly for lower permeability and lower temperature conditions. It also provided an understanding of pumping technology and some of the failures of the two main pumping technologies. We have more recently been assisting a private developer in Japan with the testing of a lower temperature well that is using pumped production – the first of its type in Japan.

1.2 Update from Indonesia

Within Jacobs' work for the New Zealand development assistance programme for the Government of Indonesia, we have been confronted with the fact that many (possibly the majority) of new geothermal prospects being brought forward for exploration drilling by government or private developers are of various types that are much lower temperature than would have been traditionally considered. It is surprising to many that in this very long volcanic archipelago, the nation may be "running low" on high-quality resources. The fact is that many of the best-known systems were prioritised for development by quite competent inventories such as that done in 1986 with New Zealand support (Mahon, 1987) which identified the early development targets. Considerable exploration since then has led to further waves of development and various state owned and private entities being allocated areas for development that are still awaiting exploration drilling. But beyond those areas the government geological agency is seeing mostly lower temperature and/or more challenging or uncertain geothermal prospect areas.

In our work supporting the Indonesia Government and World Bank-funded drilling, we were challenged with helping prioritise new prospects for selection for drilling. Geothermal advisors to the World Bank were sceptical that lower temperature projects could be economical and asked us to study the viability of lower temperature projects. Arising out of that work were project references, modelling of well productivity and overall project financial models that showed that lower temperature pumped systems could have similar costs to good quality high-temperature projects. Some of the results of this work are presented here.

Subsequently, several lower temperature projects are being actively investigated in Indonesia, and we could see some drilled soon in parallel with the more conventional ones that have been waiting some time for first exploration wells due to low tariffs for geothermal.

2. SOME BASICS

2.1 Definition of Lower Temperature: Pumped Systems

What we are looking at in this paper is geothermal systems where pumping is required to achieve economic well production rates for electricity production. Rather than define a particular reservoir temperature range, we are interested in the fact that, with all other things being equal, the production rate of self flowing geothermal wells is highly dependent on reservoir feed temperature. With low feed temperature, well output can be so low that the well will not self flow at all. This was presented nicely in the IFC report on global well success and production rates, where a simple production model was used to demonstrate the effect of reservoir temperature on well production for a range of productivity index (PI) (IFC, 2013). Figure 1 is an extract from that study that showed the major "tear" in the performance curves between self-flowing and pumped wells somewhere below 200 °C. Whereas production declines with temperature from 250 °C down to 200 °C, and there is a step up again once pumps are employed. We will investigate this further in this paper.

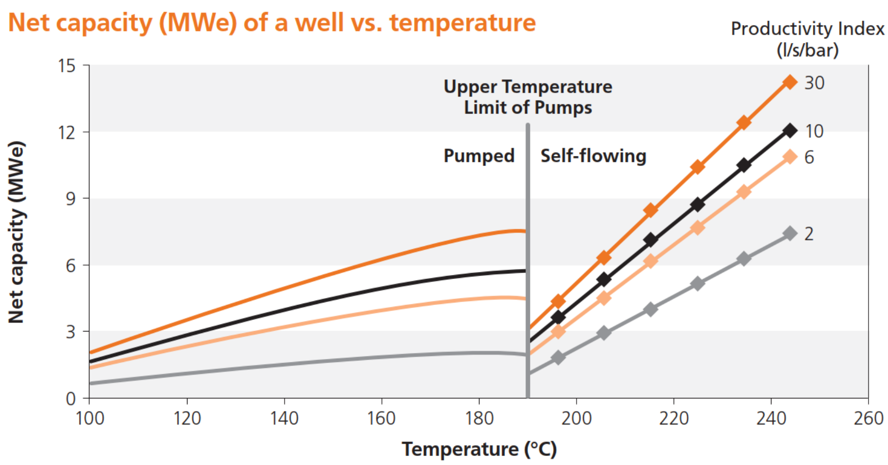


Figure 1. Relationship between temperature and well production (from IFC, 2013)

It is the fact that lower temperature systems are pumped which is the important differentiator for these systems. Pumping is a fundamentally different well lift process that maintains the production in liquid form with no flashing. Unlike in self flow wells with fluid flash, pumping retains the original feed temperature and keeps gases in solution. In pumped systems, there is no steam/brine separation, only single-phase production piping and injection systems. Binary cycle plants are universally used for energy conversion because flashing fluids after lifting them with pumps to feed a steam turbine would have a much lower energy conversion efficiency than using a binary plant. These systems have 100% water injection and so tend to broadly maintain reservoir pressures.

2.2 Typical System Configuration

A typical pumped system has the production well drawing from an aquifer/reservoir of hot water. Pumps are placed in wells below the water level but do not need to be at the feed depth, as the pump will lift water from deeper in the well. Pumps are usually placed within the production casing section of the well. The water being pumped is delivered up a large diameter pipe from pump to wellhead, with the pump and pipe set inside the cemented well casing section of the well. A wellhead arrangement then diverts the water into production pipes that lead to the power (binary cycle) plant.

The geothermal water imparts its heat to the binary plant working fluid through heat exchangers in the binary plant. This is essentially identical to the "bottoming cycle" brine heat recovery binary plant we have on some flash/steam turbine projects, such as at The Wairakei binary plant. The cooled geothermal water is then injected back to the aquifer via injection well. The production pumps typically are designed to impart enough pressure to keep the fluid above steam saturation pressure within the surface production facilities, and this avoids flashing and release of dissolved gases. This tends to avoid issues such as calcite scaling that are common if lower temperature geothermal fluids are flashed. Given the nature of the production and 100% injection, the ratio of the number of production to injection wells is quite low compared to flash systems and can typically be in the range of 1:1 to 2:1.

The behaviour of the reservoir and how we manage production in these systems can also be different to higher temperature systems. While injection to maintain reservoir pressure in high-temperature systems is (arguably) thought to have benefits for sustainability, injection in pumped systems is normally far more important for maintaining reservoir. The power needed for well pumps is directly related to the depth of the water level in the production reservoir, so if reservoir pressure declines, then pumping power increases, with a reduction of net power export. Typically, there are trade-offs between having injection close to production to maintain reservoir pressure but far enough away to avoid early cooling by fluid returns. The liquid flow in the reservoir, particularly in a porous or sedimentary aquifer, can achieve very high heat recovery factors compared to fractured reservoirs. In some systems we have modelled, the water may circulate several times before cooling is seen at the production wells. So, although lower temperature, typically, a more substantial portion of the available heat is recoverable from these systems.

The image in Figure 2 adapted from Panax Geothermal is an older, but explanatory, diagram of the overall process.

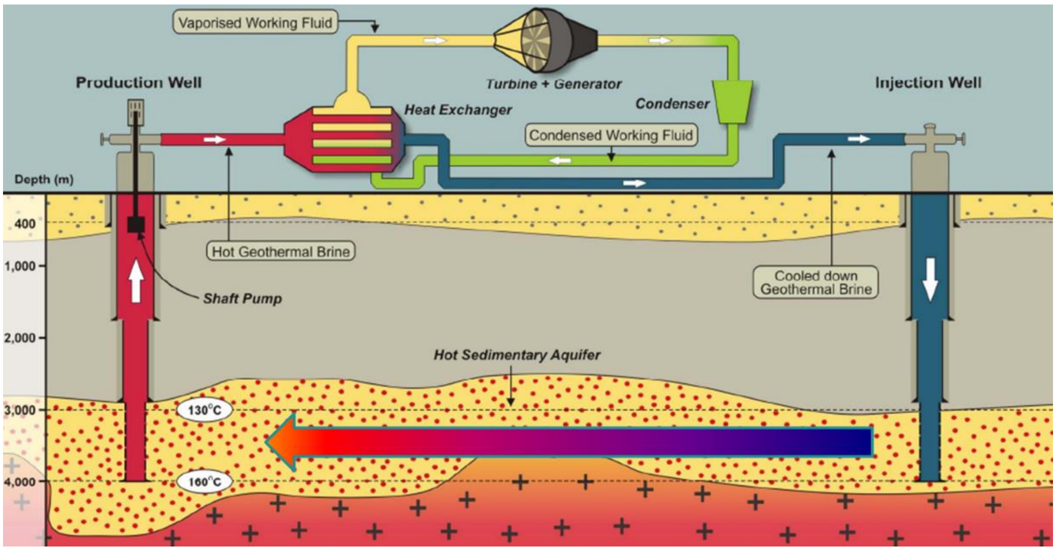


Figure 2. Schematic diagram of a pumped geothermal system for power generation (Panax, 2010)

2.3 Well Pumps

These are the technology that is the most different to that used in the self-flowing geothermal world.

The two types of downhole pumps in use are lineshaft pumps (LSP) and electrical submersible pumps (ESP), distinguishable by the location of the motor. The former has been utilised extensively in the USA since the 1970s, and the latter is less widely used in geothermal applications but are derived from oilfield applications and have been used in France, the USA and Germany.

LSP pumps have the advantage of the motor above ground and can be air-cooled, whereas ESP has a motor downhole and is cooled by the flow of geothermal water. LSP is limited in depth to about 700 m because of technical challenges in running the driveshaft down from the surface to the pump. This section of well needs to be vertical for an LSP. ESP can be run deeper and in deviated sections of wells. But it is the cooling of ESP that appears to be their limiting factor. These motors are MW class and dissipate a lot of heat, and it seems that high flow ESP is limited below 150 °C. Some new ESP variants can do smaller flows at much higher temperatures but overall are not able to deliver the flow rates needed for economic production. For high MW production, it seems that LSP are the only options presently, and these require some skilled installation. A modest local support industry is required for installing and overhauling and these pumping systems. See Figure 3 for images of the surface installation for LSP and ESP.

Figure 3 Lineshaft pump installed at a well in USA (Left, the motor is visible, but the pump is down the well). ESP installation in Germany (Right, wellhead arrangement shown – ESP itself not visible as it is installed in the well)

3. PUMPED SYSTEMS OUTSIDE THE USA

We will first look at how pumped systems have been deployed outside the USA, typically in Europe and as were proposed for Australia under the stimulation of various geothermal tariff schemes. Apart from in Turkey, these have generally been tapping areas where useful hot aquifers are found at depth due to relatively normal conductive thermal gradients. With typical thermal gradients in the range of 30 to 45 °C/km depth, temperatures useful for power generation (>130 °C) can be found at 3 to 4 km depth. But obtaining enough flow requires finding high permeability aquifers at this depth where lithostatic pressure typically is compressing sediments into low porosity and low permeability conditions. The targets are usually some different formations with high primary or secondary permeability, such as the Malm limestone in the Molasse basin of southern Germany near Munich, which has karst features and fracturing that locally can provide good permeability.

Developers have looked for these suitable locations, and that was the target for much of the "boom" in geothermal exploration in Australia in the early 2000s. But the need for high permeability was possibly not universally understood in that Australian boom.

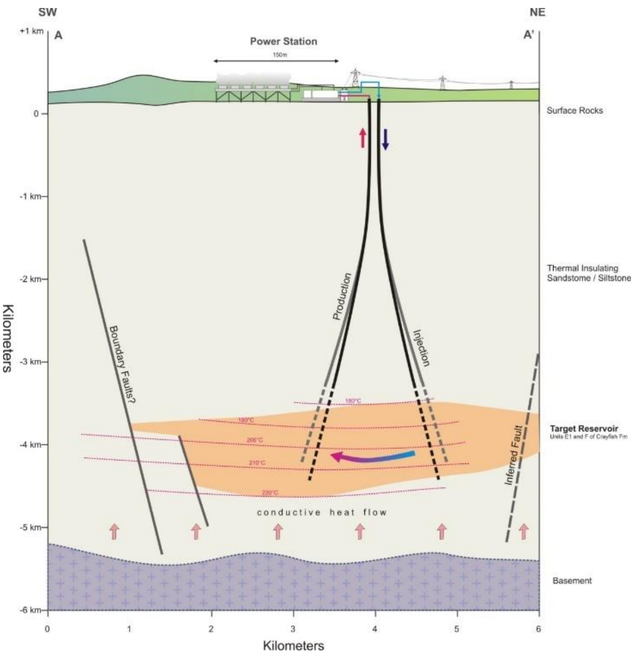


Figure 4 Typical doublet style system deployed in Europe.

The configuration of these systems is often based on a well "doublet" with production and injection wells drilled from common (or nearby) well pads. Because of the depth to target, the wells are deviated and can get separation of 2 km or more at depth in the production zones to minimise the risk of cooling from injection fluids for many decades. This is a similar configuration to that used for direct heat and district heating in Europe, such as in the production systems of the Paris basin.

These systems technically work well if finding the right reservoir conditions. Well production flows of 100-150 l/s are achieved, and 1-2 production wells can feed power plants that are typically in the 5 to 10 MW range.

In Turkey, the tensional tectonic setting, with high heat flow in grabens, provides the higher heat flows that deliver hot waters much shallower than in continental Europe. In these settings, often with carbonate aquifers, there is good permeability and hot fluids at shallower levels. Many of these systems also have high CO_2 content, which means that fluids de-gas and flash at much lower temperatures (for a given pressure) than low gas waters, and wells with high gas feeds will flash and self-flow at surprisingly low temperatures. So, most of the Turkish systems below 200 °C self-flow without the need for pumping.

The European model with doublet systems (or similar) can work anywhere there is a good thermal gradient, and sufficient permeability found at the required depth. But the cost of drilling deep wells dominates the overall capital cost of these projects, and if permeability or temperature is modest, then the amount of power needed for pumping can mean that a major portion of the gross generation is consumed on-site.

4. THE USA EXPERIENCE

Pumped geothermal probably originated (or at least gained scale) in the USA primarily due to developments driven by Ormat and other developers supported by the Department of Energy in the 1980s. The reservoir targets there have generally been hot aquifers at relatively shallow depth, and this is the key to the technical and financial viability of these projects. Finding hot fluids at a shallower depth where permeability is good, and drilling costs are low means that the capital cost of drilling is low, and the parasitic power needed for pumping is low.

There has been steady growth in the amount of pumped geothermal in the USA, and this has led to the overall growth of geothermal power in that market in the last 15 years, often supplanting the shortfalls in capacity from declining production from higher temperature projects at the Geysers and Coso. There is now over 1 GW of binary plant, and most of that is on pumped systems. All of the projects developed in the USA since 2012 have been on pumped systems. These are tabulated in Table 1. This shows the magnitude of development based on surprisingly low temperatures in a moderate power price market with limited subsidy. The USA has only had Investment Tax Credits in the past decade that has stimulated some of these projects.

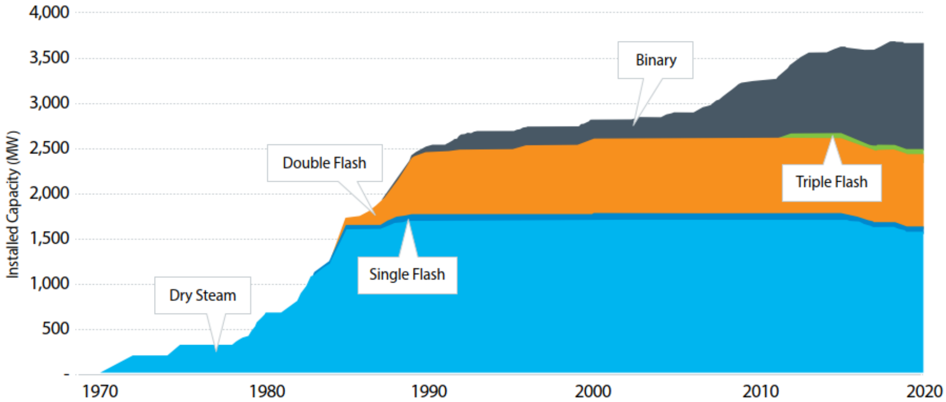


Figure 5. Growth of lower temperature geothermal developments in the USA. (NREL, 2021)

Table 1 Recent pumped geothermal projects in the USA (and Honduras)

Field Name	Development Name	MW (net)	Average Temp	Typical depth (m)	Average MW/well (MW net)	Price (USc/kWh)	Power Provider	PPA Length (yrs)	Contract Start Date
Jersey Valley	Jersey Valley Plant	10	165	950	3.5	6.6	Ormat	20	2012
Neal Hot Springs	Neal Hot Springs Plant	30	137			9.6	US Geothermal	25	2012
San Emidio	San Emidio Plant	8.6	138			8.9	US Geothermal	25	2012
Lightning Dock	Lightning Dock Plant	10	155			9.8	Cyrq	20	2013
Cove Fort-Sulphurdale	Cove Fort Binary Plant (OEC-1 and 2)	25	150	1000-1500	4	7.9	Enel Green Power	20	2013
Wild Rose	Don A Campbell 1	16.2	128	550	4	9.9	Ormat	20	2014
McGinness Hills	McGinness Hills - Phase 1, McGinness Hills - Phase 2	63.7	165	1000	6.5	8.6	Ormat	20	2015
Wild Rose	Don A Campbell 2	19	128			8.13	Ormat	20	2015
Platanares (Honduras)	Platanares 1	30	177	650	7.5	10-13	Ormat		2017

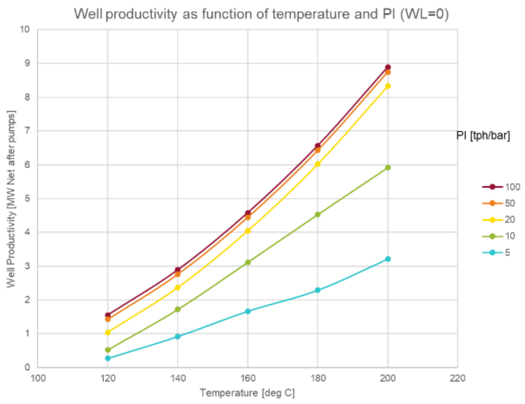
5. KEY PARAMETERS FOR ECONOMIC PROJECTS

Achieving commercial well productivity requires temperatures to be in the higher range (usually above about 150 °C), having reasonable permeability and a high water level relative to the wellhead—the following discussion analyses more of these key parameters that can enable these projects to be viable.

5.1 Well productivity

At lower temperatures, a lot of fluid has to be produced to deliver economic well production. Flows of the order of 150 kg/s or about 500 t/h are typically required. This, in turn, requires good permeability and high flow rate pumps. Complementing the approach presented by Elliot Yearsley to the 41st NZGW (Yearsley, 2019), we used our system models to simulate well productivity for the Indonesia situation.

Common with the approach of the IFC report (IFC, 2013), we tested sensitivity to temperature and productivity index, and the results are presented in Figure 6. This shows that 4-6 MW net is achievable with temperatures of 150 to 180 °C. The clear correlation with temperature is largely because hotter water has more energy, and hotter inlet temperature to the binary plant achieves a higher conversion efficiency. This is why the curves steepen with higher temperatures. However, the need for retaining a positive suction head above the pumps means pumps have to be deeper at hotter temperatures. As reservoir temperature approaches 200 °C, the set depth for pumps can become impractical, and this tends to set an upper limit on practical pumping temperature.



These plots were based on standard commercially available pumps and assuming that pump depth was limited to 700m, and pump power was limited to 1 MW. Interestingly, above a PI of about 25 tph/bar there is little gain in production. This is because the pump flow rate becomes the limiting factor rather than PI.

The power production estimated here is net after deducting the pumping power. Lower PI typically means more drawdown of water levels while flowing and hence more head to lift water within the wells and more pumping power. With pump capacity being a limiting factor, it would seem that this is an area for development, and that is exactly what Ormat has been doing in the last few years. Ormat has been designing and manufacturing larger diameter pumps to enable more MW per well from resources in the common 150-160 °C range. These pumps are larger in diameter and require larger diameter well casings.

Figure 6. Well productivity calculated assuming the standard pump

5.2 Well Depth

The depth of the target reservoir is a key one in achieving economic development. While shallower aquifers are less consolidated and typically have better horizontal permeability than deeper reservoirs, they are also cheaper to drill to. Well cost is directly related to depth because of shorter drilling time and reduced length of well casings. The recent project examples in Table 1 show that most of the recent projects have well depth less than 1000m, sometimes less. Wells are typically vertical, at least in the upper 500m, but can be deviated deeper. Often there may be only one vertical well per pad, but with projects located in flat topography and the rigs being smaller than needed for deeper drilling, pad construction is modest compared to that in volcanic terrain.

These wells have a cost that can be a small fraction of what we are familiar with when drilling to 2000 m or more in higher temperature targets, while at the same time achieving production in MW that is approaching the world average for all geothermal.

5.3 Water Level

The depth of wells and pumping power are both related to the depth of the reservoir's water levels. Water level (hydrostatic pressure in reservoir relative to the surface) has a major impact on pumping power and ultimately limits the flows that may be possible. LSP pumps that achieve the highest flows and work at the highest temperatures are limited to a set depth of about 700m. The water level under dynamic conditions has to be 50m or more above the pump level (depending on temperature and gas content), and so this sets some limits on flow rate regardless of pump capacity. Ideally, water levels should be close to the surface or no more than 100-200 m deep. This means that drilling into a lower temperature reservoir from high terrain such as ridgelines is highly counterproductive, and these systems should only be developed from low elevations in valleys or in flat terrain close to hydrostatic levels.

This topographic effect has a noticeable impact on higher temperature production (though that is not widely acknowledged) but is of high importance for pumped systems. This is why outflows of volcanic systems in low terrain could be useful targets, as well as the structural basin edge systems such as those developed in the USA. a

6. PROJECT ECONOMICS

It is apparent that pumped geothermal projects are being developed in the USA during what has been a period of subdued power growth and limited subsidy, in competition with low cost solar and wind projects, and in a decade when no new geothermal flash plants have been constructed. They must therefore be economical in this environment.

To evaluate the viability for the Indonesia situation, we used a financial model that was developed for the Ministry of Energy in Indonesia and which was designed for estimating target tariffs for geothermal (as also reported by Campen et al., 2017). Aspects of the model were modified to accommodate the parameters for a pumped project and including assumptions of shallower wells, but more production and injection wells, and including the cost of pumps and their periodic replacement. With all other parameters on a like-for-like basis, the model indicated that for a 50 MW class project, the required tariff needed by a pumped well project was within 10% of that for one using conventional steam turbines.

We summarise the comparison between pumped and higher enthalpy flash systems in the following table:

Table 2 Pumped well project vs Flash well project

Parameter	Pumped Well Project	Flash Well Project
Reservoir performance	Typically, quite stable and with a high recovery factor. Modest make-up well requirements over the project life. 100% reinjection minimises pressure decline and reach semi-stable conditions.	Typically have substantial changes in reservoir, and decline will typically cause a doubling of well numbers over the project life.
Well Depth / Cost	Can target shallow aquifers and wells <1000m depth are common. Wells is often vertical and relatively low cost. More well pads, but the developers are in moderate terrains.	The trend has been for deeper drilling for hotter production. Deviated wells, with many from each well pad.

Well numbers	MW per well can be in 5-7 MW range and typically more consistently high once the reservoir is delineated. Production to injection well ratio is low (high injection well numbers)	Well productivity is highly variable across most fields which brings down the average. Exploration failure rates are high and have a higher cost.
Exploration costs	Shallower aquifers can be delineated with low-cost slim holes. The terrain is modest and, if so, modest, the cost for access.	Can use deep slim holes to target deeper reservoir, but often warrants larger wells. Difficult terrain has high logistics costs for access. Higher cost.
Piping System	Relatively simple piping with pressurised liquid. No scaling controls or additional pumping.	2-phase separation, brine pumping and possibly silica scale management. Emergency dump ponds, steam vent stations, pressure control valves. Separate steam condensate injection system.
Power Plant	Standard binary cycle plant. Cost for which have been dropping rapidly in last five years to point we see binary cycle competing against steam turbine plant in current bidding on 2-phase projects.	Variety of options including steam turbines, 2-phase binary and combined cycles.

7. OPPORTUNITIES FOR AOTEAROA

There are likely to be many locations where pumped well production could be considered in Aotearoa (New Zealand). A few examples based on published exploration and well data are provided below. These examples are just presented to stimulate discussion of the types of targets that could be developed – we are not suggesting developments should be considered or are viable on these taonga that are under the guardianship of their respective kaitiaki.

Mokai

Hochwimmer (2015) previously identified that the northern outflow from Mokai is probably an ideal candidate for a pumped well project. This appears to be an extensive shallow outflow, as summarised by Henley and Middendorf (1985) and Ramirez et al. (2009). This has temperatures that could be suitable, although some of the 200 °C areas may be too hot for effective pumping.

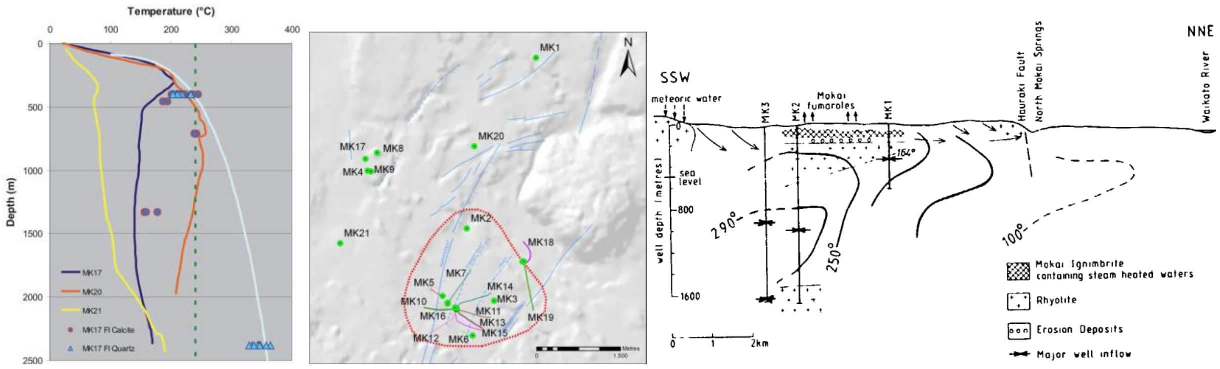


Figure 7. The shallow outflow at Mokai has temperatures of 160-200 °C, over a very large area of the northern outflow. (Two left figures are from Reamirez et al. (2009), and the section on the right is from Henley and Middendorf (1985)).

Kawerau

While almost all of the Kawerau system so far drilled and being produced appears to be a major deep outflow from a hot upflow in the south, there probably are some zones where useful, more moderate temperature fluids reach shallower levels. The northeast area used for injection (KA43, 44, 48, 50) is shown to have 150 ° to shallow levels within the stratified volcanic that may provide some useful permeability.

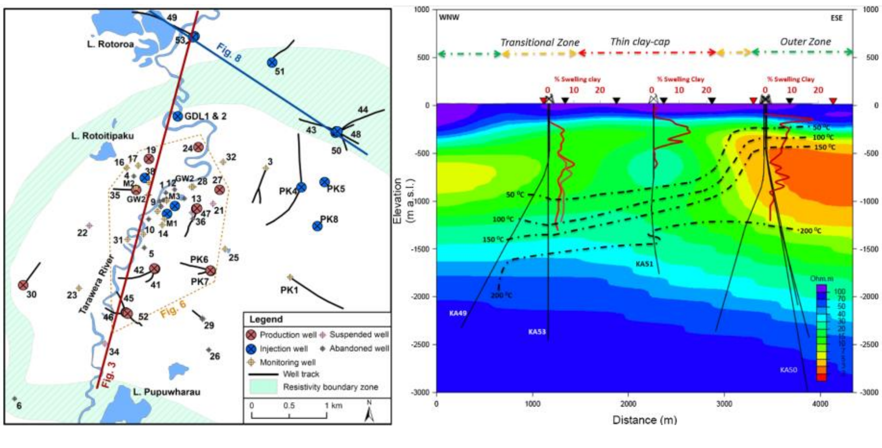


Figure 8. Cross section from northeast Kawera area showing a possible outflow of 150 °C fluid at shallow depth. Map and cross-section from Milicich (2015)

Ohaaki

The Ohaaki field has been in operation for 30 years, and the shallow parts of the field suffered substantial cool water incursion. But common with many drawn down fields, where temperatures are below those suitable for flash production, there may be potential for longer-term pumped well production. Whereas initial production was net mass extractive, using pumped wells with 100% injection may be possible without causing further shallow aquifer effects in this type of situation. Shallow extraction can cause enhanced negative impacts at the surface, so these types of projects need careful evaluation but could be considered.

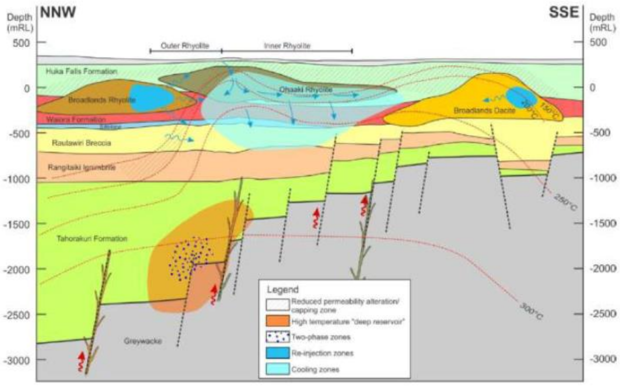


Figure 9. Ohaaki geothermal field, after 30 years of extraction, still has areas of hot fluids at shallow depth. This is an example of possible enhanced extraction for developed fields. Figure from Ratoius et al (2017)

8. CONCLUSIONS

As Aotearoa, New Zealand, heads into a period of growing demand for baseload low carbon energy, we should consider our shallower moderate temperature geothermal resources, which would readily be developed if found in other parts of the world less abundantly endowed with natural resources than ours. The potential for small scale developments may suit some owners once there is a support industry for pump servicing.

9. ACKNOWLEDGEMENTS

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