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Geothermal Water for Mining

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ABSTRACT

This paper conducts a preliminary analysis on the possibility of developing a geothermal resource, for the purpose of using geothermal water as a source of water supply for mines. It presents a general concept and is not represented as being applicable to any particular project. The intent of the paper is to identify a range of approaches to geothermal development that may be possible focusing on the occurrence of these systems in the Altiplano Region of South America. In addition, the paper explores how these different approaches may deliver useful synergies given the demand for both water and power in the region. The co-location of geothermal and mining development activities in this region and the potential synergy between the two industries highlights an opportunity that warrants further evaluation.

In this paper, we have assessed the potential for water production in conjunction with geothermal power development across five representative scenarios, considering a typical high temperature geothermal system in the Altiplano. Investigations seek to identify how the technical differences between these may affect the viability of a development in the context of a commercial operation for power and/or water production in the area of interest. We identify indicative developer requirements in terms of exploration investment (prior to investment decision), capital expenditure and operating expenditure necessary to deliver water, power and a combination of water and power, for five different scenarios. The investments or projects have been sized on the ability to deliver around 500 litres per second (l/s) of water. Importantly, any water produced from the geothermal resource is made available at the geothermal field. Additionally, water production in the combined case means the cessation of any reinjection of geothermal fluid instead the fluid is made available at the geothermal field. Injection is an area for further evaluation under site specific technical viability assessment and also for evidencing that the developer is approaching responsible and "sustainable" management practices.

While the conventional philosophy in geothermal energy development is to target the high temperature resource, which is often situated in areas of rugged and high relief, our financial analyses demonstrates that by accessing the lower enthalpy part of geothermal systems, electricity production using binary technology alongside practical utilization of the geothermal brine can deliver a comparable return on investment to the planned higher enthalpy target.

1. Introduction

The intent of this paper is to identify a range of approaches to geothermal development that may be possible given the systems available in the Antiplano Region of South America and how these different approaches may deliver useful synergies given the demand for a combination of water and power in the region.

Mines and mining activities are scattered across the Antiplano Region of South America. These mines rely heavily on either surface or groundwater for sustaining their operations. Water is mainly used for operational activities that include:

- Transport of ore and waste in slurries and suspension
- Separation of minerals through chemical processes
- Suppression of dust, both during mineral processing and around conveyors and roads
- Washing equipment

Water sources have a high value due to demand for multiple uses and often water used in mining is in direct conflict with indigenous access to water and local concerns about water-dependent ecosystems. Consequently, the pressure on water supply is compelling mining companies to adopt other means and strategies to manage water scarcity.

Nearby many of the mining tenements located in Peru and Chile are potential high enthalpy geothermal fields which are being explored for power generation. A preliminary assessment of the distances from these mines to the nearest geothermal prospect reveals that typically they are within 100 km range of each other, and often with multiple matches between geothermal field and mine development.

Geothermal developments in the region face relatively high costs for development at high altitudes where projects may struggle to meet financial hurdles required for investment. Geothermal projects typically need to achieve exploration milestones for the developer to retain tenure on geothermal licences, and poor financial prognosis for many projects tends to deter further exploration expenditure that could allow projects to be retained until market conditions improve viability. Meanwhile, mine developments that also work through many challenges to demonstrate viability are often finding that water supply is a critical element in that process.

The co-location of geothermal and mining development activities in this region and the potential synergy between the two industries highlights an opportunity that warrants further evaluation.

This paper seeks to conduct a preliminary analysis on the possibility of developing a geothermal resource, across a range of geothermal systems in the Altiplano Region of South America, to meet the potential electricity and water demands in the area.

2. Geothermal Development Scenarios

The hydrothermal systems of the Altiplano regions of Chile, Bolivia and Peru have not yet been developed, but early exploration results indicate that many of these systems may have similar characteristics seen in magmatic arc settings elsewhere (see Figure 1, Hauser 1997, Steinmüler et al., 1997, Vargas et al., 2009).

Heat sources are typically located under high elevation volcanic complexes, with hydrothermal circulation developing above the heat source, and with liquid circulation hydrology controlled by local hydrological base levels that provide the source for circulating water. The high terrain may enable the development of two-phase or steam dominated zones above the convecting liquid reservoir. Fluid that is lifted by thermal buoyancy in the centre of the system provides a hydrological gradient that can drive fluids laterally as outflows (Cumming 2009). Outflows may travel in aquifers comprising unconsolidated volcanics that have good permeability and present geothermal fluids at shallow levels on the flanks of the volcanic system. Thermal springs appear where these aquifers reach surface at topographic low points such as drainage valleys or where vertical permeability is provided by other geological structures such as faults.

The geothermal industry's accumulated experience leads us to normally target as close to the high temperature central part of the system as practically possible to achieve highest well productivity, and avoid the risk of encountering reservoir temperatures that are too low for 'commercial production' (Ussher et. al., 2000; Gunderson et al., 2000). This is the target for typical power developments that need both high quality resource and to secure access to sufficient reservoir to enable a power development that is large enough to achieve the economies of scale that are typically required to achieve a suitable return within constrained power sales pricing.

There are, however, several factors that can counter this common wisdom and should be considered in any geothermal development strategy, particularly if produced water is part of the goal of the development:

- The cost of infrastructure to reach the high elevation area can be great, and much of this cost may be required at exploration drilling stage, using developer's equity, at risk.
- Binary and combined cycle combinations can convert energy from both steam and brine phases produced by medium enthalpy wells such that MW per well is not as low as comparing that available from the steam component alone.
- The refinement of binary plant technologies have allowed reasonably efficient power generation from lower temperature resources.
- Well pumping technologies have improved allowing production from lower temperature wells that cannot self-discharge. The outflows we see from many high temperature geothermal systems are potentially more prolific and shallower to reach than many similar temperature systems that are developed in the US and Europe.

When we consider the potential for water production in conjunction with geothermal development, then consideration of the lower temperature parts of the system may be central to project optimisation because lower temperature reservoirs tend to have a higher proportion of water as a by-product (on a per MW generation basis) than high temperature systems.

We propose that, considering the type of hydrothermal model seen in Figure 1, there is potentially a range of options for developing geothermal production for power and water. It is worth considering how the technical differences between these may affect the viability of a development in the context of power and / or water production.

To facilitate evaluation of the spectrum of possibilities, five geothermal resource scenarios have been outlined and evaluated. The scenarios are summarised in Table 2.1 and graphically identified in Figure 2.

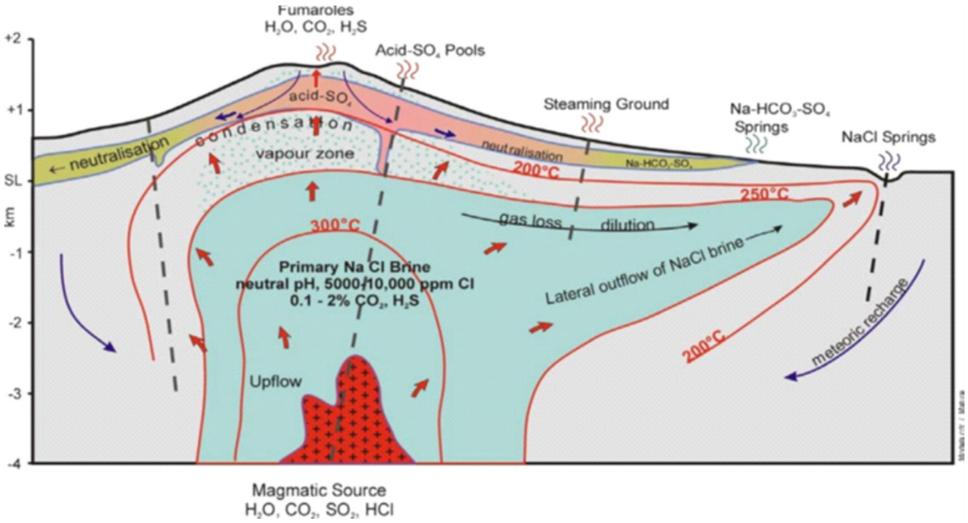

Figure 1. Typical conceptual geothermal system in a volcanic setting.

Table 2.1. Geothermal resource scenarios.

Scenarios	Description	Reference Examples
260 +stm	A high temperature core of the system (260 °C +) that has a 2-phase or steam cap that has substantial thickness and that contributes to well production that has high Well Head Pressure (WHP), and enthalpy. Wells need to be deep to secure both liquid and steam production. The development lies at high elevation and access to this area requires substantial road development. The system is likely to see enthalpy change over time, possibly drying out, but also the steam cap could decline faster than the deep liquid production.	- Olkaria IV area, Kenya - Wayang Windu, Indonesia
260	A liquid high temperature core of the system (260 °C +) is developed providing production at medium WHP, and enthalpy. Wells need to be deep to secure production. The development lies at high elevation and access to this area requires substantial road development. Steam zones may develop over time, increasing enthalpy, and reducing water production.	- Gunung Salak (Indonesia) - San Jacinto (Nicaragua) - Rotokawa (NZ)
200	Medium temperature part of system (200-220 °C) that is seldom considered for commercial production if higher temperature reservoir is available. Requires reservoir to have little under-pressure relative to surface to secure good well production, and wells will operate with low WHP. Steamfield system will probably need wellhead separation. Production could decline if reservoir pressure declines, so injection may be important for field management, unless a strong recharge is provided along the hydrological gradient.	- Asuncion Mita, Guatemala - Mokai, NZ (injection area)
150	Likely to be a distal outflow at about 150 °C but may be located quite shallow in permeable aquifers within upper 500m. Wells must be pumped as in many systems developed in the US. Pumping can sustain production in face of reservoir pressure drawdown, though at a cost in terms of parasitic power for pumping. Injection may be important for field management, unless a strong recharge is provided along the hydrological gradient.	- East Mesa, USA (Intermediate depth reservoir) - Molasse Basin projects, Germany (Deep reservoir) - Mokai, NZ (distal outflow) - Casita, Nicaragua (distal outflows mapped but not developed)
100	Outflow that has cooled and possibly mixed with ground waters, and nominally at or below local boiling point. Located quite shallow in permeable aquifers within upper 500m. Wells must be pumped, but at this temperature a range of pumps are available and proven reliability.	- Lihir, PNG (dewatering of the cooler part of system using ESP pumps)

This paper explores the investment and potential water production and power generation possible across the spectrum of development scenarios illustrated in Figure 2. We identify indicative developer requirements in terms of exploration investment (prior to investment decision), capital expenditure and operating expenditure necessary to deliver water, power and a combination of water and power, given the geothermal resource scenarios identified above.

3. Concept Models

Project concept models have been developed to enable comparison between the different resource development scenarios. The projects have been sized on the ability to deliver around 500 litres per second (l/s) of water which is indicated as a typical minimum scale of requirement for a mine operation. The project size, in terms of number of wells, has been fixed based on water generation is power plant is installed and assumes that steam and brine phases can both be captured.

The most suitable power plant technology for the resources and ambient conditions of the Altiplano is yet to be determined, although it is likely that air cooled binary or combined cycle systems are good candidates given their potential for modular construction and low water use. These plants also provide full recovery of the steam condensate that can provide a source of clean water or be mixed with separated brine.

In the water only cases, less water is available as it is assumed that high enthalpy fluid is flashed to atmosphere to achieve a first stage of cooling, and only the separated brine is available for production. Applying a heat rejection (cooling) system to the two-phase production may enable greater collection of fluid for a given number of wells.

When produced fluid is exported for mine water, no injection wells are assumed to be required and this reduces total project cost. We note that some emergency water disposal is probably required, and should be factored into a more detailed analysis. While injection is usually considered desirable for long term field management and must be considered for real projects, we note that there can be a range of views on the value of injection and will vary case by case. Lower temperature projects in confined reservoirs (such as deeper

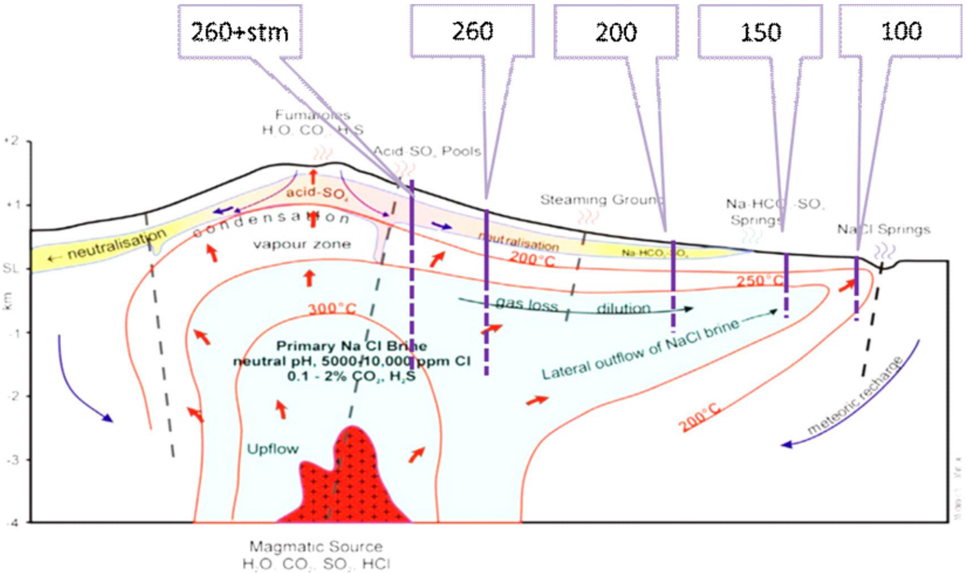

Figure 2 . Indicative development scenarios (labelled as per Table 2.1) (Note that temperatures in the model show 250 °C outflow further than may be expected in reality – hence indicative concept only).

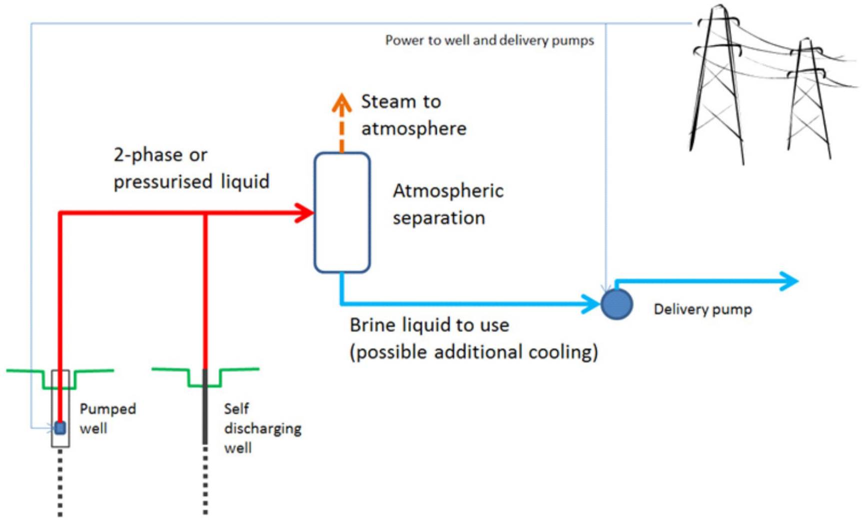

Figure 3. Water production only configuration.

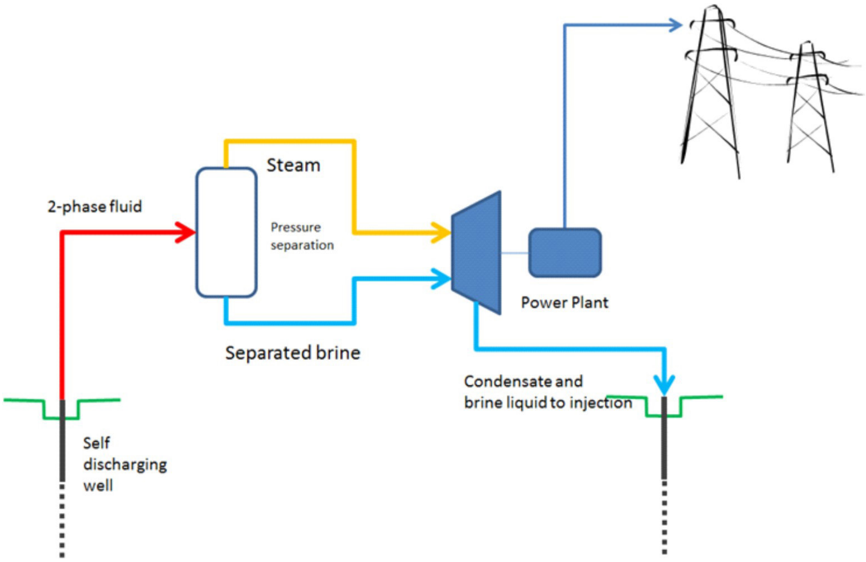

Figure 4. Power production only (assuming only self-discharging wells, power plant could be any type).

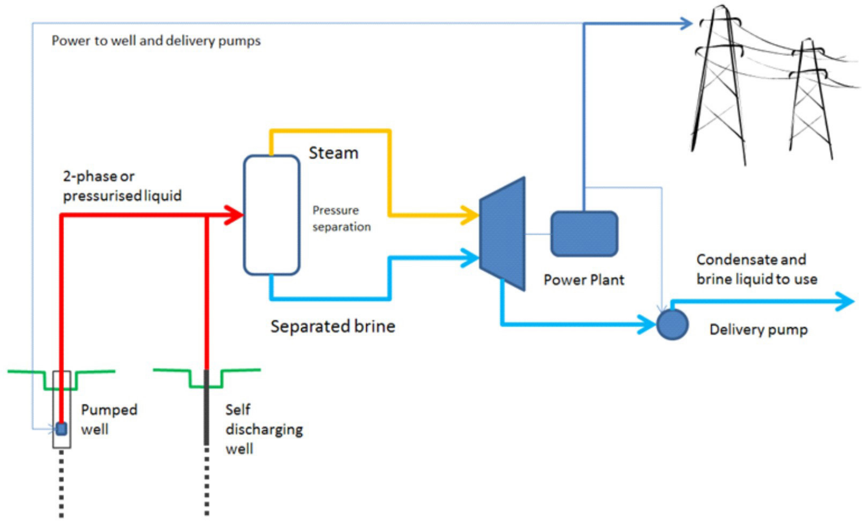

Figure 5. Power and water production configuration.

reservoirs in Nevada and the systems in Europe) tend to rely heavily on injection for pressure support there is potential that outflow systems in the highly permeable shallow aquifers will not require such pressure support. *Injection is an area marked for further evaluation under site specific technical viability assessment and also for evidencing that the developer is approaching responsible and "sustainable" management practices.*

Lower temperature projects need electric power for operating down-hole pumps (either line-shaft or electric submersible pumps – ESP). If a development is to only target water production, power can either come from power generated locally with a small modular geothermal plant (such as a small binary plant) or from power imported via transmission line – the actual case will depend on cost of local generation and transmission distance, but we have assumed local generation in our initial concept models. Transmission lines for power export are considered in the power generation cases as well as low temperature cases where modular plant exists and excess electricity is expected to be on sold.

Access roads are likely to be simpler, shorter and lower cost for accessing lower temperature resource. This may also mean lower cost for initial exploration drilling if the flanks of the system are targeted initially, and hence the capital at risk can be lower in terms of civil works, and also the depth of drilling required.

Based on an assessment of typical geographic layouts relating to the geothermal systems and mine locations, we have assumed that water sourced from high elevation parts of systems will not require further pumping power to deliver water, while lower elevation outflows that may be targeted could require water lift in the order of 500-1000m and has been factored into the concepts considered in this paper.

The general configuration of the three development types (water only, power and water, and power only) are presented below (Figures 3, 4 and 5).

4. Investment Analysis

The following section describes our approach on key assumptions in developing our analysis, taking account of the spectrum of resource scenarios and project concept models discussed above.

Each investment case has been applied to each of the identified geothermal resource characteristics scenarios – the exception being power production from the low enthalpy 100 scenario, as this scenario is considered suitable for water production only and power production is not considered feasible at such low temperatures.

A special purpose vehicle[1] (SPV) has been assumed as an appropriate investment entity for this exercise. This is because of the variation in productive output from one case to another and the opportunity for independent development each of the investments presents. As already highlighted, the investment cases focus on three key productive outputs: (i) power, (ii) water, and (iii) a combination of power and water.

Modelling has been undertaken based on discounted whole of life cash flows deriving investment indicators for each case; internal rate of return (IRR), net present value (NPV) levelised cost of water (LCOW) and levelised cost of electricity (LCOE). A post-tax nominal discount rate of 10% has been applied to cash flows resulting from pre-FID (financial investment decision) and post-FID investment and throughout an anticipated operating life of 25 years.

4.1 Resource Assumptions

Table 4.1 provides the assumptions on general attributes of the geothermal reservoir as a function of the 5 resource temperature scenarios illustrated in Figure 2, Indicative development scenarios (labelled as per Table 2.1). The scenarios assume that steamfield and power plant development is within reasonable distance from the resource.

Table 4.1. Assumptions on the characteristics of the geothermal reservoir at various resource temperature scenarios.

Parameter	Unit	260 °C +steam	260 °C	200 °C	150 °C	100 °C
Temperature	Deg C	260	260	200	150	100
Well Depth	M	2,200	2,500	1,500	1,200	1,000
Enthalpy	kJ/kg	1,800	1,135	852	632	419
Gross Capacity	MW	163.8	71.0	42.0	15.5	---
No. of prod. wells	#	12	9	12	7	7
Net Output / well	MW	15.9	9.1	3.9	3.2	0.88
Net Capacity	MW	152.4	65.8	37.5	13.7	0.0
Net Generation	GWh/yr	1,268	547	312	114	N/A
Water Only	tons/hr (m^3/hr)	767	1,263	1,593	1,821	1,960
Power & Water	tons/hr (m^3/hr)	1,920	1,800	1,920	1,960	1,960

4.2 Revenue and Economic Assumptions

The pro forma model utilizes a number of economic assumptions that have an impact on the proposed business, as shown in Table 4.2.

Table 4.2. Revenue and Economic assumptions.

Assumptions	Value
Capacity Factor	**95%**
Economic Life	25 years
Corporate Tax	30%
Depreciation Rate (Straight-line)	4%
Discount Rate (Post-Tax Nominal)	10%

Debt financing has been excluded from this preliminary analysis.

4.3 Cost Estimates

Table 4.3 presents the cost details for each geothermal development scenario. For this analysis, cost approximations were gathered and benchmarked against industry data derived from Jacobs SKM's accumulated experience in developing similar projects worldwide. The data takes into consideration exploration costs, drilling costs, steamfield development and power plant costs, and civil and transmission costs. Pre-FID[2] investment is separated out as common to each scenario and applicable to all investment cases. For clarity, total capital expenditure is calculated as resource exploration plus a specific investments capital expenditure.

Table 4.3. Cost estimates for each scenario.

Parameter	Unit	260 °C +steam	260 °C	200 °C	150 °C
Resource Exploration					
Pre-FID Capex	Million USD	61	53	39	21
Specific CAPEX					
Power	Million USD	462	289	233	108
Water	Million USD	125	113	143	108
Power & Water	Million USD	425	240	194	95
OPEX (Power)					
Fixed costs	USD(M)/yr	1.0	1.0	0.6	0.4
Plant operating costs	USD/kWh	0.01	0.01	0.01	0.01
Steamfield O&M costs	USD/MW/yr	0.08	0.08	0.08	0.08
OPEX (Water)					
Fixed costs	USD(M)/yr	0.6	0.5	0.4	0.4
Plant operating costs	USD/m^3	0.2	0.2	0.2	0.2
Steamfield O&M costs	USD/m^3	0.8	0.4	0.2	0.1

An important consideration in the present analysis is that any water produced from the geothermal resource is made available at the geothermal field. No allowance has been made for end use water treatment facilities or transportation of water from the geothermal field to end use consumption or treatment plant. Additionally, water production in the combined case means the cessation of any reinjection of geothermal fluid instead the fluid is made available at the geothermal field.

5. Investment Valuation

The results from the analysis for each of the investment cases are summarized in Table 5.1, Investment modelling results, on the next page.

The results suggest the following:

- Where the focused activity is solely for the purpose of supplying geothermal water to mines, the investment appears feasible when targeting moderate to low temperature reservoirs (particularly *150 – 200 deg C*). This, in part, reflects the benefits of an embedded modular power plant to provide electricity for consumption and export of any excess electricity generated. The higher quantities of water produced at lower enthalpy reservoirs, in excess of 10 M m3 per year, also provides greater revenues over the life of the investment.

Table 5.1. Investment modelling results.

Case	Scenarios				
	260 °C + Steam	260 °C	200 °C	150 °C	100 °C
Water Focus					
Water Delivered (m^3/yr)	6,380,536	10,509,073	13,257,585	15,155,931	16,311,120
LCOW (USD/m^3)	4.69	2.59	0.49	1.43	1.91
NPV (USD ' 000)	-105,092	-37,287	120,556	55,924	9,394
IRR	0.00%	6.69%	18.24%	15.40%	11.57%
Power Focus					
GWh per annum	1,268	547	312	114	N/A
LCOE (USDc/kWh)	0.08	0.11	0.13	0.18	N/A
NPV (USD ' 000)	160,362	-15,843	-56,993	-57,896	N/A
IRR	13.82%	9.37%	6.85%	2.98%	N/A
Power and Water*					
GWh per annum	1,268	547	312	114	N/A
Water Delivered (m^3/yr)	15,978,240	14,979,600	15,978,240	16,311,120	16,311,120
NPV (USD ' 000)	331,765	154,396	97,402	68,843	9,399
IRR	17.79%	16.03%	15.20%	16.76%	11.57%

**Calculations are based on a fixed electricity tariff of USDc 0.10/kWh and a fixed water tariff of USD 2.00/m^3*

Notes:

- NPV is based on a nominal post-tax discount rate of 10%
- 200 °C & 150 °C scenarios include generation plant for pumping water with excess generation sold onto grid (note: USDc 0.10/kWh transfer price exists for embedded/ captive generation plant).

- Where the investments main focus is be to tap geothermal water for power generation, the high-temperature case scenario (*260 deg C + steam*) provides the highest IRR at 13.82% and a positive NPV of 160 M USD. This is consistent with common wisdom that tapping higher temperature parts of geothermal systems provides greater benefits when considering power development alone.
- Where the proposed investment utilizes the geothermal water that is separated into steam to generate electricity and brine and condensate channelled for use in mining operations rather than being pumped back into the reservoir, our investment modelling shows that this option may be viable for all scenarios. The benefits of dual revenue streams suggesting returns between 12 and 18%.
- An interesting observation from the analysis is the comparable investment returns between case scenarios *260 deg C + steam* and *150 deg C* with IRRs of 17.79% and 16.76%, respectively. This can be attributed to a combination of lower capital costs coupled with higher water output at 150 deg. This suggests potential advantages when combining the production and delivery of water and power plant development at lower temperature resources.

6. Mining Developments and Their Water Requirements

Peru and Chile are two of the largest producers of copper and molybdenum in the world. The strong mining potential has attracted major international mining companies to set-up and expand activities in both countries. Many of these mines are located in desert or arid environments of the Altiplano. Therefore, access to and management of water is a major issue and a key operational focus of the mining industry in the region.

Equally, several geothermal resource areas within these 2 countries have been recently identified for power generation and direct use. Simple spatial analyses of these resources indicate that in areas where mining development or operations is ongoing, there is likely to be a high or low enthalpy field within reasonable distance from the mine site. A preliminary assessment of this spatial relationship estimated that at least 36 mines in Peru and 34 mines in Chile are within a 100-km radius from an identified geothermal resource area.

We note that mines in Northern Chile and Southern Peru are increasingly using seawater that is generally conveyed from a desalination plant located on the coast to the mine site at high altitudes through extensive pipelines. This is because desalination offers certainty in terms of technical supply and cost. However, this method to deliver water is capital intensive, as shown in Table 6.1 and may affect the hurdle for mine feasibility.

Table 6.1. Comparative matrix on actual use of desalination in Chile vis-à-vis water from proposed geothermal operations.

Feedwater	Capacity (m^3/yr)	Investment Cost	Status
Desalinated Water	16,556,400	200 M USD (50 M USD for the plant and 150 M USD for pumping system)	Operating since 2006
Geothermal Water	16,311,120	95 – 110 M USD	This concept

Source (desalinated water): Global Water Intelligence (www.globalwater-intel.com)

Already, several desalination projects are in various stages of planning and development. Nonetheless, there is a general outlook in the mining community that any alternative which avoids using seawater would be the preferred option, for cost reasons, depending on the location and availability of water. It is for this reason that geothermal water for mining may be a practical and novel solution to the challenges in water management.

Our investigations of water quality requirements for mines indicates that most mine processes have a tolerance for some total dissolved solids of the order commonly seen in geothermal brines, and also warm water has some advantages for certain processes.

It is possible that geothermal waters are suitable without further processing, but this may vary on a case by case basis.

7. Conclusions

Given the number of mines in operation and under exploration and their relative distance to identified geothermal prospect areas, the concept of geothermal water for mining presents a potential opportunity for a geothermal developer to generate electricity while obtaining additional revenue from the supply of excess geothermal fluids, in the form of brine or condensate, to sustain mining operations nearby. While the conventional philosophy in geothermal energy development is to target the high temperature resource, which is often situated in areas of rugged and high relief, our financial analyses demonstrates that by accessing the lower enthalpy part of geothermal systems, electricity production using binary technology alongside practical utilization of the geothermal brine can deliver a comparable return on investment to the planned higher enthalpy target.

Furthermore, we consider that a geothermal developer may be able to leverage off the value of the geothermal water supplied to mines in order to reduce some of the risks and financial exposure in early stages of development. An initial development that uses a lower elevation and more accessible part of the geothermal system may have lower cost for exploration and also for power and water development. There may also be potential for offering joint venture partnership with interested mining companies who can either help provide partial financing to prove and implement the geothermal power and water project or to provide legal guarantee to the developer towards obtaining and upholding the rights to a geothermal concession for development and expansion. This scheme ultimately promotes a synergy amongst investors and may assist in reducing competition for the underground water resource by deterring the mining companies from investing in infrastructure to extract the water themselves.

An initial development for water only or power and water on the outflows of a geothermal system may serve as a mechanism to secure the geothermal licences for a concession and be followed by a later power development located on the higher temperature part of a geothermal system.

The technologies for lower temperature development are well established in the USA (the pumped systems of the southern Imperial Valley, and several projects in Nevada and recently, Oregon) and Europe (particularly Germany). The companies engaged in these projects and their equipment suppliers have developed capability and operational experience that can be drawn upon by the geothermal developer who has experience predominantly in higher temperature systems. Given the different nature of combined power and water projects and a relatively slow geothermal market in the US, there may be opportunity to attract specialist operators who can build and operate binary plants and pumped well production systems, leaving the developer who may be more experienced in developing high temperature systems to focus on exploration, and the development of the main power project.

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[1] A Special Purpose Vehicle (SPV) is an investment entity established for the sole purpose of undertaking a specific investment, rather than an existing company or subsidiary.

[2] Point of Financial Investment Decision (FID) or financial commitment.