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A Holistic Approach to Geothermal Power Plant Option Selection for the Te Ahi O Maui Geothermal Project

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ABSTRACT

There are a number of power plant cycles that can be employed to convert thermal energy in geothermal fluid into electricity. They include back pressure steam turbines, condensing steam turbines (single, and multiple flash), Organic Rankine Cycle (binary), Kalina Cycle (binary), and combined cycles. In addition the conversion cycles require rejection of low grade heat at the surface and various air and water cooling options can be employed for this duty.

An optimum selection of the cycle depends on a number of considerations. The plant should be matched to the reservoir conditions including reservoir enthalpy and chemistry and the production well characteristics. The selection process needs to consider the project location and associated topography, land access, geotechnical conditions and transmission options. Environmental impacts, such as emissions and impact on the reservoir also need to be assessed.

Traditionally project developers will select a power plant option in order to maximise their return on investment by maximising net power and plant availability whilst minimising project development schedule, and capital and operational expenditure for the project. These aspects can be quantified and compared across prospective power plant cycles. Environmental and cultural considerations are sometimes considered as an afterthought or are more difficult to quantify.

The Te Ahi O Maui project, in Kawerau New Zealand, aims to develop the resource beneath the lands of the Kawerau A8D Ahu Whenua Trust. As part of the Te Ahi O Maui geothermal project we have combined a conventional optional selection process with the Mauri Assessment Model.

The Mauri model is a decision-support tool that has been developed to address contemporary practices in a manner inclusive of indigenous (New Zealand) Māori world views and values. It recognises the parallels between New Zealand legislation on sustainable development and Māori values of kaitiakitanga (guardianship and conservation). The four key pillars of the model are: wellbeing; economic; environmental; social and cultural. Under the model a geothermal development has to have a net positive impact across these pillars to be considered sustainable.

The inclusion of the Mauri model provides a holistic option selection framework, and has allowed the cultural impacts of power plant cycles to be compared and assessed in a structured way alongside engineering and economic factors. It has particular application for future geothermal projects in New Zealand developed in conjunction with Māori partners. In addition the principles here can be readily applied globally to achieve sustainable geothermal projects with indigenous communities.

1. INTRODUCTION

Geothermal waters and heat have been harnessed by indigenous people in New Zealand (the Māori) and elsewhere around the world for centuries. Historically the geothermal energy has been harnessed in a direct sense, for instance through bathing, fish farming, horticulture, or drying processes.

Power plant technology has been developed to utilize geothermal energy for generating electricity. In 1904 geothermal steam was used in Larderello, Italy to drive a small turbine to power electrical lighting. From these humble beginnings plant technology has evolved to a range of possible configurations that can be deployed to produce hundreds of megawatts of electrical power from a geothermal resource.

The optimum selection of plant configuration depends on the nature of the geothermal reservoir and expected well characteristics, project location and topography, land access, geotechnical conditions and transmission options. Environmental impacts, such as emissions and reservoir sustainability also need to be assessed.

The traditional development approach has been to focus on maximizing the return on investment, by maximizing net power whilst minimizing project development schedule, capital, and operational expenditure for the project. Cultural considerations have, in the past, sometimes been considered as an afterthought or have been difficult to quantify for the project.

In the New Zealand context, Māori trusts have had a key role as land owners for geothermal developments (McLoughlin et. al., 2010) and will continue to do so in the future. Accordingly it is appropriate to consider Māori values of kaitiakitanga (guardianship and conservation) as criteria in the plant selection process. Past work, by others (Hikuroa et. al. (2010)), has considered these values for an overall geothermal project development. This current paper considers plant selection in more detail, and defines appropriate cultural factors to be applied in a structured way with engineering and economic factors. This plant selection process has been considered with particular reference to the Te Ahi O Maui geothermal project currently under development.

2. THE TE AHI O MAUI GEOTHERMAL PROJECT

The Te Ahi O Maui (TAOM) project proposes to design and construct a geothermal power plant on a site 2.3 km NE of the Kawerau township (Figure 1) in the eastern Bay of Plenty of New Zealand.

The A8D land block contains features with specific cultural and historical significance, in particular Te Wai U o Tūwharetoa (a sacred spring). The project has a development charter to deliver the project in a culturally acceptable way to the A8D trust.

The TAOM Maui power plant will be designed to generate approximately 15-20 MW net of electricity, with around 15,000 tonnes of geothermal fluid extracted daily from the geothermal reservoir. Between 70% and 100% of this fluid will be reinjected back into the reservoir to ensure that the field is able to be replenished. The exact amount of reinjection will depend on the final configuration of the plant.

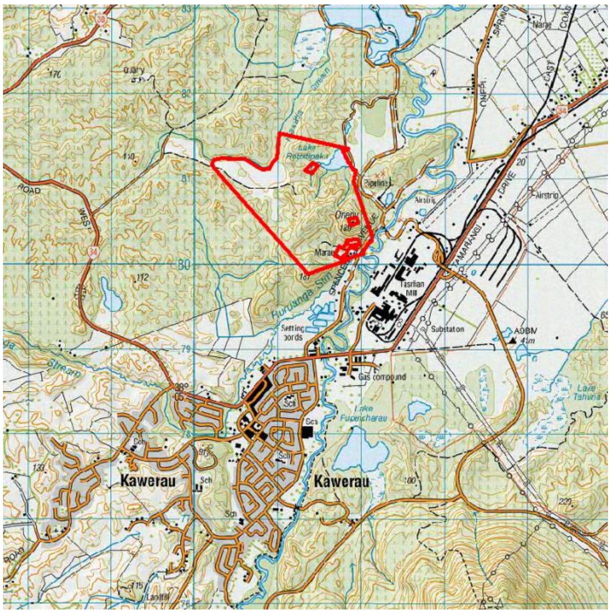

Figure 1: Location plan of Kawerau A8D, outlined in red.

3. POWER PLANT CYCLES FOR ELECTRICITY GENERATION

Kawerau is a liquid-dominated high-temperature geothermal field. This means that a wide range of power plants are technically feasible for generating electricity. The main types considered here are outlined below. The options described are not exhaustive.

3.1 Back Pressure Steam Turbines

Backpressure steam turbines are relatively simple industrial plant. After passing through the turbine, separated steam exhausts to atmosphere. They are generally limited to small machines (< 10 MW), and in a stand-alone sense are not very efficient when compared to other options.

Separated geothermal brine is normally re-injected into the reservoir. The quantity depends on the enthalpy of the resource, that is, higher enthalpy fields will produce more steam with a corresponding lower proportion of brine for reinjection.

3.2 Condensing Steam Turbines

Condensing steam turbines are typical for higher enthalpy fields. Single, double, or even triple flash cycles can be considered if supported by the resource conditions. A simplified schematic of a single flash system is shown in Figure 2, and a double flash system in Figure 3.

Separated and cleaned steam is passed through a condensing steam turbine to produce electricity. The steam is exhausted to a condenser at low (vacuum) pressure. The lower pressure increases heat extraction from the steam and increases power output. This may be twice as much from the same steam flow as a back pressure unit. The plant is more complicated, and requires a cooling system to be designed comprising of a cooling tower, pumps, and chemical treatment systems.

The cooling tower uses an evaporative process, with a visible plume. Non-condensable gases are extracted from the steam and are dispersed using the cooling tower (these gases are toxic and must be appropriate disposed of (Ware and Hochwimmer (2010)).

In this configuration brine and surplus geothermal condensate is re-injected into the reservoir. The proportion of reinjection depends on the separation pressure and fluid enthalpy. For TAOM this is expected to be about 77% combined brine and condensate.

Subject to the chemistry of the field additional equipment may be required. In particular silica can be a significant issue and may require pH modification of the separated brine to mitigate the risk of silica deposition in brine lines and reinjection wells. This is normally achieved through injection of acid into the brine.

Multiple flash systems are more efficient, although requiring additional equipment, which introduces additional complexity.

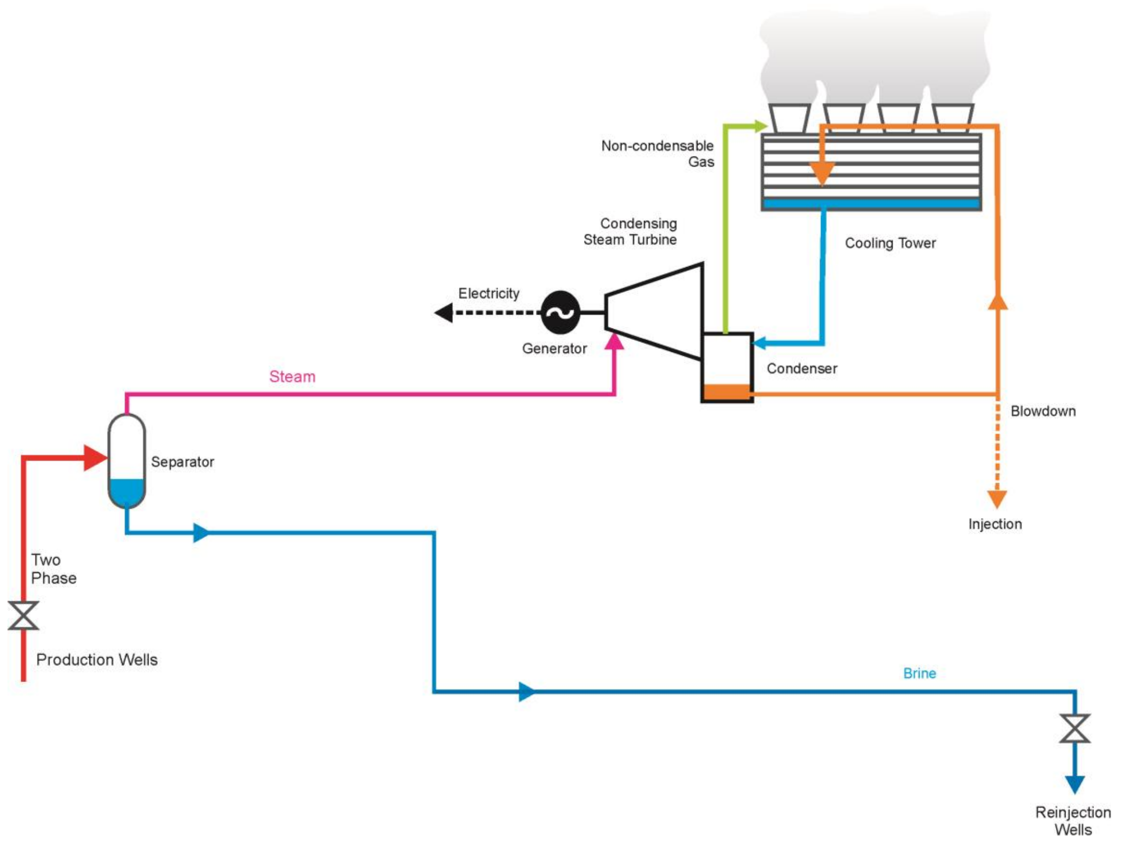

Figure 2: Single flash steam condensing power plant schematic (simplified)

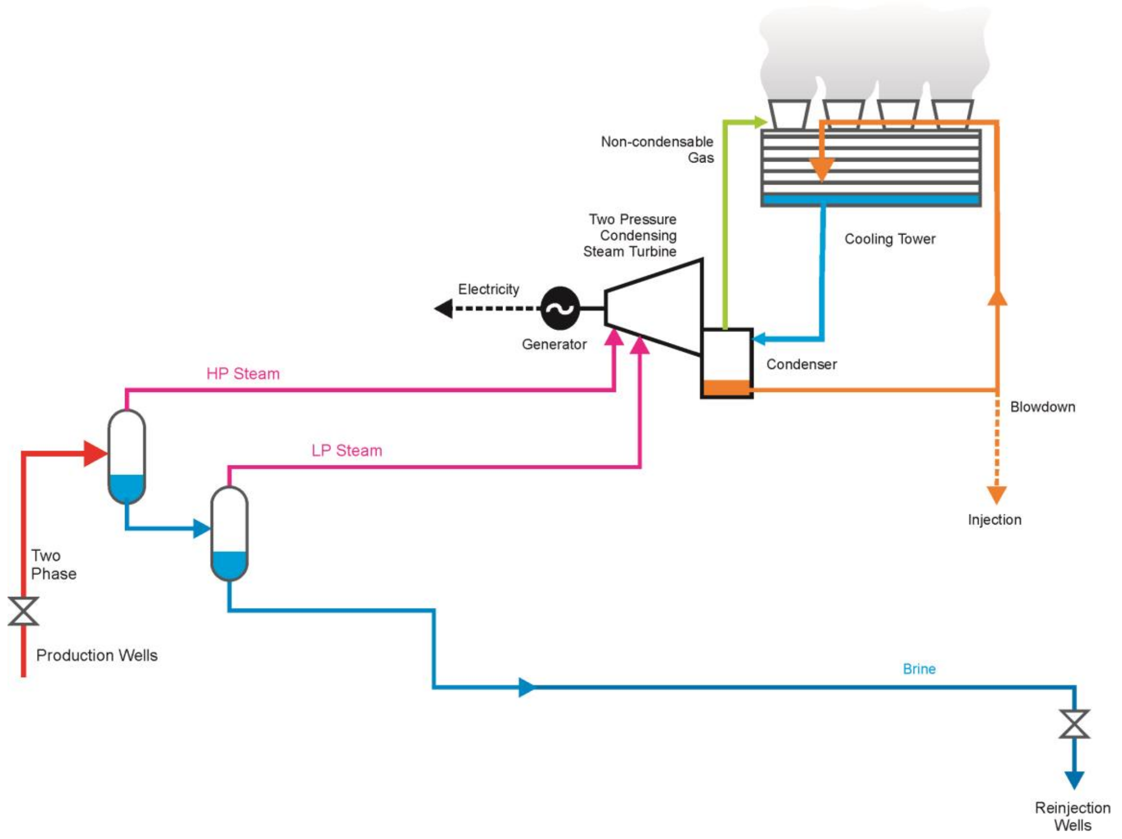

Figure 3: Double flash steam condensing power plant schematic (simplified)

3.3 Organic Rankine Cycle (ORC) / Binary

Organic Rankine Cycle (ORC) power plants are typically used to utilize low temperature heat sources for electricity generation. In some situations that require 100% reinjection of geothermal fluids they are also deployed for higher enthalpy projects.

ORC plants for geothermal applications have been in operation since 1952 (DiPippo, 2012).

The so-called binary cycle uses a secondary working fluid in the turbine, such as a volatile hydrocarbon like pentane or a synthetic refrigerant, rather than the geothermal fluid. The heat rejection system at the surface is an integral part of this configuration, and there are various options that can be considered (see for example Hochwimmer et. al. (2013)).

3.3.1 Dry Air Cooling

Dry cooling is typical of binary plants that are located in areas without a ready supply of water or where water take is environmentally or culturally unacceptable.

In this process heat is removed from the working fluid by passing air, by fans, over a bank of tubes containing the working fluid, in a ‘fin-fan’ air cooled condenser structure. Figure 4 shows one possible configuration where separated geothermal steam and brine is passed through separate steam and brine binary units before the condensate and brine is combined for reinjection.

Dry cooling systems require a large physical footprint to achieve the required heat exchange area. There is no visible cooling tower plume. Non-condensable gas is vented at the unit, with near 100% reinjection of reservoir fluid achieved.

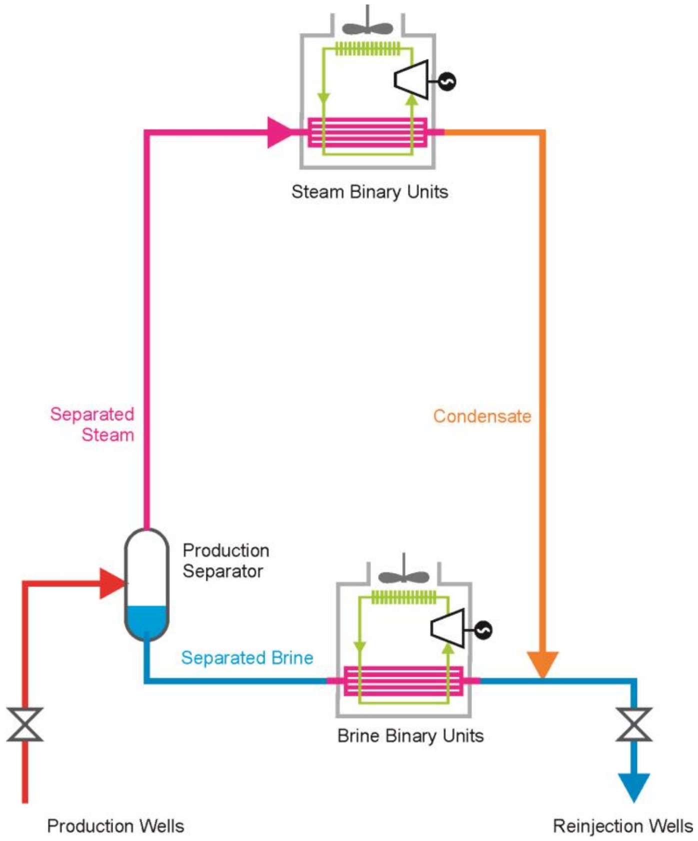

Figure 4: Separated steam and brine fed binary power with air cooled condensers (simplified)

3.3.2 Wet Evaporative Cooling

In wet cooling, heat is removed from the working fluid by exchanging it in a non-contact shell and tube condenser with cold cooling water from a cooling tower. Heat from this cooling water is then removed by evaporation of a portion of this cooling water. As with the flash condensing option a plume can be visible in certain conditions. Wet evaporative cooling is a more efficient engineering process due to a combination of sensible and latent heat transfer. Figure 5 illustrates this process. A key distinction to the flash condensing option is that this configuration is a net consumer of cooling water, and as such requires a water supply independent of the geothermal reservoir.

3.3.3 Once through Cooling

A once through cooling system also uses a non-contact shell and tube condenser. Cooling water (from a river, lake, ocean) flows through the condenser in a ‘once-through’ fashion to remove heat from the working fluid. Once the cooling water flows through the condenser it is returned to the water source or body at an elevated temperature. It is a non-consumptive use.

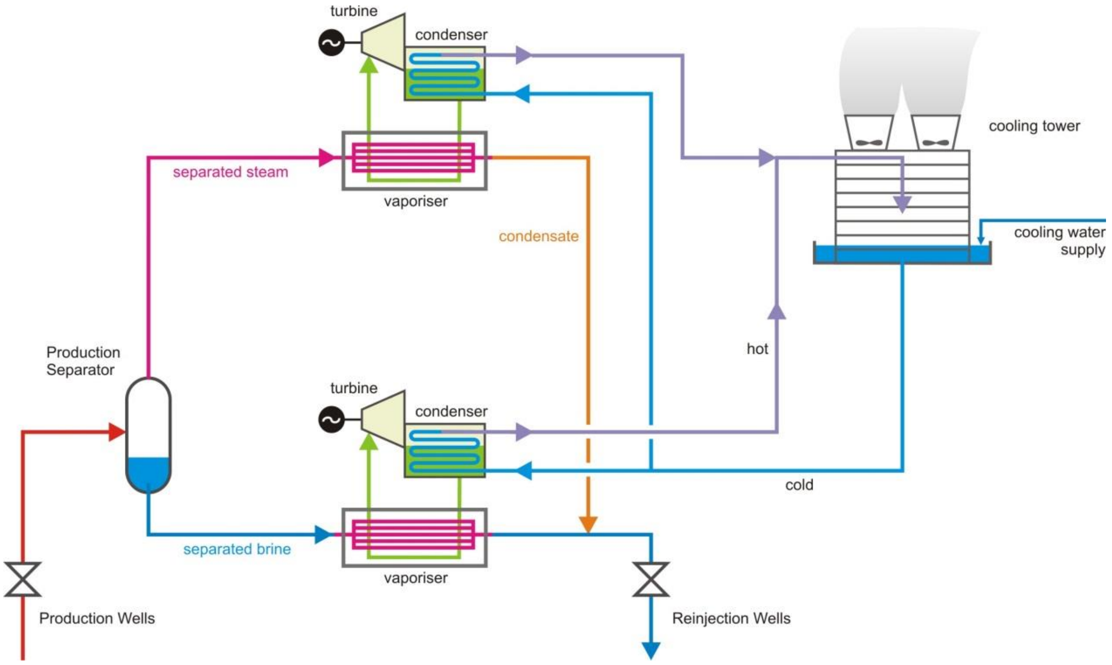

Figure 5: Separated steam and brine fed binary power plant with evaporative cooling tower (simplified)

3.4 Other Cycles

A range of other cycles can also be considered. Options include the Kalina cycle, which is a binary type configuration utilizing an ammonia-water working fluid mixture, as well as combinations of the main flash and binary elements. A single flash condensing plant with binary cycle on the brine stream is one option. A further option, shown in Figure 6, is the 'geothermal combined cycle' which uses a back pressure turbine, exhausting to steam binary unit with the separated brine powering a brine unit. This option removes the requirement for vacuum condenser and gas extraction plant and can be attractive in certain settings.

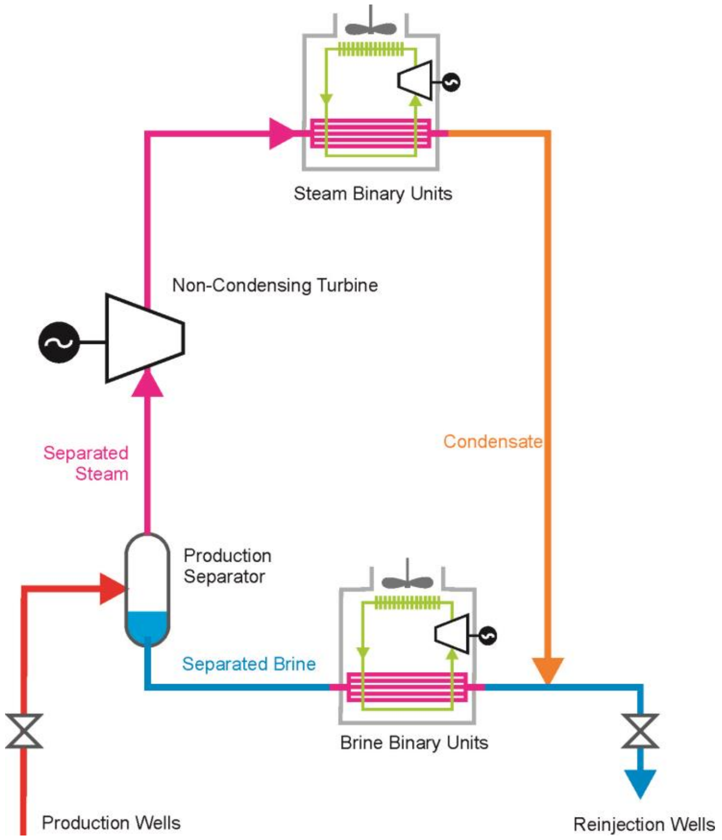

Figure 6: Non-condensing turbine (back pressure) with steam and brine binary units 'geothermal combined cycle' (simplified)

4. POWER PLANT SELECTION FACTORS (NON-CULTURAL)

The power plant cycles described in earlier can be compared in different ways. Bouche (2010) considers the key technical considerations for plant design to include:

- Reservoir Conditions
  - Production and injection well characteristics
  - Enthalpy
  - Chemistry
  - No condensable gasses
- Plant Siting
  - Topography
  - Access
  - Geotechnical Characteristics
  - Transmission
- Environmental conditions
  - Meteorological data
  - Plant emissions

In a general sense an understanding of likely changes in reservoir conditions is also an important consideration in selecting a power cycle and/or making provision in the engineering design to accommodate this change or uncertainty.

In addition to the design criteria considerations a developer needs to consider other factors. These include commonality of spares/operations/experience across an existing operating fleet, plant complexity, and security of water supply (if required).

The approach taken is to consider three classes of factors.

1) The primary definitive items relate to capital cost, and power output. These are assigned a relative weighting of 75%. Safety and environmental compliance (in the regulatory sense) are also considered as high priority for the project but it is assumed that all plant cycles being evaluated are established and acceptable technology. If there is expected to be significant variation in development schedule across cycles they can be included in this category.
2) Secondary qualitative items consider items that are perceived to have a second order impact on the project economics, and consider future expansion, commonality of spares and operation, plant degradation with changing resource, and treatment of non-condensable gases. These factors are assigned a relative weighting of 15%.
3) Other qualitative items consider plant complexity, chemical scaling, and plant overall footprint. These factors are assigned a relative weighting of 10%.

The factors considered for the TAOM project are summarized in Table 1. These are not exhaustive and in different settings there may be additional factors to consider. Within each class items are ranked equally.

The weighting of each class is somewhat arbitrary. In actuality each non-cultural/engineering item will have an impact on the project economics to a greater or lesser degree. Whilst the primary definitive items are relatively easy to quantify, the other items are either qualitative or have considerable uncertainty in the earlier stages of a project.

Table 1: Summary of Engineering Criteria

Primary Definitive Items (75%)	Net Power Output (Design Point)	Secondary Qualitative Items (15%)	Plant degradation with resource change (off-design pressure and enthalpy)	Other Qualitative Items (10%)	Plant complexity
	Annualized Net Generation (incorporates availability, and performance with ambient variability)		Commonality with operations/experience with existing fleet		Brine processing and controls (e.g. pH modification)
	Capital Cost – Power Plant		Expansion opportunities, including available site space		Stibnite scaling risk
	Operating Costs		Option "headroom" (plant improvement with higher off-design enthalpy)		Oxygenation of condensate (corrosion risk)
	Capital Cost – Steamfield and Transmission		Human resourcing requirements		Layout considerations (physical footprint, geotechnical requirements)
			Plant degradation (mechanical)		Economic factors, including commonality of spares with existing operating fleet.
			Variation in non-condensable gas levels		
			Security of supplementary water supply		

Economic evaluation is undertaken standalone to the engineering factors, although they are inter-related. That is a preliminary net present value assessment considering generic forecast power prices and screening level capital cost estimates.

5. MAURI MODEL

5.1 Overview

Mauri is a concept that permeates Māori thinking and has been shown as a suitable measure of project sustainability. Mauri is defined as the binding force that holds together the physical and spiritual components of a being or thing (Morgan, 2006).

The Mauri model is a decision-making framework that addresses contemporary practices, such as the development of a geothermal power generation project, in a manner inclusive of indigenous world views and values. It was originally created to improve water management processes by making them inclusive of all the knowledge sources available. It has since been considered in other applications, including geothermal developments as a whole (Hikuroa et. al., 2010).

This model has been applied by the A8D trustees with regard to a separate assessment of restoration of land negatively impacted by industrial waste (Hikuroa, 2011). Accordingly there was confidence in the underlying process for application to the TAOM geothermal project.

The Mauri model recognizes the parallels between existing New Zealand legislation on sustainable development and Māori values of kaitiakitanga. In particular the Resource Management Act (2011) requires any development activity that impacts the environment to hold a resource consent. The consent process must address economic, environmental, social and cultural aspects. The RMA process assumes equal status, and the conventional view is to assign 70% to economic wellbeing, with 10% on other factors. Māori groups apply weightings of 35% environmental, 15% economic, 20% social, and 30% cultural. (Hikuroa et. al., 2010). These relative weightings, summarized in Table 2, have been applied in this context.

Table 2: Mauri Model Wellbeing and Ranking

Environmental	35%
Economic	15%
Cultural	30%
Social	20%
Total	**100%**

Within the Mauri model, economic effects are categorized in the context of the mauri of the whanau (extended family). It represents the direct effect on a family's wellbeing and capabilities.

Upholding traditional cultural values has been recognized and assessed through this model. A development, or in this case the selection of a suitable power plant configuration, has to address wellbeing across all the categories in order to be viewed as sustainable.

5.1 Mauri Model Criteria

5.1.1 Environmental Criteria

The following environmental criteria were considered in the Mauri model:

- Water use (non-geothermal)
- Water use (geothermal)
- Air emissions from the project, i.e. non-condensable gases including H_2S and CO_2
- Air emissions compared to other base load electricity generation
- Motive/binary fluids, i.e. flammability, greenhouse gases
- Geothermal condensate disposal
- Reservoir impacts, i.e. reinjection %, impact on reservoir enthalpy and pressure
- Cooling tower plume
- Chemicals used in power plant processes, i.e. biocide, acid, caustic
- Thermal pond drainage to ground
- Layout considerations, i.e. physical footprint

5.1.2 Economic Criteria

The following economic criteria were considered in the Mauri model:

- Project Net Present Value, i.e. financial modelling
- Expansion opportunities
- Direct use/cascade potential

5.1.3 Social Criteria

The following social criteria were considered in the Mauri model:

- Sustainability
- Employment for local community (where appropriate)
- Education
- Safety (no one gets hurt physically or spiritually)
- Visual impact
- Noise

5.1.4 Cultural Criteria

The following cultural criteria were considered in the Mauri model:

- Kaitiakitanga
- Excluded lands
- Capacity for Marae use
- Protection of geothermal springs

5.2 Mauri Model Assessment

An assessment of each of the indicators listed in section 5.1 is made on a course -2 to +2 scale as shown in Figure 7. If an indicator has a positive net effect it scores as either +1 or +2. Likewise a negative effect is scored as either -1 or -2. If no impact is likely then a value of 0 is assigned. An example of a negative impact would be cessation of springs, or use of fresh water as a result of development.

Our assessment of a selected number of power plant configurations provides a range of results between 0 and 1, indicating net positive effect on Mauri. The range of results is shown overlain on Figure 7.

Specific scores of individual technology options are not presented at this time as the project is currently underway in the procurement and tender preparation process. This process is commercially sensitive. The overall holistic ranking results, of which the Mauri Model is an input, will be used to guide final technology evaluation and selection for the project.

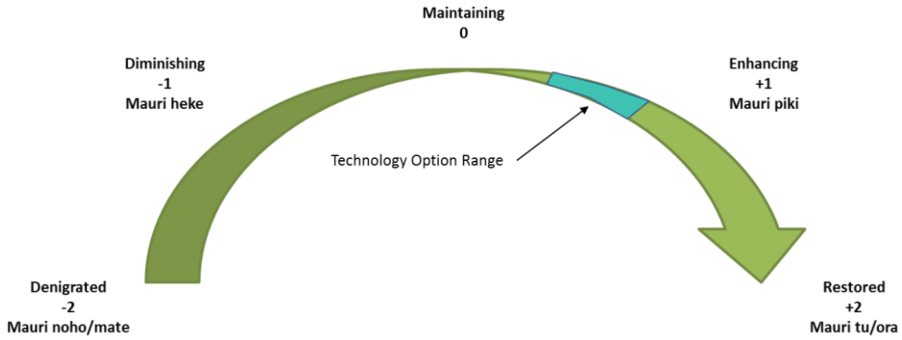

Figure 7: Graphical representation of the Mauri assessment ('mauriometer').

6. A HOLISTIC APPROACH TO GEOTHERMAL POWER PLANT OPTION SELECTION

The holistic approach undertaken combines the engineering, economic, and Mauri model assessments to rank power plant configurations.

As discussed earlier each category has its own relative weighting system which is applied.

Table 3: Holistic Ranking Spreadsheet

Plant Type	Engineering		Economic		Mauri Model	
	Score	Rank	Score	Rank	Score	Rank
Configuration 1						
Configuration 2						
…						
Configuration n						

This approach has obvious application for future geothermal projects in New Zealand developed in conjunction with Māori partners. In addition the principles here can be readily applied globally to better achieve sustainable geothermal projects with indigenous communities.

7. CONCLUSIONS

The inclusion of the Mauri model provides a holistic option selection framework for geothermal power plant selection. It allows the broader cultural impacts of power plant cycles to be compared and assessed in a structured way alongside engineering and economic factors. It recognizes and is consistent with the regulatory consenting process embodied in the Resource Management Act within New Zealand.

This approach significantly provides an opportunity for broader stakeholder involvement in what has traditionally been a technical/economic optional selection exercise.

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