INVESTIGATING RETROFITTING AN EXISTING GEOTHERMAL POWER PLANT WITH A BIOMASS GASIFIER FOR ADDITIONAL POWER GENERATION

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ABSTRACT

This paper investigates different hybrid configurations for integration of biomass gasification into an existing geothermal power plant in order to generate additional power. Gasification is a promising energy technology for New Zealand and a hybrid plant in areas where supplies of wood residue and geothermal resources coexist represents a potentially attractive first step in its utilization. Four hybrid configurations were examined to retrofit a biomass gasifier into the Wairakei Geothermal Field. Each of the configurations were evaluated against operational constraints that exist in the field..

Configuration 1: Superheating of geothermal steam for more efficient power generation. A maximum of 12 MWe additional power generated with a 14 t/hr wet wood input with a wood-electricity energy efficiency (LHV) of 31.4%.

Configuration 2: Syngas fired heating used to boil condensate available on site for additional steam generation. A maximum 6.5 MWe of additional power generated with a 16 t/hr wood input with a wood-electricity energy efficiency (LHV) of 15.5%.

Configuration 3: Boiling separated geothermal water immediately after the first separation stage. A maximum 7.3 MWe of additional power generated with a 16 t/hr wood input with a wood-electricity energy efficiency (LHV) of 17.5%

Configuration 4: Heating of separated geothermal water available at Wairakei to increase power generation at an existing binary power plant. A maximum 1.4 MWe of additional power is generated with a 3.5 t/hr wood input with a wood-electricity energy efficiency (LHV) of 15.4%

The resulting electrical efficiencies are generally lower than for gasification gas engine power plants, but are encouraging in suggesting a novel route to the deployment of biomass gasification plant in NZ. The hybrid concepts examined show significant merit in terms of improving current geothermal steam utilization at Wairakei.

1.0 INTRODUCTION

New Zealand has historically generated a large proportion of its electricity from renewable energy resources; with approximately 80% of the electricity generation in New Zealand coming from renewable sources in 2014. This is due mainly to the utilization of hydro and geothermal resources. However, current market conditions and difficulties with bringing new large scale renewables project to fruition offers opportunity for the introduction of novel approaches to augment current renewables generation though improved utilization of existing resources.

This study examines the potential for integration of biomass gasification as an additional fuel source in a geothermal power plant so as to increase steam production and to improve the steam quality and thus the isentropic efficiencies of the geothermal power system. Possible approaches to integrating gas firing into the steam system were investigated and the derived hybrid configurations modelled using the heat and material balance software UniSim to estimate the additional power generation possible. Experimental work was limited to measurements on steam/condensate in the existing geothermal systems so as to establish steam purity and required cleanup approaches. The study also addresses some of the practical problems related to silica carryover and plant integration so to allow the utilization of biomass synthesis gas to directly heat geothermal steam.

1.1 Hybrid Power Generation

Hybrid power generation is the generation of electricity using two or more fuel sources integrated such as to increase the stability of power generation and/or increase plant efficiency[1]. Geothermal power applications have been used with both biomass and solar resources for hybrid power generation.

A biomass/geothermal power plant has been in operation since 1989 in Honey Lake, California. Geothermal resources are used to preheat boiler feed water, and biomass (in the form of forest trimmings, urban wood waste, and sawmill byproducts) used to generate steam for use in a turbine[2].

An integrated solar/geothermal plant is also currently in operation in Nevada. The Stillwater plant combines solar photovoltaics, and an Organic Rankine Cycle (ORC) plant using geothermal brine for power generation. Originally the plant was an ORC plant that only utilized high temperature geothermal brine. However, declining reservoir pressures caused the power output of the plant to decrease and solar photovoltaics were introduced to supplement the power generation from the ORC. Though there was not direct hybridization of these two power sources, some electrical equipment was shared. However, in 2014 parabolic troughs were added in order to concentrate solar energy to increase the temperature of the geothermal brine before entering the ORC plant. This addition of solar thermal power generation adds 2 MWe to the power generation of the plant. It has similarly been suggested that concentrated solar thermal energy could be used in conjunction with biomass gasification in order to provide the heat for gasification [3]. These hybrid power plants illustrate that different renewable sources of power generation may be hybridized in order to attain a greater efficiency than if each were utilized separately [4].

1.2 Biomass Gasification

Gasification is the process of converting a carbonaceous fuel to a gas with a usable heating value; this gas is called synthesis gas, syngas, or producer gas. Syngas can be burned directly to supply heat, or used to produce work in a gas engine or a gas turbine. In special circumstances the syngas can be further converted to produce chemicals or liquid fuels. Gasification can occur in several different types of gasifiers; with fixed or fluidized bed material, and utilizing updraft or downdraft flow configurations. The bed material used within the gasifier can also be selected in order to aid in gasification, with some bed materials acting as catalysts to the reactions being carried out within the gasifier. Biomass gasification is near commercial and can exist in conjunction with other industrial activities, such as wood processing as there are often large quantities of biomass available that are byproducts or waste products [5].

1.2.1The University of Canterbury's Gasifier

The University of Canterbury has undertaken significant research into gasification [6]. Figure 1 provides a schematic of the 100 kWth dual fluidized bed (DFB) gasifier developed and tested by the university.

In this gasifier, the combustion of char and makeup fuel occurs in the first fluidized bed, which is a circulating fluidized bed (CFB), which then passes heated bed material to the second fluidized bed. The second fluidized bed is a bubbling fluidized bed (BFB), which uses the high temperature bed material to provide the necessary heat for the gasification reactions. Figure 1 illustrates the flow paths of the biomass, air, steam, flue gas, and syngas within the gasification system.

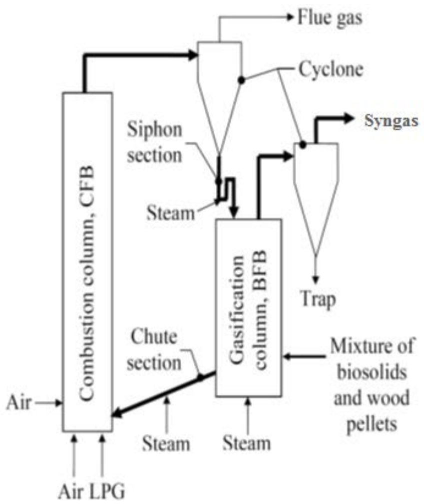

Figure 1. The Dual Fluidized Bed used at the University of Canterbury[7].

Of importance to this study is the overall energy balance within the gasifier, steam requirements for gasification and the parasitic electrical load required during operation.

1.3 Wairakei Geothermal System

The Wairakei Geothermal Field utilizes a liquid dominated geothermal reservoir. Predominantly two-stage flash separation is used to generate first intermediate pressure (IP) steam then low pressure (LP) or intermediate low pressure (ILP) steam. The Wairakei Geothermal System has three steam power plants: the Wairakei Power Plant, the Poihipi Rd Power Plant, and the Te Mihi Power Plant. These plants are connected by a steam manifold, which allows the geothermal steam to be distributed to each of these plants as demanded. The Wairakei Power plant is the oldest of the power plants, having been commissioned in 1958. Due to this, steam is preferentially utilized at the Poihipi Rd and Te Mihi Power Plants, as these utilize the geothermal steam more efficiently.

A large amount of separated geothermal water (SGW) is produced from separating the two-phase fluid extracted from the reservoir. As the SGW is still at high temperatures some SGW is used to provide heating to other companies such as a prawn farm and local hot pools. SGW is also used to provide the heat for the Wairakei Binary Plant. The SGW is disposed of predominantly by reinjection, with some discharge into the Waikato River.

1.4 Reason for Investigation

Though gasification is a promising renewable technology, there are very few commercial biomass gasification plants. This is generally attributed to the relatively high cost of biofuels compared to the fossil fuel alternatives. However, if the capital costs of a biomass gasification plant can be reduced by hybridization with an existing power plant, this may help make the gasification plant viable. It is also likely that power generation using a hybrid gasification/geothermal plant will have a higher efficiency than a standalone biomass electricity generation plant, as is commonly the case with hybrid power plants[8].

The combination of steam extraction limits imposed on the Wairakei Geothermal Field and the preferential utilization of steam at Te Mihi and Poihipi Rd, results in some unused capacity for power generation at the Wairakei Power Plant. The ability to capture this benefit would also improve the business case for hybrid generation.

Wairakei is proximate to the largest area for commercial forestry in New Zealand. (Central North Island Plateau) Thus retrofitting the Wairakei plant (or other geothermal power plants in this area) with a biomass gasifier offers the potential for an economic supply of fuel gas to augment existing steam make. While the electricity demand is decreasing, many geothermal power plants are relatively old. Hybridizing geothermal and gasification technologies will also serve to provide incremental capacity for these plants, and extend the life of the geothermal reservoirs.

2. PROPOSED HYBRID CONFIGURATIONS

Four potential configurations for integrating biomass gasification into the Wairakei Geothermal System to augment the power generation were investigated.

2.1 Configuration 1: Superheating Geothermal Steam

This configuration is perhaps the simplest concept of the different hybrid configurations. Power generation from steam turbines is proportional to the enthalpy change of the steam across the turbine. Superheating the geothermal steam will increase the enthalpy of the steam, and result in a larger amount of power generation for the same mass flowrate of steam. The concept of superheating geothermal steam is by no means a new one; it has been proposed from as early as 1924 by Coufourier [9]. An investigation into the superheating of geothermal steam using natural gas at the Ohaaki (previously known as the Broadlands) geothermal field undertaken in 1980 for the New Zealand Energy Research and Development Committee by the Kingston, Reynolds, Thom and Allardice Consultancy [10] showed that significant improvement in thermodynamic performance was possible More recently, the idea of using a biomass boiler to superheat geothermal steam was investigated by Thain and DiPippo [4]. A simplified diagram of the superheating of geothermal IP steam to utilize in a modified steam turbine is displayed in **Figure 2**.

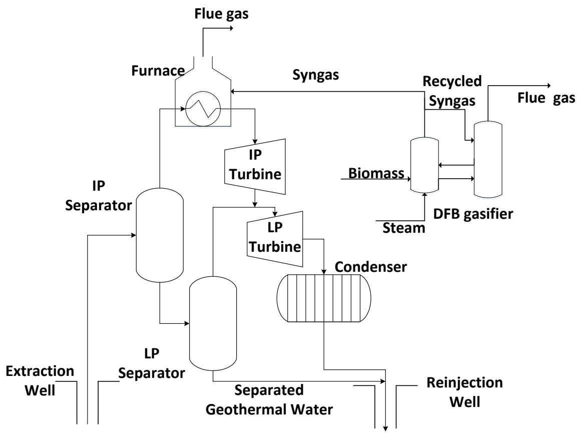

Figure 2. A simplified diagram of Configuration 1

2.2 Configuration 2: Boiling Geothermal Condensate

In this configuration, a boiler is installed to augment IP steam supply. In order to reduce the operating costs for the boiler, it would be advantageous to utilize water available on site for the feed water. The majority of the water available at the Wairakei site is in the form of SGW, and the high dissolved mineral content of the SGW would be problematic if used as boiler feed water in a traditional boiler.

However, the solubility of minerals in water is generally much higher in the liquid phase than the gas phase, and this raises the possibility to utilize the steam condensate from the geothermal steam turbines as a source of boiler feed water; as dissolved minerals (and gases) have effectively been removed from the condensate.

Even though the Wairakei A Station is currently the only Station with capacity to utilize additional steam, it is possible to position the boiler elsewhere on the steam manifold and still utilize this unused capacity. If the additional steam generated is added to the IP manifold, this will result in less steam being diverted for use at the Poihipi Rd and Te Mihi Power Plants from the Wairakei Power Plant. Doing so allows the condensate from any of the steam power plants on the Wairakei Geothermal System to be used as boiler feed water in order to produce additional power at the Wairakei A Station. A schematic of this configuration is shown in Figure 3.

Preheating of the steam condensate is performed using the high temperature SGW available on site in order to increase the steam production of the boiler.

The utilization of steam turbine condensate as boiler feed water also reduces the risk of mineral scaling in the geothermal steam turbines. This is because the steam produced by boiling the geothermal condensate will have a lower mineral content that the source geothermal steam, as the blowdown on the boiler will remove the majority of the minerals in the condensate. This helps to increase the life expectancy of the steam turbines and decrease the frequency of plant shutdowns.

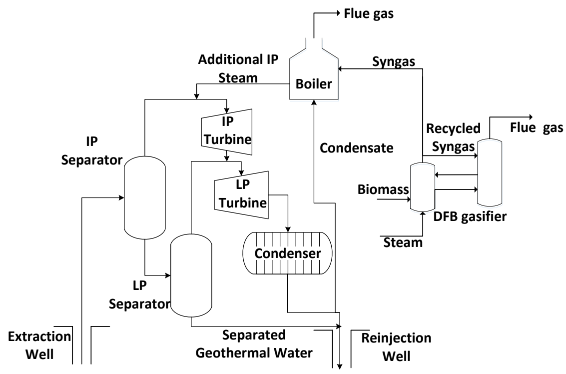

Figure 3. A simplified diagram of Configuration 2

2.3 Configuration 3: Boiling IP SGW

In this configuration separated geothermal water (SGW) after the first separation stage is used as boiler feed water in order to generate additional IP steam. As the IP SGW will still be at approximately the same temperature and pressure as the IP steam, any heat added to the IP SGW will result in additional steam generation. By boiling IP SGW, the amount of SGW being passed to the second separation stage will decrease, and consequently there will be a corresponding decrease in LP or ILP steam production. However, there are limits on the amount of ILP steam, which may be produced from Flash Plant 14 (FP14) on the Wairakei Geothermal System. Therefore the IP SGW from Flash Plant 14 is used to create additional IP steam without necessarily affecting the amount of ILP steam generated in the second separation stage. A simplified diagram of this configuration is displayed in Figure 4.

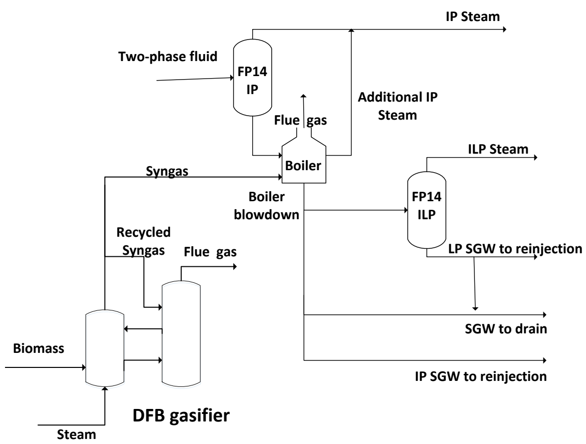

Figure 4. A simplified diagram of Configuration 3

2.4 Configuration 4: Heating Additional SGW to use in the Wairakei Binary Plant

The Wairakei Binary Plant was designed to produce an average of 15 MWe, however the Binary Plant is currently producing an average of approximately 13 MWe. This is attributed to the flowrate of SGW to the Binary Plant being lower than the designed flowrate of 2800 t/h. The current average flowrate of SGW to the Binary Plant is estimated at 2300 t/h. The current source of SGW being used in the Binary Plant is at approximately 130°C, and constitutes the highest temperature SGW available. However, the use of a second source of SGW will provide additional SGW to the Binary Plant. However, increased silica precipitation has been observed when two sources of SGW are mixed, If, on the other hand, both sources of SGW are at the same temperature then silica precipitation is unlikely to occur.

Therefore it is proposed to use syngas-fired heating on a second, lower temperature, source of SGW to increase its temperature to 130°C and thereby augment the flow of SGW to the Binary Plant. A simplified diagram of Configuration 4 is displayed in Figure 5.

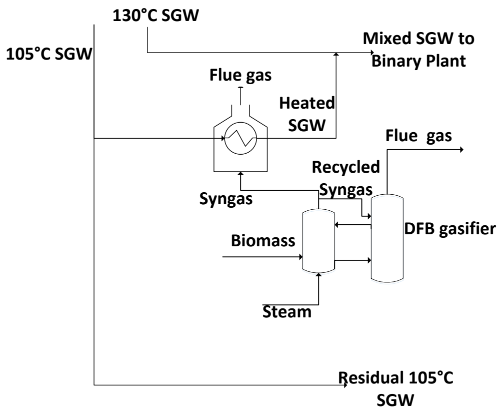

Figure 5. A simplified diagram of Configuration 4

3.0 OPERATING FACTORS

3.1 Modifying Steam Turbines to use Superheated Steam

There are four types of steam turbines in service at the Wairakei A and B Stations: one IP turbine, three LP turbines, one ILP turbine, and three MP turbines, as shown in Figure 6. If any of these turbines were to be modified to utilize superheated steam, there would be limitations on the temperature and pressure of the superheated steam imposed by the design and materials of the turbines. The operating pressure of the turbines would not change, due to designed pressure of the existing turbines.

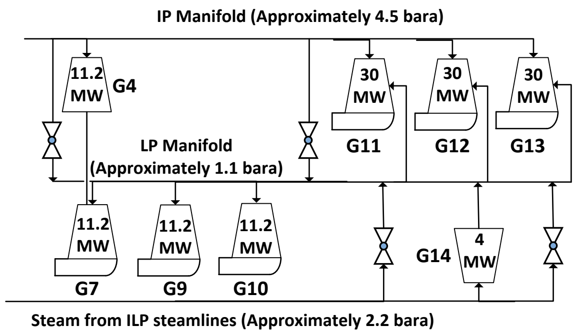

Figure 6. The steam turbines at the Wairakei A and B Stations

The superheat temperature is also limited by the creep range of the low alloy steel at 370°C[11]. Applying a safety margin of 20°C, limits the superheat temperature to 350°C [12]. The volumetric flowrate of steam to the turbines would need to remain constant, in order to avoid damage to the turbines, unless modified. This results in a lower mass flowrate of superheated steam, and thus potentially limits the benefits from superheating the steam.

Because of these constraints, it was decided that modifying the MP steam turbines at Wairakei to operate using superheated steam would likely be the best option. As the LP turbines are designed for LP steam, there are limited benefits in superheating the LP steam and retaining it at the LP steam pressure. Also, the outlet conditions of an LP turbine would likely be above the saturation line, which could cause problems when condensing the steam after the LP turbine. The IP turbines exhaust the steam into LP manifold, and if superheated steam was fed to the IP turbines, the resultant exhaust would be at a higher temperature, and therefore have a lower density than LP steam. The LP turbines would likely require modifications in order to ensure they are utilizing the higher temperature LP steam efficiently.

The MP turbines condense the IP steam input, and the LP steam added at the second pass would reduce the likelihood of superheated outlet conditions. However, caution is needed when superheating the IP steam, as evaporation of any liquid carryover present in the geothermal steam may produce small flecks of precipitated minerals. These particles will be extremely abrasive to the process equipment [12]. The particles may be able to be eliminated from the feed by utilizing high efficiency separators, and scrubbers. However, currently the relatively large distances between separators and turbines at Wairakei cause the majority of liquid carryover from the separators to form on the walls of the steam lines, and subsequently be removed in drain pots. This passive liquid removal may make further liquid removal unnecessary.

In order to utilize superheated steam in the MP turbines, modifications would need to be performed on the turbines. As there will be a reduced amount of condensation occurring in the turbines, there will be a change in the speed of the steam passing through the turbine. This will likely require new blades, nozzles, and diaphragms for the turbines. Many of the turbine casings are made from grey iron, this will likely be unsuitable when steam at 350°C is used [13]; thus new turbine casings may also be required.

It has not been possible during the course of this study to investigate all these issues in depth and thus they are recorded here as potential areas for further investigation.

3.2 Steam Condensate Purity

There are several sources of water available at the Wairakei Geothermal System: the condensate at the Poihipi Rd Power Plant, the blowdown at the Te Mihi Power Plant, and the blowdown from the Wairakei Power Plant. As direct contact condensers employ Waikato River water as the cooling agent are used to at the Wairakei Power Plant, the resultant blowdown is likely unsuitable for direct use, due to the minerals and oxygen present in the Waikato River. The Te Mihi blowdown system also operates using direct contact condensers before it is further cooled in cooling towers, and a portion recycled to be used as the cooling agent in the condensers. The Poihipi Rd Power Station is unique on the Wairakei Geothermal system, as it uses a shell and tube condenser to generate its condensate.

Steam boilers have strict tolerances on the purity of the feed water in order to ensure safe and reliable steam generation. Minerals present in the feed water may precipitate and cause scale in the boiler, which will decrease heat transfer, and can cause damage to the boiler. Corrosion may also occur within the boiler if the oxygen content of the boiler water is above recommended levels. For this study, the purity requirements for the boiler feed water and boiler water were taken from the American Society of Mechanical Engineers [14], and are shown in Table 1 and Table 2 respectively.

Table 1. The ASME boiler feed water guidelines

Drum pressure	Boiler feed water				
	Iron	Copper	pH	Oxygen	Hardness
bar	*ppm*	*ppm*	*pH units*	*mg/L*	*ppm as $CaCO_3$*
0 - 20.7	0.1	0.05	8-9.5	0.007	0.3

Table 2. The ASME boiler water guidelines

Drum pressure	Boiler water			
	Silica	Alkalinity	TDS	Conductance
bar	*ppm*	*ppm as $CaCO_3$*	*ppm*	*µS/cm*
0 - 20.7	150	700	700-3500	7000

Water sampling was performed on the Poihipi Rd condensate and Te Mihi blowdown in order to evaluate their suitability as boiler feed water. It was found that the Poihipi Rd condensate had a significantly lower mineral and oxygen content than the Te Mihi blowdown. The results, which apply to the ASME guidelines, are displayed in **Table 3**.

Table 3. Water testing results

Species	Units	Poihipi Rd Condensate	Te Mihi Blowdown
Iron	*ppm*	<0.021	<0.021
Copper	*ppm*	<0.00053	<0.00053
pH	*pH units*	7.3	4.6
Oxygen	*mg/L*	0.55	6.4
Hardness	*ppm $CaCO_3$*	<0.219	<0.236
Silica	*ppm*	<0.011	0.05
Alkalinity	*ppm as CaCO3*	11	1.5
TDS	*ppm*	<10	26
Specific conductance	*µS/cm*	22	83

As can be seen pH dosing and deaeration will likely need to be performed on the Poihipi Rd condensate in order for it to be used as boiler feed water. However in all other respects the Poihipi Rd condensate meets the purity requirements.

3.3 Reduction in Metal Discharge to the Waikato River

The Wairakei Geothermal System has limits on the amount of minerals that may be discharge to the Waikato River. As the SGW contains dissolved metal, this limits the amount of SGW which may be discharged to the river, and consequently can limit the total two-phase fluid extraction.

If Configuration 3 were implemented, then the concentration of minerals in the SGW by boiling some of the water out of the SGW would serve to decrease the total quantities draining to the Waikato. As there are limits on the amount of SGW that may be reinjected, a reduction in the amount of IP SGW passing to the second separation stage would not reduce the amount of SGW reinjected, but would reduce the amount of SGW draining into the Waikato. The greater concentration of metals in the SGW would therefore lead to an overall decrease in the discharge of minerals.

3.4 Silica Deposition in the Wairakei Binary Plant

An interesting observation made during the course of this study was that despite the average flowrate of SGW to the Binary Plant being lower than the designed flowrate, SGW is seen to frequently bypass the Binary Plant.

The SGW bypassing occurs when no more SGW can be used in the Binary Plant. This difference in the capacity for the Binary Plant to use SGW and the designed flowrate is attributed to silica scaling occurring within the binary plant. As can be seen in Figure 7, the flowrate of SGW entering the Binary Plant (black) increases after the silica removal in July. This also corresponds with a decrease in the bypassing SGW flow (red). However, it can also be seen that, even when there is no SGW bypassing occurring, the SGW flow to the Binary Plant is generally lower than the designed flowrate (blue).

Therefore if silica removal is performed more frequently it is likely that additional heated SGW supplied to the Binary Plant would increase power generation.

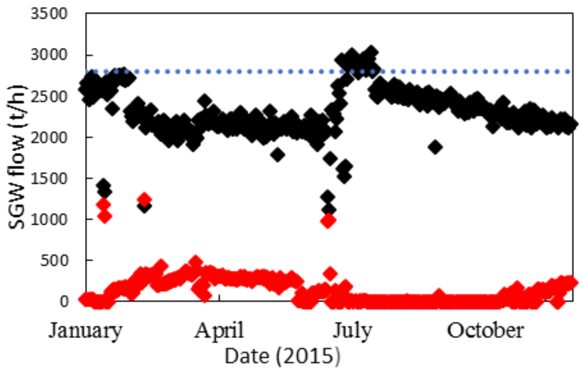

Figure 7. The estimated SGW flow to the Binary Plant (black), bypassing SGW (red), and design flowrate (blue)

3.5 Steam Flow to the Wairakei A and B Stations

Account also needs to be taken of the fact that the remaining life of the Wairakei A and B Stations may be shorter than the estimated life of any additional process equipment required for hybridization. Currently, the resource content for the Wairakei A and B Stations ends in 2026. Alternatively another Power Plant could be built in order to utilize the geothermal steam which will be unused in the absence of the Wairakei A and B Stations.

The steam flowrate to the Wairakei A and B Stations has been observed to be decreasing over time. This is generally attributed to declining average enthalpy of the two-phase fluid, the mass extraction limits imposed on the amount of the two-phase fluid that may be extracted, and the preferential use of steam at the Te Mihi and Poihipi Rd Power Stations.

Due to this, it is expected that the flowrate of IP steam to Wairakei will decrease in the future. The steam flow to Wairakei can alter the loading of the turbines. Consequently, the utilization factors of any additional steam generated by supplemental firing, as is suggested here, will be impacted by the geothermal steam flow to Wairakei. This will affect the efficiency of the hybrid configurations, and determine if turbines need to be recertified in order to utilize the additional steam.

3.6 Bypassing IP Steam

Currently IP steam sporadically bypasses from the IP manifold into the LP manifold at the Wairakei A and B Stations. This generally occurs when the flow of IP steam to Wairakei is larger than the IP steam capacity of the IP and MP turbines to utilize IP steam. If an IP turbine which had been removed from service at Wairakei were recertified, it would be possible to utilize the bypassing steam as well as the additional IP steam generated by a hybrid configuration in the IP turbine.

There are two pressure relief valves to bypass the IP steam from the IP to the LP steam manifolds. The Valve opening positions of these valves are measured, but there is no estimation of the bypass steam flow quantities. In this study bypass steam was calculated from the difference between the measured steam input to Wairakei and the expected IP steam use of the IP and MP turbines (estimated from the power generation of the turbines). However, as there is significant uncertainty associated with the flow measurements of IP steam, and estimated steam use, this method often gave positive results for the amounts of bypass steam when the bypass valves were both closed. To correct this anomaly the actual valve positions were then used to remove these estimates.

The resultant estimated bypass IP steam flow is shown in Figure 8. It can be seen that the bypass flow is steadily decreasing with the decreasing flow of IP steam to Wairakei.

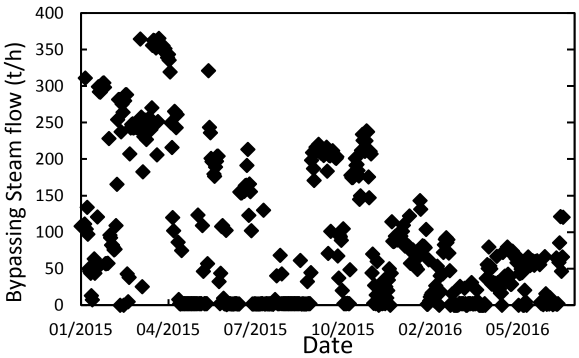

Figure 8. The estimated IP steam bypassing the IP manifold at Wairakei

4.0 PROCESS MODELLING

4.1 Gasification Model

The modelling of the biomass gasification was based on a model of a DFB gasifier created by Pulidian in her PhD studies investigating the synthesis of liquid fuels from biomass [15]. The model used in this study was created using the heat and material balance software, UniSim. This model was then modified to better suit the generation of syngas for combustion, as required for the hybrid configurations. Pulidian's model calculated the composition of the syngas based on the temperature of the BFB, and the steam input to the gasifier. The additional heat that was required for gasification was then calculated, and a corresponding amount of LPG added to the CFB reactor.

There are quite strict requirements on the composition of syngas used for Fischer-Tropsh synthesis with, for example, contaminant removal and further processing required. For combustion purposes, syngas cleaning requirements are much less stringent. Therefore superfluous process equipment could be removed from the Pulidian model. The resultant model, as used here, calculated the flow and composition of the syngas, and was optimized to provide the necessary heat for gasification and drying of the biomass prior to gasification.

4.2 Modelling of the Hybrid Configurations

4.2.1 Configuration 1: Superheating Geothermal Steam

As the volumetric flowrate of steam to the MP turbines had to remain constant for both the saturated and superheated steam cases, there is a resultant decrease in the mass flowrate of steam to the modified MP turbines. This reduction in mass flow of steam limits the potential gain in power generation from superheating. However, reduction in steam mass flow to the modified MP turbines would allow this steam to be utilized in other turbines. Though, conversely, in order to maintain consistent volumetric flow through both passes of the MP turbine, additional LP steam would need to be added to the second pass of the modified MP turbine.

A UniSim model was created in order to estimate the potential power generation from the modified turbines, the turbine outlet conditions, and the performance of the steam superheater. The syngas from the gasifier was modelled to be combusted in order to superheat the IP steam input to the MP turbines.

4.2.2 Configuration 2: Boiling Geothermal Condensate

A UniSim model was created to estimate IP steam generation from a boiler using Poihipi Rd condensate as boiler feed water. The maximum average steam generation from the boiler was set by the average available Poihipi Rd condensate, at 54 t/h. As there is SGW available in close proximity to the Poihipi Rd condensate at 106°C, the condensate was preheated to 100°C prior to the deaerator. Deaeration was performed on the Poihipi Rd condensate by recycling a portion of the IP steam generated in the boiler to further raise the temperature of the condensate to 103°C, in order to facilitate the desorption of oxygen. The vent rate from the deaerator was set at 14% of the recycled steam, in order to ensure adequate removal of the desorbed gasses. Pumping was performed on the condensate both before the preheater, and after the deaerator in order to achieve the necessary pressures for the deaerator and the boiler. Syngas from the gasifier was then combusted in a boiler to generate additional IP steam. Blowdown from the boiler was set at 2.5% in order to ensure the total dissolved solids in the boiler water did not exceed the limits in Table 2.

4.2.3 Configuration 3: Boiling IP SGW

It was assumed that there was essentially no heat loss from the IP SGW between the first separation stage and the boiler. Due to this, no preheating of the IP SGW was required to be performed, as the IP SGW was already at its boiling point. The additional IP steam generation was then calculated based on the heat released by the syngas combustion.

By performing a mass balance on the typical flows in the steam and SGW streams surrounding FP14, Equation 1 was created to estimate the percentage decrease in the flowrate of metals ($\%_{metals}$) based on the amount of steam generated in the boiler ($\dot{m}_s$).

$$\%_{\boldsymbol{metals}} = 5.97 \times 10^{-5} \dot{m}_s{}^2 + 5.76 \times 10^{-2} \dot{m}_s \quad (1)$$

4.2.4 Configuration 4: Heating Additional SGW to use in the Wairakei Binary Plant

Contact Energy staff provided information on the different factors impacting the power generation of the Wairakei Binary Plant. The correction factors for the estimated power generation from the binary plant for changing SGW flowrate to the binary plant are displayed in Figure 9. As can be seen, there are limited benefits to increasing the SGW flowrate to the binary plant above the design flowrate.

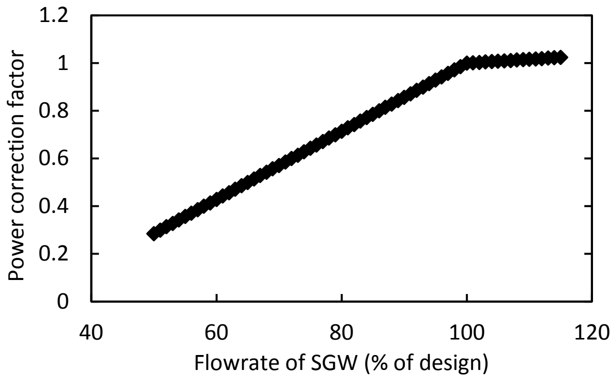

Figure 9. The power correction factors for changing SGW flowrate to the Wairakei Binary Plant

4.3 Estimating Power Generation from Additional Steam

Configurations 1-3 all result in additional IP steam supplied to the Wairakei A and B Stations. Information on the power generation typical of the geothermal turbines using IP steam was used in order to estimate the power generation from the additional IP steam supply. As the MP turbines at Wairakei are fully loaded, and likely to remain so, it was assumed that the power generation would occur using the IP and LP turbines. The power generation rates and no load flow requirements (the amount of steam required before power generation occurs) for the IP and LP turbines are given in Table 4.

Table 4. The no load flows and power generation rates for IP and LP turbines

Turbine	No load flow	Power generation rate
	t/h	*t/h/MW*
IP	100	14
LP	13	11

Due to the no load flow requirements for the turbine, the existing steam flows to Wairakei greatly impacts the power generation and efficiency of the hybrid configurations. Currently, the turbines which use IP steam are usually fully loaded, there is one LP steam turbine in operation that is usually completely unloaded, and sporadic bypassing is seen to occur, as shown in Figure 8. However, as the steam flow to Wairakei is decreasing, three scenarios were created to represent the changes in the efficacy of the hybrid configurations with changing steam flow:

Scenario 1: IP steam flow to Wairakei consistent with the average steam flows for January 2015-July 2016. Sporadic bypassing occurs, IP turbine G4 is fully loaded, and LP turbine G7 is completely unloaded. Bypassing steam may be used in recertified IP turbines.

Scenario 2: IP steam flow to Wairakei has decreased. Effectively no steam bypassing occurs, IP turbine G4 is fully loaded, LP turbine G7 is completely unloaded.

Scenario 3: IP steam flow to Wairakei has significantly decreased. No steam bypassing occurs, IP turbine G4 is partially loaded, LP turbine G9 is partially loaded. Power generation may occur with additional steam without providing the no load flow requirements for G4 or G9.

5.0 RESULTS

It was found that for each turbine modified for Configuration 1, the full load power output of the turbines decreased by 2.6 MWe. However, there was an IP steam saving of 74.3 t/h, though the use of LP steam in the MP turbine also increased by 23.9 t/h. For Configuration 1, two of the MP turbines were assumed to be modified, as otherwise the unused IP steam flow would be too large for the unused steam capacity in Scenario 3.

It was decided that the maximum available flowrate of Poihipi Rd condensate would be used for the boiler feed water for Configuration 2. For simple comparison between Configuration 2 and Configuration 3, the same sized gasification plant was used for both situations. This led to a 2.7% reduction of the metals flowing into the Waikato River for Configuration 3 in every Scenario.

For Configuration 4, the gasifier was sized in order to heat the additional SGW for a maximum combined flow of 2800 t/h. As historical data was used for the flowrates of both sources of SGW, the heating required to be performed was highly variable.

The energy input from the wood was calculated using the lower heating value (LHV) for bone dry softwood, at 19.2 MJ/kg. The combustion energy of the syngas was calculated using the LHV for the syngas, at 7.15 MJ/kg, based on the amount of H_2, CO, and CH_4 in the syngas. The ratio of the combustion energy of the syngas to the energy inputs to the gasifier is known as the cold gas efficiency, and was found to range from 79%-84% for the proposed configurations. This is a relatively high cold gas efficiency for biomass gasifiers, as this efficiency is generally within the range of 60-70% [16]. The efficiency of the hybrid configurations is high due to using geothermal steam for gasification, removing the need for steam generation.

The wood-electricity energy efficiency of the additional power generation from the hybrid configurations was calculated using the energy input of the wood and the estimated additional electrical energy generated from each of the hybrid configurations. The fuel gas-electricity efficiency was then calculated using the cold gas efficiency and the wood-electricity energy efficiency. The fuel gas-electricity and the wood-electricity efficiencies include the use of geothermal steam in the gasifier.

The results of the modeling for each of the four Configurations are displayed in Tables 5-7 below.

For Scenario 1, an average estimated flowrate of 88 t/h was estimated for the bypassing IP steam; which served to increase power generation from the recertified IP turbine for Configurations 1-3, and reduce the power losses from the IP steam utilized in the gasifier for Configuration 4.

Table 5. The modelling results for Scenario 1

	Wood feed rate (wet)		Net IP steam made	Additional Power	Wood-electricity efficiency	Fuel gas-electricity efficiency
	t/h	*MW*	*t/h*	*MWe*	*%*	*%*
1	15.0	40.1	137.5	6.3	15.7	18.7
2	15.6	41.7	41.2	4.4	10.1	12.8
3	15.6	41.7	44.6	4.6	11.0	14.0
4	3.5	9.3	-2.5	1.4	15.5	19.6

For Scenario 2 the efficiency of each the hybrid configurations decrease without the additional steam from bypassing. The net additional power generation of Configuration 4 is seen to decrease without bypassing steam, as this increases the power losses from utilizing IP steam in the biomass gasifier.

Table 6. The modelling results for Scenario 2

	Wood feed rate (wet)		Net IP steam made	Additional Power	Wood-electricity efficiency	Fuel gas-electricity efficiency
	t/h	*MW*	*t/h*	*MWe*	*%*	*%*
1	15.0	40.1	137.5	2.7	6.6	7.9
2	15.6	41.7	41.2	1.7	4.1	5.2
3	15.6	41.7	44.6	2.0	4.8	6.1
4	3.5	9.3	-2.5	1.3	13.8	17.5

Scenario 3 results indicate relatively large values for power generation for Configurations 1-3. This results from the assumption that the no load flows for the IP and LP turbines had been met by the existing geothermal steam flow to Wairakei. The results for Configuration 4 are identical for Scenario 2 and Scenario 3, as no additional steam is generated, the loading of the steam turbines does not affect the power generation of the Binary Plant.

Table 7. The modelling results for Scenario 3

	Wood feed rate (wet)		Net IP steam made	Additional Power	Wood-electricity efficiency	Fuel gas-electricity efficiency
	t/h	*MW*	*t/h*	*MWe*	*%*	*%*
1	15.0	40.1	137.5	11.9	29.7	35.4
2	15.6	41.7	41.2	6.2	14.9	18.9
3	15.6	41.7	44.6	6.8	16.2	20.6
4	3.5	9.3	-2.5	1.3	13.8	17.5

6.0 CONCLUSIONS

It can be seen that the superheating of geothermal steam had the largest additional power generation of all the designed hybrid configurations. Interestingly the reduction in the power generation associated with modifying the MP turbines was greatly outweighed by the potential power generation that could be performed using the increased flow of IP steam to the remaining turbines at Wairakei. However, significant modifications will need to be performed to the MP steam turbines in order to utilize this hybrid configuration.

The configuration that is least likely to encounter obstacles with implementation is the boiling of Poihipi Rd condensate to create additional steam. As there is much experience with operating steam boilers, it is believed that if correct treatment is performed on the Poihipi Rd condensate, there will be no further practical barriers to implementation. Unfortunately this configuration was also seen to exhibit the lowest wood-electricity efficiency; however further consideration of this case may indicate further improvements.

Finally, and uniquely, this study has examined the practical obstacles to retrofitting the existing Wairakei geothermal system to accommodate a range of biomass hybridization options. The results indicate that retrofitting a biomass gasifier to an existing geothermal power plant is practically feasible, but requires a good understanding of the underlying nature of the steam system and its utilization The dissimilarity between the modelling results for the three geothermal steam supply scenarios illustrates the high dependency that the current geothermal steam loading has on the additional power generation possible from hybridization. The results of this energy analysis are subject to an economic feasibility assessment in order to determine overall cost/benefits.

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