EXERGY ANALYSIS OF SOUTHERN NEGROS GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

Exergy analysis is important for identifying the sources of ineffeciency in a thermal process and for determining options for optimizing the system (Szargut et al., 1988). In a common geothermal power plant set-up, the overall second law (exergy/utilization) efficiency of the process is obtained from the actual electric power generated by the available exergetic power from the produced geothermal fluids at the wellheads.

This work calculates the second law efficiency of the geothermal system using exergetic power from the geothermal reservoir, instead of the wellhead. In Southern Negros Geothermal Project (SNGP), the utilization efficiency is 28.8 % based on an available exergy of 670 MWe at the reservoir. Reservoir parameters that are used for exergy analysis are obtained through numerical reservoir modeling. An optimization and sustainability assessment of the resource shows that highest utilization efficiency (geothermal heat source) is obtained at a 190 ºC reinjection temperature.

1. INTRODUCTION

1.1 Background information of SNGP

SNGP field is located in Negros Oriental at the central region of the Philippines (Figure 1). It is composed of two main geothermal sectors namely Palinpinon, and Baslay de Dauin. Palinpinon has two steam fields, i.e. Palinpinon-1 and Palinpinon-2, which are divided into four geographical areas. Puhagan is encompassed in Palinpinon-1 while Balasbalas, Nasuji, and Sogongon are covered by Palinpinon-2, with installed power capacities of 112.5MWe, 20MWe, 49.4MWe, and 40MWe, respectively. Commercial operation of SNGP began in May 1983. As of December 2018, there are 48 production wells and 15 reinjection wells in operation. Utilization of the wells depends on the electrical power demand at any given time.

Over the 35 years of exploitation, electrical generation has increased from around 10 MWe to 221 MWe (Figure 2). However, the available steam at the wellhead showed a declining trend in the first 10 years of production. This was due to the rapid deterioration in the output of Puhagan wells caused by the cold inflow from the infield reinjection (Candelaria et al., 1995). After this period, steam production increased and maintained an output of above 200 MWe. On the other hand, reservoir liquid pressure measured at -1000 mRSL had a declining trend. A sudden pressure drop from 1983 to 1999 for Palinpinon-1 was observed. Since then, pressure decline within the field has occurred at an estimated rate of 0.06 MPag/year.

In addition to pressure drawdown and cooling from reinjection fluids, other factors that affected the steam supply were; wellbore mineral deposition and formation deposition (Orizonte et al., 1999). Casing issues (e.g. casing and liner break due to acidic fluid inflow and casing bulge) also resulted in the reduction of output.

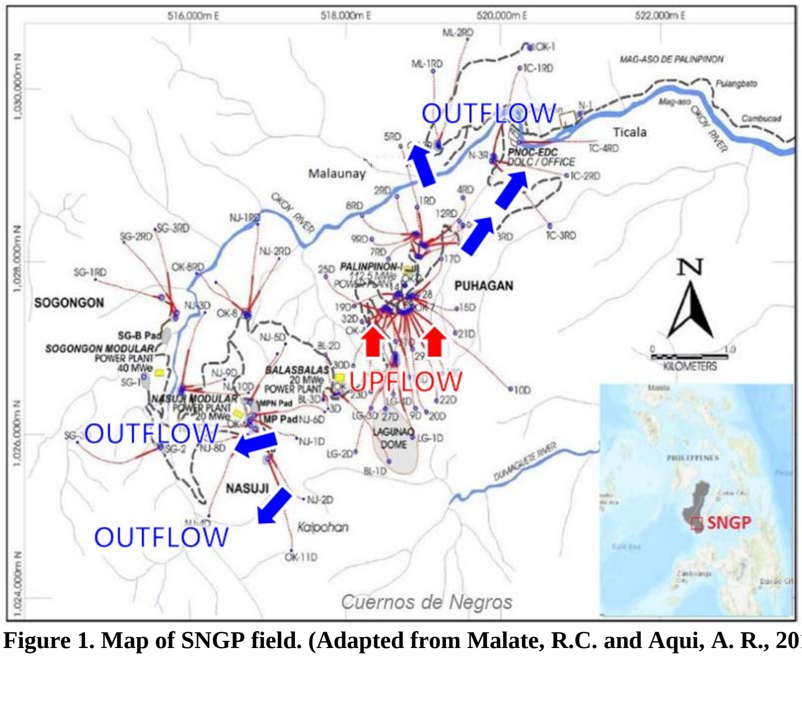

Figure 1. Map of SNGP field. (Adapted from Malate, R.C. and Aqui, A. R., 2010)

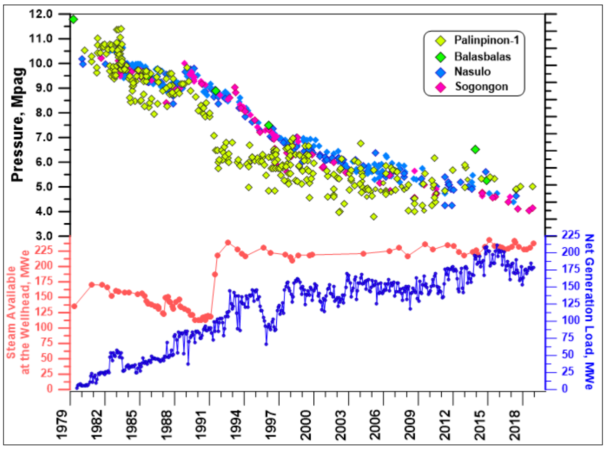

Figure 2. Palipinon field measured downhole liquid pressure at -1000 mRSL, steam available at the wellhead and power plant net generation load from 1983 to 2018.

1.2 Sustaining the steam supply

In order to maintain the supply of steam required for power plant generation, a couple of reservoir management strategies were implemented in 1989. First reinjection was shifted towards the Ticala and Malaunay sector (Figure 1), lying on the northeast borderline of the field, farthest from the production sector. However, with the massive extraction in the Puhagan area, reservoir pressure drawdown persisted. Utilization of Puhagan reinjection (RI) wells was ceased in 1996. The amount of waste brine had been reduced through the prioritization of high-enthalpy production wells. For wells affected with calcite and anhydrite deposition, mechanical workover and acidizing had been employed to clear out the obstructions. Milling operations and casing relining was done on wells with casing breaks. However, all these actions were still not enough to sustain the supply of steam. Thus, drilling of maintenance and replacement wells, as well as step-out wells was undertaken (Orizonte et al., 1999).

Since steam decline persisted, optimization assessments were needed to improve the operation of SNGP field. In a study by Aqui et al. (2005), the exergy of the various phases of the Palinpinon-1 Fluid Collection and Reinjection System (FCRS) and power plant was determined. Fluid properties were based on the first quarter data of 2003. The temperature of the surroundings was set at 25ºC. The separator pressure used was 0.68 MPaa (164 °C) while the turbine had an inlet pressure of 0.63 MPaa and an outlet pressure of 0.0153 MPaa (54 °C). The utilization efficiency was computed to determine the degree of steam conversion to electrical power. The calculation gave a result of 39.9%, based on the ratio of the electrical output from the power plant over the exergy at the wellhead of the producing wells. Significant waste exergy of the power plant facilities was identified as accounting for the highest percentage of exergy loss from the separated brine (16%). The study suggested two possible approaches for steam augmentation through the production of electrical power from the waste brine:

(1) Send the brine to a secondary flash separator at optimum operating temperature of 105 °C.

(2) Hook-up the low-pressure production wells to the secondary flash plant, together with the separated brine from the main plant, producing a total power output of 17.6 MWe at a flash separator temperature of 115 °C.

The two options could increase the utilization efficiency up to 44.4% and 45.6%, respectively. However, the drawbacks of the options are: (i) the need to re-configure the piping system for the low-pressure geothermal fluid conveyance from the wellhead to the secondary flash unit and (ii) the adverse effects of cooler reinjection fluids (i.e. lower than the existing 165 °C temperature) on the productivity of wells situated within a 1.0 km radius from any reinjection well. Nonetheless, the work showed the optimization recommendations to be reasonable as possible mitigating measures to be implemented.

1.3 Related studies

Other exergy analyses on geothermal fields worldwide have reported utilization efficiency values ranging from 27 to 58% for single-flash plants (Aqui et al., 2005; Jalilinasrabady et al., 2010; Kwambai, 2005; Ozturk et al., 2015). These values are based the ratio of the input exergy computed for two-phase fluid from the production wells and the net power output distributed to the electrical grid. Exergy from brine is considered as waste as it is reinjected back into to the reservoir. The overall utilization efficiency was determined to increase if reinjection was considered to be effective in maintaining the sustainability of the resource, i.e., the reinjected brine attains the original pressure and temperature of the reservoir (Jalilinasrabady et al., 2010).

Unlike the conventional computations of utilization efficiency where the input exergy is referenced at the production wellhead, this work calculates the available exergy of the geothermal reservoir and computes the utilization efficiency of SNGP power plant system using the generated electrical power output over the input exergetic power from the reservoir. The available exergy of the reservoir is obtained from the total specific exergy of fluid streams coming into the production well through the feed zones. Total specific exergy of the reinjection fluid streams going out of the reinjection well feed zones is also computed. Properties of the fluid at the feed zones are determined through numerical modeling. Moreover, optimization and sustainability of the resource is evaluated through changing the separator pressure, thereby affecting the brine temperature reinjected into the reservoir, and modeling its impact on the geothermal resource in terms of available exergy. A range of utilization efficiencies is computed over a set of separator and turbine pressures to get the optimum utilization efficiency.

2. EXERGY AND UTILIZATION EFFICIENCY

Exergy analysis is done to identify the causes and estimate the extent of deficiency of a process (e.g. thermal or chemical). It aids in understanding the influence of thermodynamic phenomena on the effectiveness and optimization of processes. However, the expediency of a discovered process improvement can only be done through economic analysis (Szargut et al., 1988).

2.1 Basic concept

Rant (1956) defined the capacity to do work relative to zero level as "exergy" (cited in Szargut et al., 1988). It is further described as the available amount of work when matter is brought to a thermodynamic state of equilibrium with the surroundings through a reversible process. Therefore, to compute exergy, the thermodynamic conditions of the environment should be specified (Szargut, 1980).

The principles of exergy are based on the Laws of Thermodynamics, principally on the second law. The first law states that the total amount of energy is constant. When energy dissipates in one form, it simultaneously appears in another form (Smith et. al, 2001). For a steady-state process, the first law is expressed in the equation:

$$\Delta\left[\left(H+\frac{1}{2}u^2+zg\right)\dot{m}\right]_{fs}=\dot{Q}+\dot{W}_s \qquad (1)$$

where H is the enthalpy, $\dot{Q}$ is the heat transfer rate, $\dot{W}$ is the work rate, u is the bulk-mean velocity, g is the local acceleration of gravity, z is the elevation above datum level and $\dot{m}_{fs}$ is the mass of flowing streams into and out of the system.

On the other hand, the second law states that; work can be readily converted into heat but no cyclic process can be devised to fully convert the heat absorbed by a system into work done by the system. Heat is a form of energy that is essentially less useful or valuable than an equal amount of work. In addition, the second law says that the flow of heat between two bodies is always from the hotter to cooler region. When applied to a steady-state system, the second law is written as:

$$W_{max}=\Delta[(H+\frac{1}{2}u^2+zg)\dot{m}]_{fs}-T_0\Delta(S\dot{m})_{fs} \qquad (2)$$

where T_0 is the surrounding temperature, S is the entropy and W_{max} is the maximum work that can be theoretically obtained from a given change in the properties of a fluid.

Since kinetic and potential energy terms are negligible in most processes as compared to the other terms, the maximum work equation simplifies to:

$$W_{max}=\dot{m}_{fs}(\Delta H-T_\sigma\Delta S) \qquad (3)$$

This maximum power output is referred to as 'exergy'. It is used to identify the specific exergy, *e*, of a fluid stream at temperature T_1 and pressure P_1, relative to a given set of ambient conditions T_0 and P_0 (DiPippo, 2015). The specific exergy is expressed as:

$$e\equiv h_1-h_0-T_0(s_1-s_0) \qquad (4)$$

2.2 Exergy loss

Exergy accounting within a system is given in equation 5, where $\dot{E}_{IN}$ is the summation of the exergy of the incoming streams, and $\dot{E}_{OUT}$ is the summation of exergy of the outgoing streams. The difference of the two terms is the exergy loss, $\Delta\dot{E}$, which is always numerically positive (DiPippo, 2015).

$$\Delta\dot{E}=\dot{E}_{IN}-\dot{E}_{OUT} \qquad (5)$$

2.3 Utilization efficiency

DiPippo (2015) defined exergy efficiency as utilization efficiency or Second Law efficiency. The utilization efficiency is "functional", i.e. the exergy efficiency is calculated from the ratio of the desired exergy output over the required input exergy to obtain the desired output.

In this work, the functional efficiency, $\eta^{II}_{p,FUN}$, can be expressed by the equation:

$$\eta^{II}_{p,FUN}=\frac{e_{\dot{W}}}{e_{reservoir}} \qquad (5)$$

where $\dot{e}_W$ is the electrical power output produced by a turbine and $\dot{e}_{reservoir}$ is the input exergetic power taken from the total specific exergy of the fluids at the production feed zones.

3. THE SNGP GEOTHERMAL POWER PLANT SYSTEM

Figure 3 is an illustration of the overall SNGP geothermal power plant system, where steam is produced through a cyclic cycle. Steam production begins at the sub-surface level (point 0), where geothermal fluid at high temperature and pressure conditions is extracted from the reservoir, and enters the wellbore through the production well feed zones. The two-phase geothermal fluid moves up along the wellbore and exits at the production well head (point 1) at the surface level. At a slightly reduced pressure, the two-phase fluid is separated into steam (point 2) and brine (point 3) at the separator vessel. Brine at relatively lower temperature is reinjected back into the subsurface reservoir. The steam that is excess to the power plant requirements is blown-off (point 4) while a certain amount of motive steam is used in the gas removal system (GRS) at point 6 to eject the non-condensable gases (NCG). The NCG-steam mixture is entrained within the GRS (point 10) and NCG is further extracted through condensation with the cooling water return (point 15) in the inter-condenser (inter-

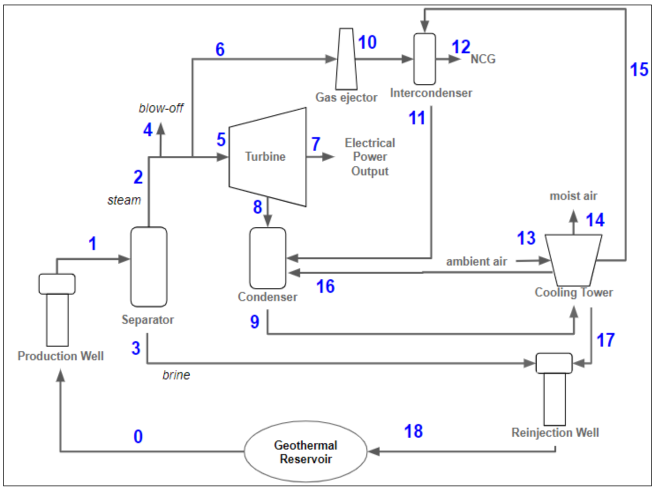

Figure 3. SNGP geothermal power plant system

cooler), leaving the unit at point 12. Condensate flows into the main condenser (point 11). Meanwhile, steam at the interface (point 5) enters the turbine-generator system and electrical energy is produced (point 7). Exhaust steam, at a decreased temperature and pressure, is condensed (point 8), through the transfer of heat to the surroundings within the main condenser. The condensate is transported to the cooling tower (point 9). Steam condensate at the cooling tower falls into a stream of air at ambient condition (point 13). Heat is lost to the surroundings and moist air leaves at point 14. A fraction of cooling water is returned to the main condenser (point 16) while a portion of the condensate blowdown (17) is injected into the reinjection well feed zones (point 18), thus, finishing the cycle.

4. METHODOLOGY

The study incorporates the calculation of the exergy at the surface and sub-surface level of the geothermal power plant system, the estimation of exergy losses at different stages of the process of steam conversion to electrical power and the determination of the optimum utilization efficiency at specific separator and turbine pressure.

Operating conditions within the steam field and power plant were acquired and ambient conditions according to the location of the field were identified for the exergy analysis at the surface level (point 1 to 17 of Fig. 3). Exergy loss in each phase was determined. Exergy at the sub-surface level was computed through extracting the fluid properties at the production and reinjection feed zones from the simulation results of the TOUGH2 numerical modelling. The total specific exergy of fluid streams that enter the production well at the feed zones was referred to as the available exergy (point 0) of the geothermal system. This available exergy was used to compute the utilization efficiency of the power plant conversion process. Meanwhile, the total specific exergy of the fluid streams going out of the reinjection feed zones (point 18) was also analysed. The temperature at the feed zone was determined through radial modelling of the reservoir near a reinjection well to confirm if the separated brine temperature is the same as the temperature of the fluid that goes out of the reinjection feed zone and into the reservoir. Lastly, an optimization assessment was conducted through running the reservoir model at different reinjection temperatures and computing the corresponding available exergy. Wellhead conditions of the fluid at various scenario runs were estimated through wellbore modelling (SIMGWEL, Marquez et al., (2015)). The equivalent power output generated was calculated through the consequent fluid properties at the wellhead and approximated pressure losses along the major components of the power plant (e.g. separator and turbine). A set of utilization efficiencies were obtained and were plotted against various separator and turbine pressure values.

5. EXERGY RESULTS AND ANALYSIS

5.1 Exergy at the surface facility

In most studies, exergy analyses within a geothermal system are done at the surface level and the available exergy is referred to the wellhead. In this section, the exergy at the surface facility (point 1 to 17 of Fig. 3), is computed. Equation (4) was used in the analysis of the data dated December 30, 2018. The following assumptions were used in the calculations: (1) all processes occurring within the system are completely reversible (i.e. no sources of irreversibility); (2) fluid discharged from the system is in thermodynamic equilibrium with its environment (i.e. dead state). Thus, discharge fluids have no ability to do more work with respect to their surroundings.

Results are presented in the Table 1. The exergy available at the wellhead is 521.5 MWe and the net electrical output is 192.9 MWe, giving a utilization efficiency of 37 %. There were a couple sources of significant exergy degradation, i.e. from pipeline (52.5 MWe), gas removal system (31.4 MWe), turbine (72.4 MWe), condenser (42.7 MWe), cooling tower (39.9 MWe) and reinjected brine (75.5 MWe). Exergy is destroyed along the pipeline by friction, heat losses and draining of condensed steam, while exergy loss in the turbine occurs due to steam expansion along the blades of the turbine. Exhaust steam is condensed as it is mixed with cooler water at a lower temperature and pressure at the main condenser unit and exergy is lost as heat is transferred to the surroundings. In the cooling tower, exergy from the cooling water is transferred to the surrounding air as the condensate and air are mixed together within the unit. The largest loss was the reinjected brine at an average temperature of 165 ºC. A grassman presentation of exergy losses in SNGP is shown in Figure 4.

5.2 Exergy at the sub-surface level

Exergy analysis at the sub-surface level determines the total specific exergy of the fluid streams that (1) enter the production well feed zone from the reservoir, and (2) leave the reinjection well feedzone to the reservoir (Figure 5). It involved establishing a numerical model of the SNGP geothermal system.

Palinpinon is a liquid-dominated system with the upflow region identified in the vicinity of Cuernos Volcanics Complex near Kaipohan (Figure 1). Outflow of the geothermal system is directed towards west, where Nasuji and Sogongon sectors are located, and towards the northern and northeastern areas of Puhagan (Aniceto-Villarosa et al., 1988). The conceptual model was the basis in establishing the numerical model of SNGP for the representation of the natural mass and heat flow through the geothermal system. Mass and heat flows were used for the computation of the exergy values in the reservoir.

A single-porosity numerical model was generated using the AUTOUGH2 software (Pruess et al., 2012; Yeh et al., 2012) that had been converted from an existing numerical model of the field based on the TETRAD software. The model has a regular rectangular grid covering an area of 1,128.80 km^2 and containing 55 × 52 blocks, 2860 columns and 5613 connections. The reservoir was divided into 15 layers, representing the zone from the top to the bottom of the reservoir as well as all the permeable zones in the field.

The surface of the model is set at 0.0 mRSL which represents the top of the reservoir and the model extends to the depth of -5500 mRSL to incorporate the bottom drainage. Layer thickness varies from 50 to 800m. There are 42,901 grid blocks in the model. Thermodynamic property equations for pure water were used to represent the characteristic of the reservoir fluid. Liquid and gas (steam) relative permeability equations were fitted to linear curves. The model covers a sufficient area to incorporate the recharge (aquifers) region, and thus there is negligible flow from outside of the model boundary.

Natural state modeling was conducted to replicate the pre-exploitation condition of the field. The model was run up to

Table 1. Exergy at the surface facilities

Stream No.	P (Mpaa)	T (°C)	H (kJ/kg)	S (kJ/kg-K)	e (kJ/kg)	MF (kg/s)	Exergy, MWe
0*	7.5877	283	1619	4.1238	0.5139	1301.8	668.96
1	0.9333	176	1618	4.7487	0.4328	1204.8	521.49
2	0.7130	176	2635	6.6713	0.7567	566.25	427.34
3	0.7130	165	693	2.0539	0.1136	664.64	75.530
4	0.6727	163	2761	6.7207	0.7567	1.7000	1.3100
5	0.6788	163	2759	6.7205	0.7480	526.07	393.49
6	0.6504	162	2757	6.7338	0.7575	40.521	38.980
7	-	-	-	-	-	-	192.94
8	0.1493	115	2303	6.3207	0.1666	470.10	78.300
9	-	45	188	0.6497	0.0028	18,377	52.160
10	0.6504	162	2600	8.0754	0.0973	3.8381	0.5000
11	-	40	164	0.5753	0.0020	5,5614	10.990
12	-	55	2600	8.0784	0.1091	4.5551	0.5000
13	-	23	100	0.3508	0.0001	12,329	0.0400
14	-	23	100	0.3508	0.0001	12,375	0.1000
15	-	32	145	0.4764	0.0011	5,574.8	6.1400
16	-	31	133	0.4553	0.0004	12,347	6.0100
17	-	32	139	0.4764	0.0005	87.163	0.0400
18**	28.3841	192	1372	3.3547	0.4093	637.10	260.76

** & ** are discussed in section 5.3 & 5.4, respectively*

100,000 years to ensure steady-state thermodynamic conditions were achieved. After validation, the pressure, temperature and saturation distribution of the natural state model were applied as the initial condition of the geothermal system for production history matching. Exploitation history matching of each production and reinjection well was done by specifying the total mass flow rates measured at the wellhead, from 1983 to 2018. The mass flow distribution between the feedzones of each well was estimated through mass and energy balance computations. A single block was assigned per feed zone. There were 118 feed zones for 49 production wells and 88 feed zones for 25 reinjection wells. At dates when wells were shut or cut-out from the operations, zero mass flows were assigned.

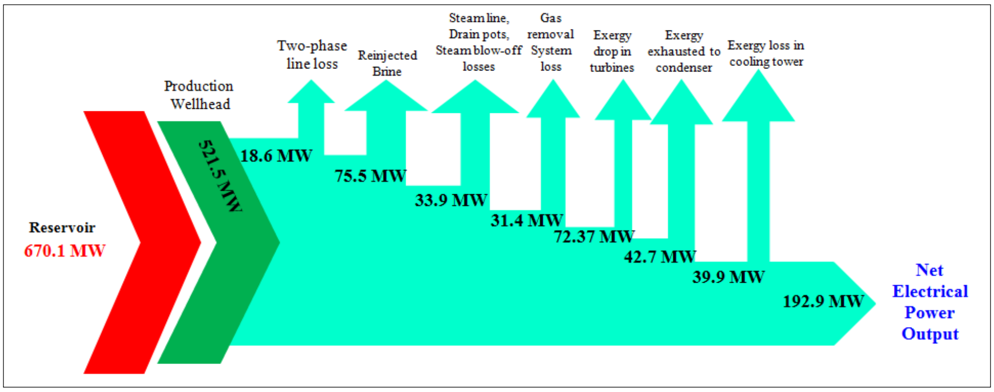

Figure 4. Grassman presentation of Exergy in SNGP

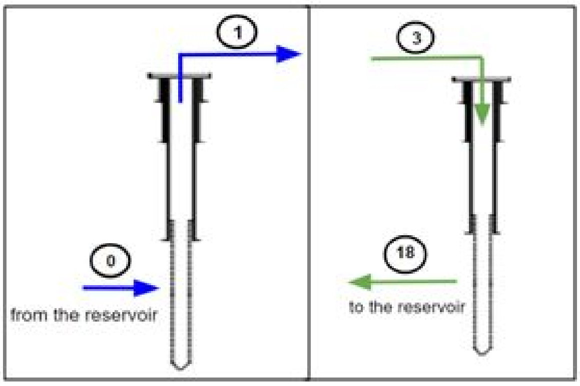

Figure 5. Exergy accounting at the Production Well (left) and Reinjection Well (right)

5.3 Exergy at the production feed zone

The SNGP production model used a brine reinjection fluid temperature of 165ºC, with equivalent enthalpy, H, of 675 kJ/kg, as these were the existing separation parameters in the steam field. The production model was run until the end of December 2018 and the fluid properties (i.e. pressure, temperature, enthalpy, dryness) of each production feed zone were extracted. Specific exergy values of the fluid stream for feed zone were summed up to get the total exergy available at the reservoir. Exergy computed was 670 MWe. This exergy value represents point 0 in Figure 5 (left). Using the exergy of this stream as the input exergetic power in the SNGP power plant system, a utilization efficiency of 28.8 % is calculated. Given that the exergy of the fluid at point 1 is 521.5 MWe (as discussed in Section 5.1), about 22% of exergy is degraded along the wellbore by friction losses, along a pipeline length of about 1600 – 3400 m.

5.4 Exergy at the reinjection loss zone

Figure 5 (right) illustrates the flow streams coming into and out of the reinjection wellbore. The incoming stream is the separated brine with an exergy of 75.53 MWe (section 5.1) at 165º C. To account for the exergy of the outgoing stream (point 18) at the reinjection wellbore, a radial model was first created from the SNGP numerical model to represent a single reinjection well in the field. The model is a regular rectangular grid encompassing an area of 971.46 km^2. A well radius of 0.1 m was used to represent the volume occupied by the wellbore. A 0.02 m-thick grid block is assigned adjacent to wellbore block to represent casing. Outside this, the block sizes increase logarithmically. It has 748 grid blocks, 52 columns, and 51 connections. The layers of the model were divided into 14 structures, representing the ground layer, cap rock, a single feed zone and the reservoir. The initial conditions of the model were based on the pre-exploitation pressure and temperature measurements within the reinjection well. The feed zone was set at layer 6 (-600 to 400 mRSL). Mass flow reinjection rates used in the model were based on the actual measurements in the field at specific periods of time. Porosity and permeability values used in the radial model are given in Table 2. The model was run until the end of December 2018 and the resulting pressure and temperature profiles at the wellbore block are illustrated in Figure 6. Temperature at the feed zone is 165 ºC (697 kJ/kg), which is nearly constant from the wellhead. This reinjection fluid condition was set in the reservoir production model. The resulting fluid properties (i.e. pressure, temperature, enthalpy, dryness) at the reinjection feed zones were extracted and the total specific exergy computed was 260.76 MWe.

Table 2. Porosity and permeability values in the radial model

	porosity, %	permeability r, m^2	permeability z, m^2
Well	99.0	1.00E-06	1.00E-06
Casing	1.0E-10	9.00E-20	9.00E-20
Feedzone	20.0	5.75E-11	5.75E-11
Ground	10.0	6.00E-15	6.00E-15
Cap	5.0	2.50E-16	2.50E-16
Reservoir	10.0	1.75E-14	1.75E-14

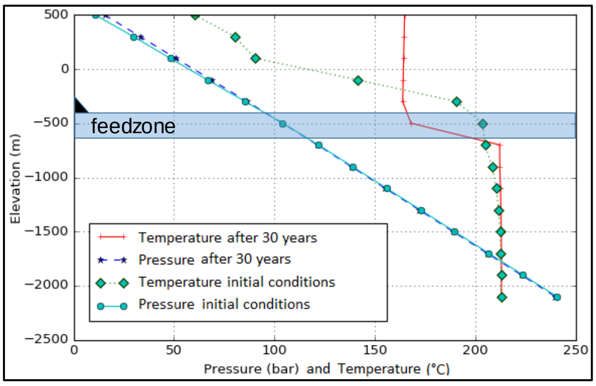

Figure 6. Pressure and Temperature Distribution along a Reinjection Well from the Radial Model

6. OPTIMIZATION ASSESSMENT

6.1. Varying the reinjection temperatures

The optimization study was done through establishing different scenarios or conditions of brine reinjection temperature values ranging from 120 ºC to 220 ºC, with an increment of 10 ºC. The maximum brine temperature was based on the maximum temperature recorded from the reinjection well model (Section 5.4) while the minimum brine temperature was based on the recommended minimum brine temperature in SNGP to control risks in silica deposition (Aqui et al., 2005). The brine temperatures correspond to various separator and turbine pressures at the surface facility. Reinjection conditions (i.e. temperature and enthalpy) were specified in the numerical model of the field using TOUGH2 from the start of the exploitation to the end of year 2018. Validation of the applicability of the numerical model in this research was done primarily through the removal of reinjection parameters from the input file, starting from 2010 to end of 2018, and through running the model to check if there were significant changes in the pressure and temperature of the field. After this step, scenario runs were conducted. At each condition, total available exergy at the reservoir was calculated. Results are illustrated in Figure 7.

The overall trend in Figure 7 shows that with increasing reinjection temperature, the exergy of the reservoir decreases. The highest exergy value is at 120ºC and has a linear declining trend down to 160ºC. Beyond this temperature up to 220ºC, exergy values range from 668 to 675MWe. Lowest exergy is at 180ºC. It should be noted that this figure only represents the exergetic power calculated at a specific time (30 Dec 2018). During the overall production period, this may show different trends as a function of changing flow rate and enthalpy histories. Varying reinjection temperature affects the pressure dynamics within the reservoir differently at different times of production i.e. warm reinjection may supress deep hot recharge, or can prevent production induced boiling (Kaya and O'Sullivan, 2010, Diaz et al. 2015), hence, may affect the available exergy at the reservoir. Other factors that may have affected the trend on the available exergy at the reservoir are injectivity of wells and permeability of the fractures. The increase in injectivity and permeability provides enough recharge and more pressure support delivered by the reinjection fluids to the reservoir, consequently improving the available exergy. In the study of Siega et al., 2014 on the wells in Wairakei-Tauhara geothermal system, injectivity decreases with an increase in the reinjection temperature.

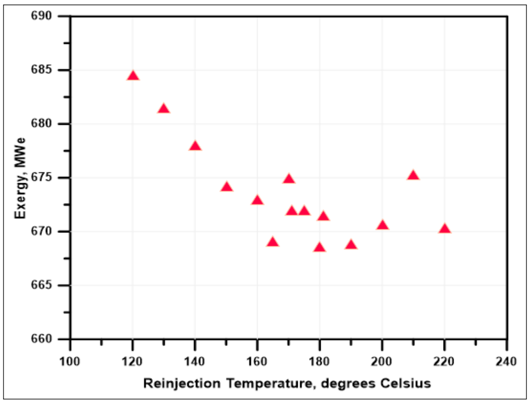

Figure 7. Input exergetic power of the reservoir at various reinjection temperatures

6.2 Fluid properties at the Wellhead

At different reinjection temperatures, the fluid properties at the wellhead or surface were identified. Using SIMGWEL, the fluid conditions at the wellhead were simulated through inputting the reservoir pressure and enthalpy values of the production feed zones generated from TOUGH2 for various reinjection temperature scenarios. A productivity index established from the calibrated well bore model was used in the bottom-up simulation using the Orkiszewski flow correlation. In this paper, only one wellbore model was run and the result was used to represent each of the 55 active production wells in SNGP.

6.3 Separator and turbine pressures

The equivalent separator operating pressure of four brine reinjection temperatures (i.e. 120 ºC, 140 ºC, 190 ºC , 220 ºC) set in Section 6.1 was determined. The baseline reinjection temperature of 165 ºC was also added in the optimization assessment. Meanwhile, turbine-operating pressures were estimated based on the pressure difference between the actual separator and turbine units acquired on Dec. 30, 2018. Referring to the approximate formulation of the maximum power output of a single flash geothermal system (DiPippo, 2008) and the operating parameters in the power plant (i.e. condenser temperature, cooling water temperature, ambient air humidity), the generated net electrical power was computed corresponding the fluid properties produced at the wellhead (Section 6.2). Table 3 displays the set of separator and turbine pressure values correlated with the five reinjection brine temperatures.

Table 3. Utilization efficiency at various separator and turbine pressure

Separator Pressure, MPaa	Separated brine temperature, ºC	Turbine Pressure, MPaa	Utilization Efficiency, %
0.1487	120	0.0834	21.8
0.3115	140	0.2462	29.5
0.6508	165	0.5856	34.0
1.2050	**190**	**1.1398**	**35.5**
2.2693	220	2.2040	34.0

6.4 Utilization efficiency at various separator and turbine pressure

The utilization efficiency was computed based on the calculated turbine-generator electrical output at various separator and turbine pressure over the input exergetic power from the reservoir. Results are tabulated in Table 3 and an illustration in Figure 8 is given.

From the given reinjection temperatures, the optimization assessment obtained the highest utilization efficiency of 35.5% for separator pressure 1.2050 MPaa (190 ºC) and turbine pressure of 1.1398 MPaa. The lowest utilization efficiency computed was 21.8% for separator pressure of 0.1487 MPaa (120 ºC) and turbine pressure of 0.0834. Although the available exergy was highest for reinjection temperature of 120 ºC, the generated power output is lowest at this condition. Turbine efficiency is hampered when the turbine inlet pressure is low, resulting to a higher steam consumption for a certain power requirement. It is also observed that the existing separator pressure of 0.6508 MPaa (165 ºC) does not give the highest utilization efficiency in reference to the available exergy at the reservoir. Thus, in SNGP, maximum utilization of the reservoir fluid can be attained at 190 ºC.

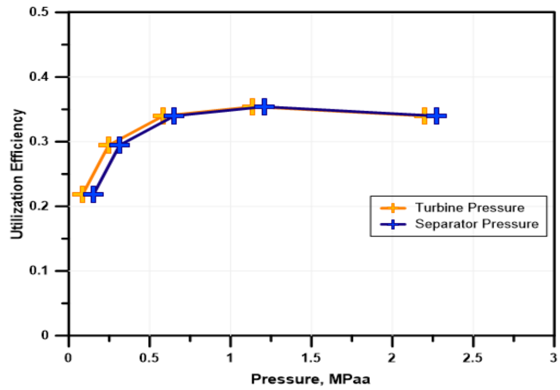

Figure 8. Utilization at various separator and turbine pressure

6. CONCLUSIONS AND RECOMMENDATIONS

SNGP field has an available exergy at the wellhead of 192.9 MWe. Exergy waste degradation can be attributed to thermal losses in the pipelines, gas removal system, turbine, condenser, cooling tower and waste brine.

Meanwhile, available exergy of the reservoir is 670 MWe. Optimization assessment results show that with decreasing reinjection temperature, the exergy available at the reservoir increases. Highest available exergy of 684.44 MWe is obtained at 120 ºC reinjection temperature. Utilization efficiency is highest at separated brine temperature of 190 ºC, separator pressure of 1.205 MPaa and turbine pressure of 1.1398 MPaa in terms of available exergy referenced at the reservoir.

It is important to use the exergy of the reservoir as the input exergetic power in the computation of the power plant utilization efficiency since the reservoir is part of the cyclic process of steam production and the geothermal resource at the sub-surface is the heat source from where work is produced. Rather than the conventional power plant design where the separator and turbine unit specification are optimized based on the required power output, the design should be based on the evolving available exergy from the reservoir and the exergy regeneration supplied by the reinjection fluids into the reservoir.

For a better representation of the reservoir and more accurate exergy calculations, it is recommended to improve the calibration of the natural state model and the matching of the production model with the historical measurements of the field. Also, it is recommended to extend the boundary of the field beyond the top of the reservoir to encompass the surface (above 0 mRSL) to consider all mass and heat flows into the geothermal system. It is also recommended to perform radial modelling and wellbore modelling for both reinjection and production wells for more accurate results.

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