

EXERGY ANALYSIS OF THE MINDANAO ■ & 2 GEOTHERMAL POWER PLANTS

Medel E. Aligan

Bicol University, Legazpi City 4500, Philippines

ABSTRACT

An exergy analysis was made on Mindanao 7 & 2 Geothermal Plants, both based on the MHI turbine and flash system. A program was used to simulate actual plant operation to calculate exergy, identify exergy losses and estimate the efficiencies of both plants. A comparative analysis of both plants was made using the same reference environment and their actual operating environment. The exergy analysis shows that at their actual operating environment, M1GP has a net plant second law efficiency of 60.4 % while M2GP has 57.2 %. At the same reference environment, the efficiency of M1GP dropped to 56.3 %. The analysis showed that the cooling water system, particularly the condenser and cooling tower and the turbines need further investigations to improve exergetic efficiency.

The extraction and utilization of low-pressure steam from M1GP to generate additional power for M2GP maximizes the efficient utilization of the available geothermal resource and resulted to an increase in net plant second law efficiency of 63.32%. Since exergy analysis expresses the relationship between the system and the environment, it should be integrated in the design of engineering systems and in life cycle analysis of geothermal systems.

1.0 INTRODUCTION

Exergy analysis, as an analytical method, uses the principles of the First Law of Thermodynamics, together with the Second Law of Thermodynamics, for the analysis, design and improvement of energy and other systems. First law analysis often fails to identify losses of work and potential improvements of the effective use of resources while the Second Law shows that for some energy forms, only a part of the energy is converted to work, e.g. exergy (Gong and Wall, 1997).

The exergy analysis was conducted using data provided by Marubeni Energy Services Corporation (MESCO) and Philippine National Oil Company Energy Development Corporation (PNOC-EDC) - Mindanao Geothermal Production Field (MGPF) as input values. To simulate plant operation, a computer simulation of the plant was developed, using Engineering Equation Solver Software Ver. 6.313 (EES) to calculate exergy, identify exergy losses and estimate the efficiencies of both plants.

This study is limited to the analysis of the physical exergy with the system boundary set at the plant boundary. It is not an energy audit of each component of the plant. A physical exergy analysis of a geothermal plant used in conjunction with an energy analysis enables the locations, types and true magnitudes of wastes and losses to be determined. More revealing insights can be made if the analysis is conducted using varying reference environments and compared using the same reference environment.

2.0 SURVEY OF RELATED STUDIES AND LITERATURE

Geothermal resources can be classified as renewable at some small level of production, although production can take place at a higher level for a certain period of time. Wright (1995) classified geothermal resources as on a boundary between being renewable and non-renewable and recommended the conduct of more meaningful studies on the sustainability of geothermal production. Such studies should go far beyond the usual reservoir study to be more useful in providing information and guidance.

The exergy of an energy form or a substance is a measure of its usefulness or ability to do work as it comes to equilibrium with a reference environment. It is synonymous with the terms *available energy*, *essergy*, *utilizable energy*,

available work, availability. It can be destroyed whenever an irreversible process occurs (Dincer and Cengel, 2001). When the energy loses its quality, it results in exergy destroyed. The destroyed exergy or the generated entropy is responsible for the less-than-theoretical efficiency of a system. Exergy destruction is often referred to as lost work and should be minimized. By calculating the exergy losses, possible process improvements can be identified. Dincer and Cengel (2001) highlighted the importance of exergy analysis as leading to a substantially reduced rate in the use of natural resources and the environmental pollution by reducing the rate of discharge of waste products.

Rosen and Dincer (1999) asserts that the impacts on the environment arising from use of an energy resource and increasing the efficiency of use of these resources can be analyzed better by using exergy analysis. Kanoglu and Cengel (1999) conducted a performance evaluation of a 12.8 MW single flash geothermal power plant in Northern Nevada, USA using actual plant operating data, simulated the operation of the plant using an engineering equation solver and identified potential sites for improvement. From their study, it appeared that utilization of the unused brine for further power generation, before re-injection, could provide a substantial increase in the power generated from the geothermal resource.

In analyzing the 55 MWe plant of the Darajat Geothermal Plant, Soekono (1995) found that most of the exergy losses were located at the condenser and turbine, although considerable losses were found at the well bore pipes and valves. Rosen and Dincer (1999) studied the impact of the environment model in exergy analysis and concluded that the potential usefulness of exergy analysis in addressing and reducing environmental impacts is substantial although the relations identified need to be investigated with a larger database if utilizable objective measures of the potential of a substance to impact on the environment are to be developed.

Villena (1997) conducted a comparative exergy analysis of the MIGP (North Cotabato, Philippines) and the Mahanagdong Geothermal Field (Leyte, Philippines) based on heat and mass balance diagrams at different loads. He found that operating at partial load condition and

increased gas content increases the irreversibility losses of the individual component system. The study was carried out primarily to compare both plants and locate possible losses of exergy.

While exergy analyses are best conducted during commissioning of the plants, it is enlightening to know how the plants compare with the design values.

3.0 EXERGY ANALYSIS OF MINDANAO GEOTHERMAL PLANT

3.1 Background

The Mindanao 1 & 2 Geothermal Power Plant Project is located in Barangay Ilomavis, Kidapawan, North Cotabato, Philippines. The project is a BOT (Build-Operate and Transfer) scheme, between Marubeni Energy Services Corporation and PNOC-EDC.

The project area is generally mountainous with elevations ranging from 1200 MASL in the Northwest to 2100 MASL in the Southeast. MIGP is rated at 52.0 MWe while M2GP is rated at 50.93 MWe. Power potential estimates ranged from 498 - 934 MWe with a reservoir temperature range of 220-260°C and final temperature of 180°C (Fara-on, 1998).

At the power plant boundary, steam was supplied with the conditions given in Table 1. The analysis was carried out using the actual ambient conditions as the reference environment or "dead state" (Table 2). The second analysis was done at a common reference environment, using the dead state of M2GP.

3.2 DISCUSSION OF RESULTS

Based on data provided by MESC, the exergetic efficiencies of both plants are calculated. Table 3 shows the summary of the exergy analysis. Figures 1 and 2 show the Sankey Diagrams based from the calculated values. From the information gathered and computed data, the following points are noted:

1. The results of the exergy analysis showed MIGP has a higher exergetic efficiency (net plant Second Law Efficiency) than M2GP.

Process Parameter	Unit	MIGP	M2GP
Steam Pressure/ Temperature	bar a/ C	7/165	HP : 7 / 165 / LP : 4.37 /142
Steam flow	kg/sec	106.9	HP: 94.33 / LP: 13.17
NCG content	% wt.	1.0	1.0
Steam dryness	%	99.98	99.98

Table 2. Reference environment (Canlobo, R., 2001, pers. comm).

		MIGP		M2GP
		HBD	Case 1	Case 2
Generator Load, MW	52.300	50.330	54.920	52.500
Parasitic Load, MW	3.600	2.814	2.678	2.583
Net Output	48.700	47.516	52.242	49.917
Dry bulb Temp, C		19.800	21.300	20.400
Wet bulb Temp, C	25.500	17.600	19.400	17.010
Pressure, bar a	0.851	0.891	0.881	0.864

Table 3. Summary of exergy analysis.

	At actual operating environments				At common reference environment		
	MIGP			M2GP	MIGP		M2GP
	HBD	Case 1	Case2	Case 1	Case 1	Case 1A	Case 1
					Original	Adjusted	Unchanged
Exergy rate at Plant boundary (MW)	81.47	78.69	79.75	87.32	78.693	84.41	87.32
Exergy drop through meter & pipes	0.34	1.128	1.13	0.22	1.128	2.33	0.22
% of Total	0.42	1.43	1.42	0.25	1.43	2.76	0.25
Exergy rate entering turbine (MW)	79.04	76.46	77.51	85.1	76.46	80.89	85.1
Exergy rate leaving turbine (MW)	11.93	11.39	11.55	19.31	11.39	21.78	19.31
Exergy drop through turbine (MW)	67.11	65.07	65.97	65.8	65.07	59.1	65.8
% of total	82.38	82.69	82.72	75.4	82.69	70.02	75.4
Turbine Internal Exergetic Efficiency	77.93	77.35	83.25	79.8	77.348	85.15	79.8
Irreversibility loss (MW)	14.81	14.74	11.05	13.3	14.74	8.77	13.3
% of total	18.18	18.73	13.85	15.23	18.73	10.39	15.23
Turbine Absolute 2nd Law Efficiency	66.17	65.83	70.85	61.7	65.83	62.22	61.7
Exergy rate of motive steam (MW)	2.093	1.105	1.105	1.99	1.105	1.2	1.99
Exergy rate of leaving GES (MW)	0.024	0.004	0.004	0	0.004	0.01	0
Exergy drop through GES (MW)	2.069	1.101	1.101	1.99	1.101	1.19	1.99
% of total	2.54	1.4	1.38	2.28	1.4	1.41	2.28
GES Exergetic Efficiency	23.51	29.78	29.79	23.39	29.777	44.83	23.39
Irreversibility loss	1.583	0.773	0.773	1.53	0.773	0.66	1.53
% of total	1.94	0.98	0.97	1.75	0.98	0.78	1.75
Exergy rate entering condenser (MW)	11.93	11.39	11.55	19.303	11.39	21.78	19.303
Exergy rate leaving condenser (MW)	0.21	0.2	0.21	0.47	0.2	0.43	0.47
Exergy drop through condenser (MW)	11.72	11.19	11.34	18.81	11.191	21.35	18.84
% of Total	14.38	14.22	14.22	21.57	14.22	25.29	21.57
Exergetic Efficiency of condenser	63.5	65.88	64.97	86.83	65.875	75.74	86.83
Irreversibility loss (MW)	4.277	3.819	3.971	2.48	3.819	5.18	2.48
% of Total	5.25	4.85	4.98	2.84	4.85	6.14	2.84
Mechanical Power Dev. by turbine (MW)	52.3	50.33	54.92	52.5	50.33	50.33	52.5
Parasitic load (MW)	3.58	2.814	2.678	2.58	2.814	2.81	3.58
Net Plant Output (MW)	48.72	47.52	52.24	49.92	47.516	47.516	48.92
Net Plant 2nd Law Eff. (%)	59.8	60.4	65.5	57.2	60.38	56.29	57.17
Available energy, MW	284.1	275.1	279	292	275.1	279	292
First Law efficiency	17.14	17.27	18.72	17.1	17.3	17.27	17.1

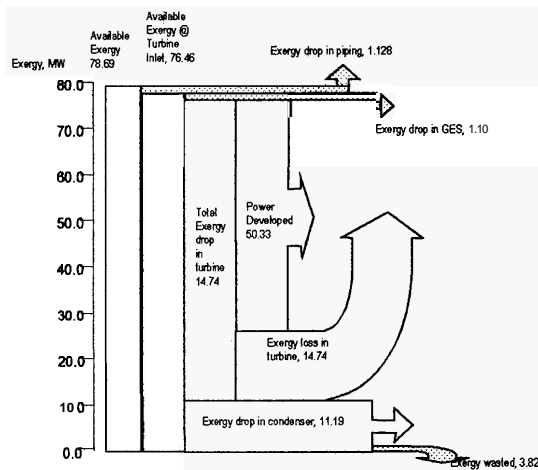


Figure 1. Sankey diagram of M1GP.

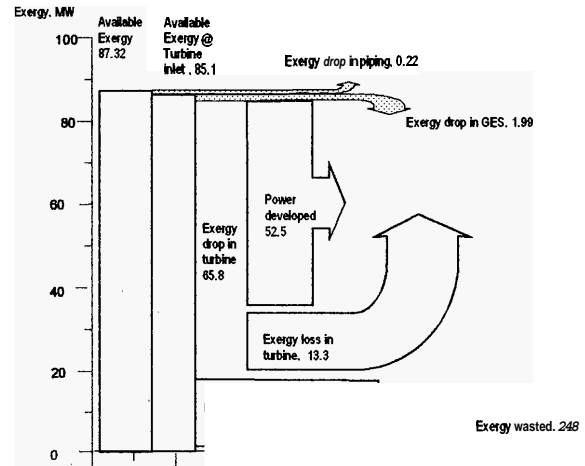


Figure 2. Sankey diagram of M2GP.

Exergetic efficiency at design conditions i.e. 100% load, is 59.8%. Case 1 attained a slightly higher efficiency, 60.4% while Case 2 achieved considerably higher exergetic efficiency at 65.5%.

- M2GP attained a lower net plant second law efficiency of 57.2%. This is primarily due to a lower turbine absolute 2nd law efficiency, 61.7%. MIGP Case 1 has a turbine absolute second law efficiency of 65.8%, higher than M2GP, which had 61.7%. Case 2 for MIGP, however, showed a higher absolute efficiency of 70.8%. The absolute second law efficiency depends on the power developed by the turbine and the available exergy at turbine inlet.
- First law efficiency calculations showed that actual value for MIGP, 17.3 - 18.7% are higher than designed value of 17.2%. Similarly, for M2GP, 1st law efficiency is 17.1%. This is a measure of the net plant output compared to the available energy at the turbine.
- While M2GP has a higher exergy rate entering the turbine, due to the addition of the low-pressure steam from the secondary flasher, it has a slightly higher exergy drop but lower irreversibility loss upon exit. Irreversibility loss was low as a result of the LP steam introduced at the 3rd stage. Losses due to irreversibility are highest at the last stages of the turbine. This is shown in the case of M1GP, which

operates on a single pressure, with steam exiting at a lower quality. Compared with M2GP where steam is introduced at the latter stages, steam has a higher exit exergy. The exergy drop in the turbine is due to the conversion of exergy into power and internal losses, or exergy used in the process.

- The exergetic efficiency for the gas ejector system is higher in MIGP compared with M2GP. This may be due to a higher exergy drop and irreversibility loss through the air ejectors although M2GP had a higher exergetic rate for its motive steam. The irreversibility loss of 1.5 MW in M2GP represents an amount of work that could have been converted to power. In both cases, MIGP has a lower loss due to irreversibility.
- There is not much difference in the condenser exergetic efficiency in all cases for M1GP. However, MIGP has lower exergetic efficiency, 65%, compared with M2GP, which had 87%. The exergy drop in the condenser is due to the condensation of steam, which is the desired effect, in order to attain a lower vacuum. MIGP condensers have almost the same exergy rate in all cases, upon exit, 0.20 MW. M2GP, however, had almost double the value of M1GP's exit exergy rate but has a higher exergy drop and lower irreversibility loss than MIGP. The combined effect of these factors is higher exergetic efficiency for M2GP.

7. When the reference environment of MIGP was set to be equivalent to M2GP, results showed that there is not much difference between net plant 2nd law efficiencies of the two plants, 56.3% vs. 57.2%. First law efficiency remained the same since the reference environment does not affect this measure of performance.
8. After adjusting the reference environment, there were significant changes in the measures of performance in MIGP:
 - a. increase in turbine exergetic efficiency from 77 to 85%; higher than M2GP @ 80%
 - b. increase in gas extraction efficiency from 30 to 45%; higher than M2GP @ 23%
 - c. increase in condenser exergetic efficiency from 66% to 76%; lower than M2GP @ 87%
 - d. decrease in net plant 2nd law efficiency from 60 to 56%, lower than M2GP @ 57%.
9. When MIGP and M2GP were taken as a single system, the following are noted (Table 4):
 - a. Net Plant Second Law Efficiency of 63.32% for the whole system (MIGP and M2GP at 100% load), which is higher than the exergetic efficiency of either plant. The increase in exergetic efficiency was due to the utilization of the additional exergy from the MIGP waste brine to produce low-pressure steam for M2GP.
 - b. The corresponding First Law Efficiency was 18.35% for the entire system.
10. The data were not of sufficient quantity and quality however to differentiate and detect heat losses hence heat exchange processes were assumed to be ideal.

4.0 CONCLUSIONS AND RECOMMENDATIONS

Based from the results and findings of the study, the following conclusions and recommendations are made:

1. The exergy analysis shows that there are areas that need further investigations to improve exergetic efficiency. These areas

Table 4. Efficiency of Mindanao geothermal

	Total	MIGP ¹	M2GP Case 1
MW Available exergy, MW	539161	284505	254656
Net Power developed, MW	104.35	51.85 ²	52.5
Net Plant 2nd Law Eff. (%)	63.32	49.036 ³	49.917

¹ At 166 °C steam boundary condition; 17 °C WBT, 0.881 bar abs ambient conditions
² Actual generator load at the same taken at the same time as Case 1-M2GP
³ Using assumed value of parasitic load of MIGP Case 1

- include the gas extraction unit and coding water system, particularly the cooling tower.
2. The extraction of as much steam as possible from the geothermal brine maximizes the efficient utilization of the available geothermal resource.
3. The utilization of waste brine, from MIGP, to increase steam rate in M2GP resulted in a high exergetic efficiency of the system.
4. A parallel study should be conducted to compare the performance of both plants and determine how each plant contributes to the performance of the entire geothermal system.
5. Since exergy analysis expresses the relationship between the system and the environment, it should be integrated in the design of engineering systems and in life cycle analysis of geothermal systems.

ACKNOWLEDGMENTS

The author wishes to thank the following who helped in the preparation of this report: New Zealand Ministry of Foreign Affairs and Trade; The Geothermal Institute Staff, The University of Auckland; Austin Herrick and Romy Canlobo of Marubeni Energy Services Corporation; Peter

Barnett, Sinclair Knights Merz; Tom McAuliffe of Power Engineers, The PNOC-Energy Development Corp- Mindanao Geothermal Project.

NOMENCLATURE

Case 1 refers to the first set of actual operating data for MIGP

Case 1A refers to the first set of actual operating data for MIGP with reference environment set equivalent to M2GP

Case 2 refers to the second set of actual operating data for MIGP

Case 1 under M2GP refers to the first set of actual operating data for M2GP

- i - refers to state points
- 0 - refers to the environmental state
- h - enthalpy, kJ/kg
- s - entropy, kJ/kg K
- T - temperature ° K
- ω - Humidity ratio, mass of water vapor per mass of dry air
- m_s - mass of steam at turbine inlet
- H - enthalpy of steam at turbine inlet

EQUATIONS USED

- (1) $E = E_{ph} = (h_i - h_0) - T_0(s_i - s_0)$
- (2) Exergy of steam (Es) $E_s = m_s * e_s$,
where $e_s = (h_s - h_0) - T_0(s_s - s_0)$
- (3) Exergy of water (Ew) $E_w = m_w * e_w$,
where $e_w = (h_w - h_0) - T_0(s_w - s_0)$
- (4) Exergy of non-condensable gases (Eg),
 $E_g = m_g * e_g$,
where $e_g = (h_g - h_0) - T_0(s_g - s_0)$
- (5) Exergy of humid air @ cooling tower (Ea) (Moran, 1989), $E_a = d_{ry\ air} * e_a$
- (6) $e_a = T_0 \{ C_{pa} + \omega C_{pv} [(T/T_0) - 1 - \ln(T/T_0)] + (1+\omega)R_a \ln(P/P_0) \} + R_a T_0 \{ (1+\omega) \ln(1+\omega)/(1+\omega) + a \ln(\omega/\omega) \}$
- (7) $a = 1.6078 * \omega$
- (8) Exergetic efficiency:
 $\eta = \frac{\text{Exergy entering the system} - \text{exergy loss}}{\text{Exergy entering the system}}$
- (9) First Law Efficiency:
 $\eta = \frac{\text{Power developed}}{\text{Available energy}} = \frac{W}{m_s H}$
- (10) Efficiency = $\frac{\text{Work developed by turbine}}{\text{Exergy yielded by steam}}$

REFERENCES

- Dincer, I. and Cengel, Y.A. (2001). Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering. Entropy 2001, Vol. 3, MDPI, 116-149.
- Fara-on, R. (1998). A resource assessment review for the Mt. Apo resource, Mindanao, Philippines. Diploma Course Project No. 98.09, Geothermal Institute, University of Auckland.
- Gong, M. and Wall, G. (1997). On exergetics, economics and optimization of technical processes to meet environmental conditions. In: Ruixian Cai, et al. Eds. "Thermodynamic Analysis and Improvement of Energy Systems," June 10-13, Beijing, China, 453-460.
- Kanoglu, M. and Cengel, Y.A. (1999). Retrofitting a geothermal power plant to optimize performance: A case study. ASME Journal of Energy Resources Technology, Vol. 121, December 1999, 295-301.
- Soekono, H. (1995). Exergy audit and plant optimization of Darajat geothermal power plant, Indonesia. Diploma Course Project No. 95.19, Geothermal Institute, University of Auckland.

Rosen, M. and Dincer, I. (2001). Exergy as the confluence of energy, environment and sustainable development. Exergy International Journal, Vol. 1, 3-13.

Villena, J. (1997). Exergy analysis and design comparison: Mindanao 1 and Mahanagdong 1 geothermal power plants, Philippines. Diploma Course Project No. 97.27, Geothermal Institute, University of Auckland.

Wright, P.M. (1995). The sustainability of production from geothermal resources. Proceedings World Geothermal Congress 1995, Florence, vol. 4, 2825-2835.