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# EXERGY ANALYSIS AND DESIGN COMPARISON
# MINDANAO 1 AND MAHANAGDONG (UNIT 1) GEOTHERMAL POWER PLANTS

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**Abstract**

*This project presents the exergy analysis of two Geothermal Power Plant in the Philippines; namely the 52Mwe Mindanaol and the Mahanagdong (Unit I) Geothermal Power plant. The purpose of this analysis is to compure the components system design i. e. the main steam ystem, the gas extraction system, cooling water system and the condenser in terms of exergetic efficiency. Basic similarities of the two plants, such as operating pressure and unit capacity and their differences e.g. gas content and type of condenser, provides a good basis for comparison. Areas of possible exergy loss recovery have been identified and the merit and dement of both plant design was discussed*

*In this study, the Mahanagdong plant appears to have a slightly more efficient ystem design. Three areas of possible exergy lost recovery were identified. These are the selection of flowmetering device, the arrangement of the gas extraction equipment, and the treatment of the cooling water comingfiom the cooling tower.*

## 1.0 INTRODUCTION

The efficient use of energy is always of *great* concern in design and analysis of systems and processes. The exergy method, which is based on the Second Law of Thermodynamics, considers the concept of irreversibility and regards the environment as the reference state. *Any* process stream which has a thermodynamic or mechanical property which is in excess than that contained by the same component in the environment is capable of doing work The maximum work that is available through a reversible process *is called " exergy "*. *Any* actual process cannot deliver the maximum work and its variation is accounted for by the process irreversibilty. In this regard this is considered superior than the energy balance analysis.

PNOC- Energy Development Corporation is now engaging not *only* in steamfield development but operation and development of the geothermal power plant as well. After engaging in BOT contracts, the 52Mwe Mindanao 1 and 3 x 60 Mwe Mahanagdong Geothermal power plants have just started comercial operation These plants have a number of similarities such as, operating pressure and unit capacity, and also same differences, i. e. gas content, system desingn and equipment selection It is nteresting to know how this would affect each *component* system's exergetic efficiency. In so doing areas where exergy losses can be possible recovered are identified-

## 2.0 THEORY AND CONCEPT OF EXERGY

The 2nd law states that if a *system* is taken through a cycle and produces work, it must be exchanging heat with at least two reservoirs at different temperatures (Rogers and Mayhew, ). The difference in temperature provides the difference in energy level between the heat source and the heat sink which determines the amount of available work that *can* be developed by the working fluid operating at a certain process or cycle between the two reservoir. If the cycle or process that the fluid has undergone is reversible, meaning no heat loss, then we have generated the maximum available work which is *called* "exergy". Energy level denotes not only temperature, but pressure, as in the case of hydroelectric plant, and *chemical* concentration, or *any* other property that is in excess of that which the environment contains, which *can* cause heat and/or mass to flow between the two reservoir. Szargut defined exergy as the "work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common component of the natural sorroundings by means of reversible process involving interaction only With the above-mentioned component of nature". Thermal equilibrium means the same temperature, pressure, entropy, chemical concentration, radiation emission and other property which the same component contains as it exist in the environment. Following this definition we have:

$$E = \hat{E}_1 - \hat{E}_0 \qquad (2.10)$$

where:
$E$ = Exergy
$\hat{E}_1$ = Total energy contained in the source
$\hat{E}_0$ = Total energy contained in the sink

where the total energy is composed of the internal energy, entropy, flow work, kinetic energy, potential energy, chemical and radiation emission According *to* Ahern, exergy *can* be calculated as follows:

$$E = (u - u_0) + P_0 *( v - v_0) - T_0 *(S - S_0) + V^2/2g + (z - z_0)*g + \Sigma_i (\mu_i - \mu_0) *N_0 + E*A*F*(3T^4 - T_0^4 - 4T_0T) + ..... \qquad (2.11)$$

where the subscript $_0$ refers to the environment. Variation of this general equation depends on the application wherein some components *can* be neglected for simplification. For the purpose of most thermal cycle evaluation the last four terms *can* be neglected considering their negligible effect. Recognizing that;

$$(h - h_0) = (u - u_0) + P_0 *(v - v_0) \qquad (2.12)$$

then;

$$\text{Exergy} = (h - h_0) - T_0 *(S - S_0) \qquad (2.13)$$

Based on the formula, it is apparent that the exergy is dependent not only on the fluid condition but on the environment condition, i.e. dead state, as well. The greater is the difference between this two conditions the greater is the amount of exergy. Since this formula refers to unit mass flow then some literatures called this as specific exergy denoted by symbol "e" which will be used for the rest of this report. Note that the maximum work available (exergy) is *equal* to the total energy less an amount *equal* to the product of the environment temperature and the difference between the entropy contained in the matter and the entropy contained on the same component as it exist in the environment.

## 3.0 APPLICATION TO GEOTHERMAL POWER SYSTEM

Despite the numerous advantage over the energy balance analysis, the exergy method of analysis has not gained popularity and usage within the technical community. It is interesting to note that this *system* bas not gained popularity in geothermal power system being an open type of system. Whatever the thermodynamic cycle employed in processing the geothermal fluid for power generation, the geofluid has a temperature and pressure that exceeds that of the environment and therefore has a potential to do useful work After passing through the turbine the fluid *can* either pass to a condenser before rejecting to the environment. The *geothermal* power system is an open cycle system which makes it more suitable for exergy method of performance analysis. Performance indicator is the exergetic efficiency or Second Law efficiency or sometimes *called* the utilisation efficiency denoted by the symbol $\eta_B$. The basic equation used in *calculating* exergetic efficiency is as follows: (Moran )

$$\eta_B = \frac{\text{Exergy of useful product}}{\text{Feeding exergy}}$$

where the exergy in useful product *can* be in form of work as in the *case* of turbine or exergy *gained* in case of heat transfer or any other desired effect that will consume exergy. On the other hand, feeding exergy means the exergy consumed or yielded to achieve the desired product.

Given the Heat and Mass Balance Diagram for 52 Mwe Mindanao 1 Geothermal Power Plant and 61 Mwe Mahanagdong (Unit 1) *Geothermal* Power Plant for 100% load condition the following equations was used in the calculation:

1. Exergy of steam (Es)

$Es = ms*es$

$es = (h_s - h_0) - T_0 * (S_s - S_0)$

2. Exergy of water (Ew)

$Ew = mw*ew$

$ew = (h_w - h_0) - T_0 * (S_w - S_0)$

3. Exergy of non-condensible gases (Eg)

$Eg = mg*eg$

$eg = (h_g - h_0) - T_0 * (S_g - S_0)$

4. Exergy of humid air at cooling tower outlet (Ea) (Moran, 1989)

$Ea = m_{dry\ air}*ea$

$$ea = T_0 *\{(Cpa - \omega * Cpv)*[T/T_0 - 1 - \ln(T/T_0)] + Ra*\ln(P/P_0)\} + Ra*T_0*\{(1+\varpi)*\ln((1+\varpi_0)/(1+\omega)) + w * \ln(\varpi/\varpi_0)$$

$w = 1.607*\omega$

Note from the above equations that the specific exergy of NCG was calculated considering the difference in specific heat at constant pressure Cpg between the state points condition and the environment. Since the difference in temperature between these points are considerable *then* the Cpg m o t be assumed constant. Also since 97% - 98% of the NCG is $CO_2$ then the properties of pure $CO_2$ *gas* was used for simplification. It should be noted that the enthalpy and entropy of CO2 was taken at T, Pg and $T_0$, $Pg_0$ where Pg and $Pg_0$ where partial pressure of the gas at at the state point and environment condition, respectively. In *case* of the specific exergy of water, the exergy increase due to pump work was neglected this having a negligible effect on enthalpy. For calculating the specific exergy of humid air at cooling tower outlet, it is assumed to be consisting of ideal *gas* mixture of water vapor and air with constant specific heat since the dry bulb temperature difference at inlet and outlet of tower is small. (Moran , 1989).

## 4.0 DEAD STATE

According to Gagioli (1980) the dead state of a component is its stable condition as it exist in the environment. For water and $CO_2$ this is the saturated condition of water and the stable configuration of $CO_2$, respectively, as they exist in air *saturated* with liquid water i.e. at *dry* buld temperature equal to wet buld temperature. Based on the given heat balance diagram the ambient wet bulb temperature is 25.5°C for Mindanao and 23°C for Mahanagdong which is taken as $T_0$. Pressure $P_0$ is also given as 0.851 bara for Mindanao and *0.94* bara for Mahanagdong. To calculate the specific exergy of the gas, the partial pressure of $CO_2$ in air is necessary. Below is the characteristic of the stable dead state.

| AIR CONSTITUENTS | MOLE FRACTION |
|---|---|
| $N_2$ | 0.7560 |
| $O_2$ | 0.2034 |
| $H_2O$ | 0.0312 |
| Ar | 0.0091 |
| $CO_2$ | 0.0003 |
| $H_2$ | 0.0001 |

## 5.0 DESIGN COMPARISON

### BACKGROUND AND BASIC PROCESS DATA

Mindanao 1 Geothermal Plant (MlGP) is located at Barangay Ilomavis, municipality of Kidapawan, province of Cotabato. It is the first geothermal plant at the Mount Apo Geothermal Field. The 52 Mwe power plant was *commissioned* and *started* commercial operation last M a r 4 1997. The power plant was designed and built by BOT (Build Operate and Transfer) contractor and will be operated by the same for **a** period of 10 years then eventually transfer the plant operation and ownership to **PNOC-EDC.** The steamfield was designed, constructed and operated **by PNOC-EDC.** Meanwhile, Mahanagdong is one of the five geothermal systems that have been developed **on** Greater Tongonan Geothermal Field in the Island of Leyte. The 180 MWe power plant will supply the power to the island of Luzon through a submarine cable. Commissioning of the **plant was** completed last June, 1997. Like Mindanao, this plant was developed through **a** BOT contract with 10 year cooperation period. The plant is composed of **3 x** ***60*** MWe single pressure condensing turbines. The steam gathering **system** was designed, constructed and operated **by PNOC-EDC. At** the **plant** boundary the delivered **steam has** the following condition:

**Mindanao and** Mahanagdong **Specification (Source** BOT -PNOC Interface **Data Sheet)**

| PROCESS PARAMETER | UNIT | MINDANAO 1 | MAHANAGDONG |
|---|---|---|---|
| 1. Steam Pressure / Temperature | bara / °C | 7 / 165 | 6 / 158 |
| 2. Steam Flow | kg/sec | 106.9 | 131.3/unit |
| 3. NCG content | % wt. | 1.0 | 2.9 |
| 4. NCG composition | | 97 | 98.2 |
| | | 3.4 | 1.6 |
| $NH_3$ | | 0.8 | 0.27 |
| 5. Steam dryness | | 99.98 | 99.98 |

## 5.1 MAIN STEAM SYSTEM

### 5.1.1 BASIC DESIGN FEATURES

**The main** ***steam*** **system of the** geothermal **power plant is** composed **of the turbogenerator, gland sealing system and** auxilliaries, the **flowmetering devices, demister, and associated pipings Below is the** *tabulated* **comparison of the** basic **design** feature of **the Main Steam System of the two plants**

Main *Steam* System **Comparison**

| FEATURE | MIGP | MHNGP |
|---|---|---|
| Steam pressure (bara) | 6.86 | 5.82 |
| Steamflow (kg/sec) a) Main | 106.9 | 131.1 |
| b) Motive | 2.82 | 4.98 |
| Steam Line size (inch) a) Main | 42 | 48 |
| b) Motive | 10 | 16 |
| Flowmetering Device a) Main | Venturi | Venturi |
| b) Motive | - | Venturi |
| Steam Demister (Y / N) | N | Y |
| Turbine Isentropic Efficiency | 73.6% | 79.3% |
| Gland Exhaust system | Exhaust to drain/flash tank which uses drain eductor to exhaust in the condenser | Uses gland *steam* surface condenser then NCG are *exhausted* to atmosphere using blowers (2 x 15 Hp) and condensate goes to drain |

ource :PE / MHI P &I Dwg. No. MOO and MOO15 Rev 1
CBEP &I Dwg. No 20221-1-32110 and 32111 Rev3

### 5.1.2 COMPARISON OF SYSTEM EXERGETIC EFFICIENCY

Based **on the 100% Heat Balance diagram** the exergetic **efficiency of** the **main** ***steam*** **system for** both plants is **calculated.** Please **note** that due to **insufficiency of Qta** the calculation was **limited to considering** the gland steam exhaust condition immediately at the turbine exit. Exergetic efficiency is calculated as follows:

$$\eta_B = \frac{\text{Work developed by turbine}}{\text{Exergy Yielded by Steam}}$$

$$= \frac{W}{Et1 - Et4 - Et5} \qquad (5.1)$$

For the case of MHNGP there was no data on the condition of the gland steam at the immediate exhaust near the turbine. To make the comparison, the calculation for the efficiency does not consider the lost exergy at this condition.

### 5.1.3 DISCUSSION

Considering the design data and the result of the exergy calculation the following was noted:

| | MlGP | MHNGP |
|---|---|---|
| Exergy rate at plant boundary (MW) | 81.47 | 97.37 |
| Exegy drop on turbme (MW) | 67.11 | 77.08 |
| Exergy drop on flowmeter and demisters (MW) | 0.34 | 1.15 |
| Power developed by turbme (MW) | 52.3 | 61.14 |
| Turbine exergetic Eff. | 77.9 % | 79.3% |
| System Exegetic Eff. | 77.54% | 79.15% |

2. With regards to the system arrangement, the deciding factor will be between the cost of using the exhausters and shell and tube intercondenser versus the cost of steam lost to the drain eductor. Since no data was available basis for this the decision cannot be discussed in this report.

## 5.2 GAS EXTRACTION SYSTEM

### 5.2.1 BASIC DESIGN FEATURES

The Gas Extraction System is composed of the steam jet ejectors, inter and after condensers, the Liquid Ring Vacuum Pump (LRVP), the drain separator and the associated pipelines. Both plants use a "Hybrid" type of extraction system for normal operation, which is a combination of the jet ejectors and rotodynamic extractors. The basic difference lies in the number, type and arrangement of the equipment. Note that for MlGP the 3rd stage ejectors are in parallel with the LRVP and direct contact intercoolers. Two drain separators and the check valves are used at the gas outlet to avoid back flow of the corrosive gases. During normal operation the 3rd stage ejectors are on stand-by. In the case of the MHNGP plant the 2nd and 3rd stage ejectors are in parallel with the LRVP and shell and tube intercondensers. Due to the increase in gas content from 2.0% to 2.9% it became necessary to use 5 x 20% steam jet ejectors for the 1st stage then passing it to 5 units of LRVP . During normal operation the 2nd and 3rd stage jet ejectors are on stand-by. Table below gives a summary of the basic design feature of the Gas Extraction system for the two plants.

**Gas Extraction System Comparison**

| FEATURE | | MIGP | MHNGP |
|---|---|---|---|
| Gas flow (kg/sec) | | 1.113 | 3.726 |
| Main Gas Line size (inch) | | 30 | 2 x 48 |
| No. of Jet Ejector Stages | | 3 | 3 |
| Compression Ratio | 1st Stage | 2.17 | 2 |
| | 2nd Stage | 2.4 | 5.83 (combined |
| | 3rd Stage . | 2.77 | 2nd and 3rd stages) |
| No. of ejector units | 1st Stage | 2 x 50% | 5 x 20% |
| | 2nd Stage | 2 x 50% | 1x 100% |
| | 3rd Stage | 1x 100% | 1x 100% |
| Inter/After Condenser Type | | Direct contact | Shell and tube |
| No. and Size of LRVP Units | | 1 x 350 Hp | 5 x 400 Hp |

*source :PE / MHI P &I Dwg. No. M0010 Rev 1*
*CBEP &I Dwg. No 20221-1-32113 to 115 Rev 3*

### 5.2.2 COMPARISON OF SYSTEM EXERGETIC EFFICIENCY

Based on the 100% Heat Balance diagram the exergetic efficiency of the Gas Extraction System for both plants is calculated. Exergetic effficiency is calculated as follows:

$$\eta_B = \frac{\text{Exergy Gained by Gas and Cooling Water}}{\text{Exergy Yielded by Steam plus Work Supplied to LRVP}}$$

$$= \frac{(Eg6\text{-}8 - Eg6) + (Eg4\text{-}8 - Eg4) + (Ew16 - Ew12) + (Ew15 - Ew11)}{(Es4 + Es6 - Es16 - Es15 - Es8) + W} \qquad (5.2)$$

### 5.2.3 DISCUSSION OF RESULT

1. Despite the high NCG load to be evacuated, Mahanagdong Gas Extraction System (GES) manages to match the exergetic efficiency of the Mindanao plant. This is mainly due to high gas compression process efficiency of the system despite the use of surface type intercoolers which lowers its condensation process efficiency. Note that for Mahanagdong at normal operation, most of the compression process takes place in the LRVP which has a higher efficiency than jet ejectors. LRVP has an efficiency in the order of 40% while jet ejectors are less than 5% efficient (Dunstall, 1997). Using a similar set-up with a lower gas content, calculated system efficiency of MIGP GES will increase to 31%. Below is the summary of the exergy audit.

| | MIGP | MHNGP |
|---|---|---|
| Exergy gained by Gas (KW) | 230.23 | 739.75 |
| Exergy Gained by Water (KW) | 331.76 | 517.96 |
| Exergy yielded by steam (KW) | 2127.56 | 3786.45 |
| Work supplied to LRVP (KW) | 261 | 1492 |
| Gas Compression Process Eff. | 9.65% | 14.01% |
| Condensation Process Eff. | 13.9% | 9.8% |
| GES Exergetic Eff. | 23.5% | 23.8% |

2. The exergetic efficiency of the GES is low compared to the other systems in the geothermal plant. The exergy gained by the gas, which *is* the desired effect, is considerably less **than** the exergy lost in condensation; a consequence of using **steam** for gas ejection.

## 5.3 COOLING WATER SYSTEM

### 5.3.1 BASIC DESIGN FEATURES

The cooling water **system** of a **geothermal** power plant is composed of the condenser **,** the **cooling** tower, the condensate and auxilliary pumps, the coolers, and **associated** pipings. For the two plants the basic differences are as follows:

1. The Mindanao plant uses a direct **contact** type of condenser while tlie Mahanagdong plant uses a **surface** type of condenser and auxilliary coolers due to the high amount of NCG.

2. Cooling water coming **from** the auxilliary coolers (i.e. generator and oil coolers) ***at*** the Mindanao plant is discharged to the cooling tower basin. In the Mahanagdong plant, this is mixed with the condensate and then pumped ***to*** the **top** of the tower.

3. The cooling **water** supplied to the **LRVP is part** of the cooling water supply **from** the cooling tower **that** passes through the auxilliary **pumps** in **MIGP** system. ***On*** the other **hand, MHNGP** has a *direct* supply from the cooling tower without passing the auxilliary pumps. Considering the **water** requirement of **5 x 400 Hp pumps,** this is a **big** saving on pump size.

In view of the foregoing, exergetic efficiency of the condenser **and** the whole cooling system was analysized separately for comparison. Table below gives the basic design **features** of the Cooling Water **system** for the two plants:

Cooling Water System Comparison

| FEATURE | MIGP | MHNGP |
|---|---|---|
| Cooling Water Flow (kg/sec) | 4456.4 | 6533.4 |
| Main Water Line size (inch) | 54 | 66 |
| Hotwell / Condensate **Pump** | | |
| No. of **Units** / Rating | 2 x 50% / 827 Hp | 3 x 50% 175 Hp |
| Condenser Type | Direct Contact | Shell and Tube |
| Auxilliary Cooling Water **Pump** | | |
| **No. of** Units / **Rating** | 2 x 100% / 150Hp | 3 x 50% / 1350 Hp |
| Cooling Tower Type | Mech. Induce Draft | Mech. Induced Draft |
| No. of **Cells** / **Fan** Rating | 5 cells / 200 Hp | 7 cells *1200* Hp |
| Blowdown Pump | | |
| **No.** of **Units / Rating** | *2* x 100% / 35 Hp | 2 x 100% / 40 Hp |

*Source :PE / MHI P &I Dwg. No. M0010 Rev 1*
*CBE P &I Dwg. No 20221-1-32113 to 115 Rev 3*

### 5.3.2 COMPARISON OF SYSTEM EXERGETIC EFFICIENCY

Based on the 100% **Heat** Balance diagram the exergetic efficiency of the Condenser for both plants is calculated. Exergetic effficiency is calculated separately for **MIGP and** MHNGP since they have different set-up.

CONDENSER!?

MIGP

$$\eta_B = \frac{\text{Exergy Gained by Gas and Cooling Water}}{\text{Exergy Yielded by Steam}}$$

$$= \frac{(Eg6 - Eg5) + (Ew14 - Ew15 - Ew16 - Ew10)}{(Es5 + Es15 + Es16 - Es6 - Es14)} \quad (5.3.1)$$

MHNGP

$$\eta_B \quad \frac{\text{Exergy Gained by Gas and Cooling Water}}{\text{Exergy Yielded by Steam}}$$

$$\eta_B = \frac{(Eg6 - Eg5) + (Ew14 - Ew10}{(Es5 - Es6 - Es19)} \quad (5.3.2)$$

COOLING WATER SYSTEM

$$\eta_B = \frac{\text{Exergy Gained by Gas and Air}}{\text{Exergy Yielded by Steam and Cooling Water}}$$

$$- \frac{(Eg6 - Eg5) + (Ea22 - Ea0 - Ea18)}{(Es5 + Es15 + Es16 - Es6 - Es23) + (Ew15+Ew16-Ew11-Ew12) + W} \quad (5.3.3)$$

Where $Ea0$ and $Ea18 = 0$

### 5.3.2 DISCUSSION OF RESULT

Comparing the design features and the calculated exergetic efficiency of the two systems the following was noted:

1. Based on the condenser exergetic efficiency comparison the direct contact condenser performs better than the surface type condenser. The difference lies in the exergy gained by the cooling water, which is about 61% of the total exergy yielded by the steam due to mixing. Note however, that the gas cooling process in the surface condenser has higher efficiency than the direct contact condenser. This could be due to the high stream capacity of the gas in Mahanagdong plant and the gas absorption process which takes place in the direct contact condenser. This is considered as one disadvantage of the direct contact condenser. Since no design data was available for each condenser then this cannot be evaluated further in this report. Below is a summary of exergy analysis for the condenser:

| | MIGP | MHNGP |
|---|---|---|
| Exergy gained by Gas (kW) | 269.63 | 662.65 |
| Exergy Gained by Water (kW) | 7110.5 | 7751.78 |
| Exergy yielded by steam (kW) | 11623.19 | 14560.19 |
| Gas Cooling Process Eff. | 2.32% | 4.55% |
| Condensation Process Eff. | 61% | 53.24% |
| Exergetic Eff. | 63.49% | 57.79% |

2. Although the condenser efficiency on the Mindanao plant is higher, the cooling water system efficiency of the Mahanagdong plants turns out to be slightly higher. The difference is due to its higher gas cooling efficiency. However, possible improvement of GES efficiency in the Mindanao plant can be made considering the cooling water coming from the auxilliary coolers. In the Mindanao plant 200 kg/sec of water from the coolers is discharged to the cooling tower basin yielding its exergy to the cooled water coming from the top of the tower. This causes an increase in exergy yielded by the water which is not gained by air passing through the tower. At the Mahanagdong plant about 120 kg/sec of cooling water is mixed with steam condensate then pumped to the top of the tower to yield its exergy to the incoming air stream. This set-up requires bigger pump size to pump against the height of the cooling tower.

| | MIGP | MHNGP |
|---|---|---|
| Exergy gained by Gas (KW) | 269.63 | 662.65 |
| Exergy Gained by Air (KW) | 5882.36 | 7437.6 |
| Exergy yielded by steam (KW) | 11781.07 | 14799.0 |
| Exergy yielded by water (KW) | 338.2 | 529.64 |
| Work Supplied to pumps and fans (KW) | 2122 | 2790 |
| Gas Cooling Process Eff. | 1.89% | 3.65% |
| Water Cooling Process Eff. | 41.3% | 41.05% |
| Exergetic Eff. | 43.2% | 44.7% |

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

1. Pressure drop through the flowmeter and demister causes a steam exergy loss of about 0.5% to 1% of the initial steam exergy at the plant boundary. Selection of flowmetering device shoulb be done considering the cost of the unit and the exergy lost. Magnetic flowmeters, which do not provide flow restriction, could be a possible Option. In order to avoid the use of demisters, efficiency of scrubbing on steamline drainpots should be enhanced.

2. Considering the exergy drop in the Gas Extraction System (GES) and its low system efficiency we can say that proper equipment selection and optimisation is critical in GES design. In cases of high NCG content, higher efficiency can be gained by using higher efficiency exhausters such as rotodynamic machines instead of jet ejectors. For "Hybrid" operation, higher compression ratio should take place m the LRVP to effect higher system efficiency. However, since such an increase in efficiency always comes with increase in cost, then cost evaluation should be conducted.

3. Cooling water used for auxilliary coolers contains high exergy that should be yielded to the incoming air stream at the cooling tower. Mixing this with the cooled water at the cooling tower basin results in a decrease in system exergetic efficiency. For high capacity plants where a large amount of water is required for this purpose, a cost evaluation should be done with regards to the increase in efficiency and pump size.

4. With regards to plant design comparison, result of the exergy evaluation shows that the Mahanagdong plant has a more effective system design than the Mindanao plant. However, since the efficiency difference is small, cost evaluation could favor the Mindanao plant.

MINDANAO 1 (62 MW) GEOTHERMAL POWER PLANT

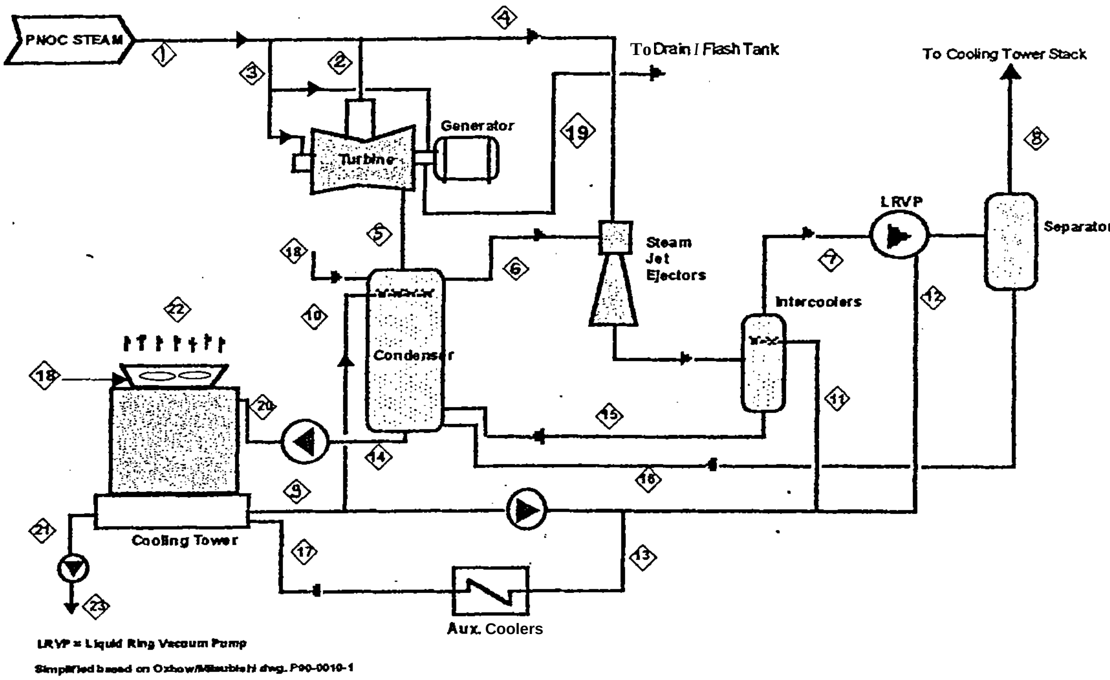


**Table 1: EXERGY ANALYSIS OF MINDANAO 1 (52 MW) GEOTHERMAL POWER PLANT (@ 100% LOAD CONDITION)**

| State Point | Temperature ( C) | Pressure (bara) | Enthalpy | Mass Flow ms (kg/sec) | mg (kg/sec) | mw (kg/sec) | Specific Exergy es (kj/kg) | eg (kj/kg) | ew (kj/kg) | Exergy Et (MW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 165.70 | 6.86 | 2763.00 | 105.86 | 1.069 | 0.00 | 766.70 | 288.90 | 0.00 | 81.469 |
| 2 | 165.30 | 6.76 | 2762.00 | 102.90 | 1.039 | 0.00 | 765.30 | 287.90 | 0.00 | 79.047 |
| 3 | 165.30 | 6.76 | 2762.00 | 0.17 | 0.002 | 0.00 | 765.30 | 287.90 | 0.00 | 0.128 |
| 4 | 160.20 | 6.22 | 2757.00 | 2.79 | 0.028 | 0.00 | 746.90 | 281.70 | 0.00 | 2.093 |
| 5 | 44.90 | 0.10 | 2259.00 | 90.28 | 1.040 | 12.70 | 131.50 | 32.03 | 2.60 | 11.938 |
| 6 | 35.50 | 0.09 | 2567.00 | 0.84 | 1.113 | 0.00 | 80.55 | 272.10 | 0.00 | 0.371 |
| 7 | 44.50 | 0.47 | 2583.00 | 0.28 | 1.147 | 0.00 | 146.80 | 398.10 | 0.00 | 0.498 |
| 8 | 53.30 | 1.30 | 2598.00 | 0.08 | 1.147 | 0.00 | 207.90 | 474.00 | 0.00 | 0.559 |
| 9 | 30.50 | 0.85 | 127.70 | 0.00 | 0.000 | 4436.34 | 0.00 | 0.00 | 0.18 | 0.791 |
| 10 | 30.50 | 0.85 | 127.70 | 0.00 | 0.000 | 4076.02 | 0.00 | 0.00 | 0.18 | 0.727 |
| 11 | 30.50 | 3.50 | 127.70 | 0.00 | 0.000 | 154.03 | 0.00 | 0.00 | 0.18 | 0.027 |
| 12 | 30.50 | 3.50 | 127.70 | 0.00 | 0.000 | 4.42 | 0.00 | 0.00 | 0.18 | 0.001 |
| 13 | 30.50 | 3.50 | 127.70 | 0.00 | 0.000 | 201.87 | 0.00 | 0.00 | 0.18 | 0.036 |
| 14 | 42.90 | 0.10 | 179.50 | 0.00 | 0.000 | 4320.16 | 0.00 | 0.00 | 2.10 | 9.068 |
| 15 | 44.50 | 0.47 | 186.20 | 0.00 | 0.000 | 156.65 | 0.00 | 0.00 | 2.49 | 0.390 |
| 16 | 53.30 | 1.30 | 222.90 | 0.00 | 0.000 | 44.86 | 0.00 | 0.00 | 5.21 | 0.234 |
| 17 | 53.30 | 3.50 | 222.90 | 0.00 | 0.000 | 200.02 | 0.00 | 0.00 | 5.21 | 1.042 |
| 18 | 25.50 | 0.85 | 299.10 | 0.00 | 0.073 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 |
| 19 | 100.00 | 0.85 | 2676.00 | 0.03 | 0.090 | 0.00 | 483.40 | 154.80 | 0.00 | 0.027 |
| 20 | 42.90 | 3.50 | 179.50 | 0.00 | 0.000 | 4320.16 | 0.00 | 0.00 | 2.10 | 9.068 |
| 21 | 30.50 | 0.85 | 127.70 | 0.00 | 0.000 | 20.32 | 0.00 | 0.00 | 0.18 | 0.004 |
| 22 | 38.00 | 0.85 | 159.00 | 0.00 | 0.000 | 84.67 | 0.00 | 0.00 | 1.10 | 0.093 |
| 23 | 30.50 | 11.24 | 127.70 | 0.00 | 0.000 | 20.32 | 0.00 | 0.00 | 0.18 | 0.004 |
| 0 | 25.50 | 0.85 | 106.80 | 0.00 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 |

ote : Values underlined are assumed

## MAHANAGDONG (UNIT 1) GEOTHERMAL POWER PLANT

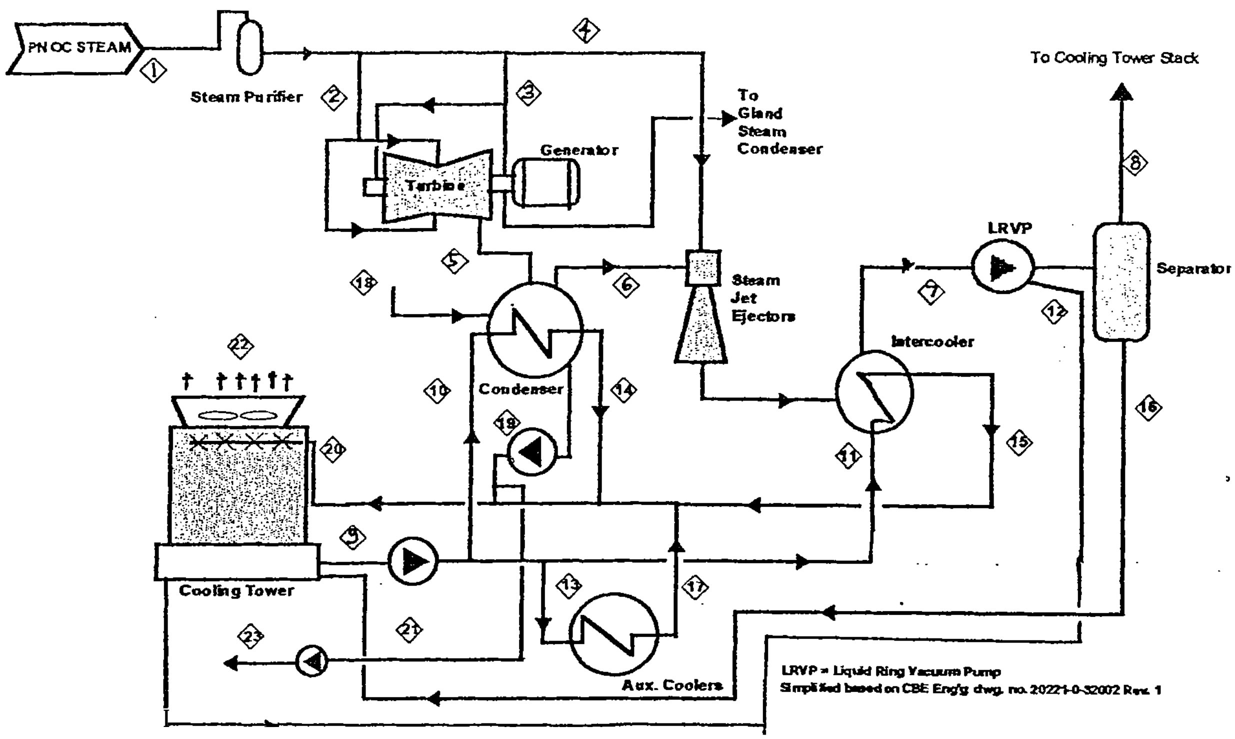


**Table 2:** EXERGY ANALYSIS OF MAHANAGDONG (60 MW) GEOTHERMAL POWER PLANT (@ 2.9% NCG)

| State Point | emperatu ( C) | Pressure (bara) | Enthalpy | Mass Flow ms (kg/sec) | mg (kg/sec) | mw (kg/sec) | Specific Exergy es (kj/kg) | eg (kj/kg) | ew (kj/kg) | Exergy Et (MW) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 157.80 | 5.82 | 2754.00 | 127.49 | 3.808 | 0.00 | 754.00 | 330.50 | 0.00 | 97.382 |
| 2 | 156.10 | 5.39 | 2752.00 | 122.35 | 3.654 | 0.00 | 747.70 | 325.70 | 0.00 | 92.672 |
| 3 | 156.10 | 5.39 | 2752.00 | 0.30 | 0.009 | 0.00 | 747.70 | 325.70 | 0.00 | 0.229 |
| 4 | 150.60 | 4.83 | 2746.00 | 4.83 | 0.144 | 0.00 | 726.80 | 317.80 | 0.00 | 3.558 |
| 5 | 44.20 | 0.09 | 2266.00 | 106.50 | 3.663 | 16.15 | 143.00 | 85.71 | 3.09 | 15.593 |
| 6 | 35.90 | 0.09 | 2567.00 | 2.89 | 3.726 | 0.00 | 103.50 | 262.10 | 0.00 | 1.275 |
| 7 | 32.20 | 0.18 | 2561.00 | 7.72 | 3.871 | 0.00 | 75.43 | 261.20 | 0.00 | 1.593 |
| 8 | 37.80 | 1.03 | 2571.00 | 0.10 | 3.871 | 0.00 | 117.70 | 455.30 | 0.00 | 1.775 |
| 9 | 27.60 | 0.94 | 115.60 | 0.00 | 0.000 | 6451.28 | 0.00 | 0.00 | 0.14 | 0.931 |
| 10 | 27.60 | 2.84 | 115.60 | 0.00 | 0.000 | 5512.57 | 0.00 | 0.00 | 0.14 | 0.795 |
| 11 | 27.60 | 2.84 | 115.60 | 0.00 | 0.000 | 816.79 | 0.00 | 0.00 | 0.14 | 0.118 |
| 12 | 27.60 | 0.94 | 115.60 | 0.00 | 0.000 | 67.49 | 0.00 | 0.00 | 0.14 | 0.010 |
| 13 | 27.60 | 2.84 | 115.60 | 0.00 | 0.000 | 121.92 | 0.00 | 0.00 | 0.14 | 0.018 |
| 14 | 38.30 | 2.07 | 160.30 | 0.00 | 0.000 | 5512.57 | 0.00 | 0.00 | 1.63 | 8.974 |
| 15 | 33.30 | 2.07 | 139.40 | 0.00 | 0.000 | 816.79 | 0.00 | 0.00 | 0.74 | 0.605 |
| 16 | 37.80 | 1.03 | 158.20 | 0.00 | 0.000 | 75.11 | 0.00 | 0.00 | 1.52 | 0.114 |
| 17 | 31.10 | 2.07 | 130.20 | 0.00 | 0.000 | 121.92 | 0.00 | 0.00 | 0.46 | 0.056 |
| 18 | 23.00 | 0.94 | 296.60 | 0.00 | 0.063 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 |
| 19 | 43.50 | 2.07 | 182.00 | 0.03 | 0.000 | 119.77 | 0.00 | 0.00 | 2.89 | 0.346 |
| 20 | 37.50 | 2.07 | 156.90 | 0.00 | 0.000 | 6533.38 | 0.00 | 0.00 | 1.46 | 9.565 |
| 21 | 43.50 | 2.07 | 182.00 | 0.00 | 0.000 | 37.67 | 0.00 | 0.00 | 2.89 | 0.109 |
| 22 | 33.60 | 0.94 | 140.70 | 0.00 | 0.000 | 89.72 | 0.00 | 0.00 | 0.79 | 0.070 |
| 23 | 43.50 | 3.07 | 182.00 | 0.00 | 0.000 | 37.67 | 0.00 | 0.00 | 2.89 | 0.109 |
| 0 | 23.00 | 0.94 | 96.40 | 0.00 | 0.000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 |

Note : Values underlines are assumed

Table 1 Main Steam System Efficiency Comparison

| | Exergy (MW) | |
|---|---|---|
| | M1GP | MHNG |
| Et1 | 81.47 | 97.37 |
| Et4 | 2.09 | 3.56 |
| Et5 | 11.93 | 15.58 |
| Ex | 0.03 | |
| W | 52.30 | 61.14 |
| Eff | 77.54% | 79.15% |

Table 2 Gas Extraction System Efficiency Comparison

| | Formula | Exergy (KW) | |
|---|---|---|---|
| | | M1GP | MHNG |
| Es4 | ms4*es4 | 2084.82 | 3511.78 |
| Es6 | ms6*es6 | 67.77 | 298.60 |
| Es15 | (ms4+ms6-ms7)*ew15 | 8.23 | 0.00 |
| Es16 | (ms7-ms8)*ew16 | 1.08 | 11.68 |
| Eg4 | mg4*eg4 | 7.98 | 45.90 |
| Ew16 | mw12*ew16 | 23.25 | 103.46 |
| Ew12 | mw12*ew12 | 1.96 | 9.74 |
| Ew15 | mw11*ew15 | 377.98 | 697.70 |
| Ew11 | mw11*ew11 | 68.36 | 273.46 |
| Eg4-8 | mg4*eg8 | 13.43 | 65.77 |
| Eg6-8 | mg6*eg8 | 527.72 | 1696.50 |
| Es8 | ms8*es8 | 15.71 | 12.25 |
| W | Vacuum Pump | 261.00 | 1492.00 |
| Eff | | 23.49% | 23.83% |

Table 3 Condenser Efficiency comparison

| | Formula | Exergy (KW) | |
|---|---|---|---|
| | | M1GP | MHNG |
| Es5 | ms5*es5 | 11862.59 | 15218.80 |
| Eg5 | mg5*eg5 | 33.31 | 313.96 |
| Es6 | ms6*es6 | 67.77 | 298.60 |
| Eg6 | mg6*eg6 | 302.94 | 976.61 |
| Ew10 | mw10*ew10 | 726.75 | 1845.61 |
| Ew14 | mw10*ew14 | 8245.79 | 9597.39 |
| Es14 | See note 1 | 180.93 | 180.39 |
| Ew15 | mw15*ew15 | 384.43 | 697.70 |
| Es15 | (ms4+ms6-ms7)*ew15 | 8.23 | 0.00 |
| Ew16 | mw16*ew16 | 23.25 | 103.46 |
| Es16 | (ms7-ms8)*ew16 | 1.08 | 11.68 |
| Es19 | mw19*ew19 | 0.00 | 360.01 |
| Eff. | | 63.50% | 57.79% |

Note :

1. Es14 = (ms5+ms15=ms16-ms6)*ew14

Table 4 Cooling Water system Exergetic Efficiency comparison

| | Formula | Exergy (KW) | |
|---|---|---|---|
| | | M1GP | MHNG |
| Es5 | ms5*es5 | 11862.59 | 15218.80 |
| Eg5 | mg5*eg5 | 33.31 | 313.96 |
| Es6 | ms6*es6 | 67.77 | 298.60 |
| Eg6 | mg6*eg6 | 302.94 | 976.61 |
| Ew11 | mw11*ew11 | 68.36 | 273.46 |
| Ew12 | mw12*ew12 | 1.96 | 9.74 |
| Ew15 | mw15*ew15 | 384.43 | 697.70 |
| Es15 | (ms4+ms6-ms7)*ew15 | 8.23 | 0.00 |
| Ew16 | mw16*ew16 | 23.25 | 115.14 |
| Es16 | (ms7-ms8)*ew16 | 1.08 | 11.68 |
| Ea22 | mg22*eg22 | 5882.36 | 7437.60 |
| Ea23 | mw23*ew23 | 23.05 | 116.99 |
| W | Pump work | 2122.00 | 2790.00 |
| Eff. | | 43.20% | 44.67% |