Sensitivity analysis of a novel geothermal multigeneration system with liquefied natural gas, proton exchange membrane, absorption refrigeration system, and water desalination

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Abstract. Renewable energy, such as geothermal, is very effective in reducing the effects of greenhouse gas emissions. Therefore, a geothermal-based multi-generation system can produce commodities for power, hydrogen, liquefied natural gas, cold energy recovery, cooling, and water desalination. Power the multigeneration, energy, and exergy analyses are conducted using Engineering Equation Solver (EES) software. Constraints used are a steam fraction, geothermal temperatures, and MER (mass extraction ratio). Sensitivity analysis is given to the parameters of exergy efficiency, net output power, a mass flow rate of natural gas, a mass flow rate of hydrogen, a mass flow rate of pure water, and the coefficient of performance of the absorption refrigeration system. Thermal efficiency is 27.2%. Exergy efficiency is 35.89%. The net power output from turbine 1 is 997.8 kW, from turbine 2 is 343.2 kW. The hydrogen mass flow rate is 0.0008 kg/s. The natural gas mass flow rate that can be used is 1.252 kg/s. The coefficient of performance (COP) of the absorption refrigeration system (ARS) is 0.8876, and the mass flow rate of pure water of the water desalination system is 0.3914 kg/s.

1. Introduction

One renewable energy source, geothermal, can generate electricity and heating with minimal greenhouse gas emissions. Research by Parikhani, T. et al. [1], multiobjective simulation, and optimization of a multi-generation system (MGS) was carried out using geothermal heat sources. The MGS system consists of the Kalina cycle, liquified natural gas (LNG), proton exchange membrane (PEM), and domestic water heater (DWH). The analysis carried out includes exergy and exert economically. Energy and exergy analyses were also carried out in a Salak geothermal powerplant study, Indonesia [2]. An Organic Rankine Cycle (ORC) research has been conducted by Pili, R. et al. [3].

Salehi, S. et al. [4] conducted multiobjective optimization of the dual flash geothermal power plant system that integrated with absorption heat transformers (AHT) and water desalination system. The analysis included thermodynamic and thermoeconomic. Reverse osmosis desalination and absorption refrigeration research have been conducted by Gnaifaid, H. et al. [5]. Freshwater production research using a process membrane distillation has been carried out by Tomaszewska, B. et al. [6].
Research on cooling systems in geothermal systems has been carried out in a study by Wibowo, A.S., et al. [7]. This research includes multiobjective optimization on the geothermal powerplant system integrated with the double effect absorption refrigeration system (DEARS). Wibowo, A.S. [8] examined the utilization of waste heat from geothermal separation for absorption refrigeration system (ARS).

The Kalina cycle system’s exergy optimization combined with LNG cold energy recovery was carried out in the research by Ghaebi, H.et al. [9]. A comprehensive review has been conducted on proton exchange in membrane water electrolysis [10] and can guide further research. Analysis of energy and exergy of desalination combined with cooling, heat, and power (CCHP) has been carried out in study by Mohammadi, A. et al. [11].

Sensitivity analysis of geothermal heat pumps has been done in research by Han, C. et al. [12]. Research on Organic Rankine Cycle (ORC) geothermal powerplant has been conducted in a study by Liu, X. et al. [13].

This research aims to design and analyze a thermal generating system, electricity and produce hydrogen, daily use of LNG, cooling, and water desalination. The source of geothermal energy in Indonesia is enormous, so it is essential to conduct this research to utilize geothermal energy.

This study is a continuation of the study of Parikhani, T., et al. [1]. Previous research has not been done in the sensitivity analysis in the MGS system consisting of Kalina cycle, LNG, PEM, ARS, and water desalination system. The analysis that needs to be done includes energy and exergy. This study aims to make several sensitivity analyses: MGS generate power, hydrogen, LNG, cooling, and water desalination thermodynamically.

2. System description

Figure 1 shows the geothermal research scheme offered consists of the Kalina cycle, LNG, PEM, ARS, and water desalination. Geothermal sources come from a mixture of ammonia and water. The following sub-section describes each system, including Kalina cycle subsystem, LNG system, PEM system, ARS system, and water desalination system.

2.1. Kalina cycle system

The Kalina cycle system consists of a vapor generator, two separators, a turbine, four throttling valves, four heat exchangers, a condenser, an evaporator, a mixer, and a pump. The geothermal heat source is fed in stream 22, and then the heat transfer is conducted in a vapor generator resulting ammonia-water mixture in stream 1. Separator 1 separates steam in stream two, and steam is fed in turbine 1 generating electricity. In-stream 3, steam enters the mixer. Meanwhile, the saturated liquid is divided into two streams; one is in stream 5 throttled in expansion valve 1, then enters separator 2. Afterward, steam enters heat exchanger 3 and then is condensed by cold energy LNG and throttled in expansion valve 2 and enters the evaporator, and then it enters mixer. Stream 11 enters heat exchanger 4 (HX4) for cooling by cold energy LNG, then enters expansion valve 3 (EV3). In-stream 13, it enters the mixer in stream 3. In-stream 14, saturated liquid enters HX1 heats stream 20 and then enters HX5 and is throttled in EV4, then joins mixer and finally enters a condenser.

2.2. LNG system

LNG at a low temperature of -162°C is pumped using pump 2 into HX3 and HX4. Then, LNG is turned into gas as saturated natural gas and flowed into turbine 2 to produce electricity or power. After that, natural gas is heated in HX5 and then distributed to the city users.

2.3. PEM electrolyzer system

As shown in Figure 1, electricity and heat are required to drive the electrochemical reactions of the PEM electrolyzer supplied by turbine 2, ARS geothermal waste heat, and the water
desalination system (flow 24). HX6 reuses the residual from geothermal ARS and water desalination to heat water in the PEM electrolyzer. Refrigerated steam (stream 24) enters HX6 and then is cooled to stream 41. The overall PEM electrolysis reaction is to separate water into hydrogen and oxygen components, using supplied electricity, geothermal heat, and water. Therefore, hydrogen can be stored in a tank for further use.

2.4. ARS system
The ARS consists of an absorber, pump, two valves, solution heat exchanger (SHX), desorber, rectifier, condenser ARS, and evaporator ARS [14]. It is a single effect absorption refrigerant system that uses ammonia water (NH$_3$H$_2$O) as the working fluid. The process starts from a robust solution that leaves the absorber and then enter the pump. The pump then distributes the solution to enter the solution heat exchanger (SHX). There is a heat transfer in SHX, and the temperature increases. Then the resolution goes to the desorber to be heated and boiled. The weak solution (stream 45) back to SHX, and there is a drop in pressure in the expansion valve and back to the absorber. The saturated vapor from the desorber enters the rectifier to be precooled, while the saturated liquid goes back from the rectifier to the desorber. After that, the saturated steam from the rectifier enters condenser ARS to be condensed. The condenser’s solution enters the expansion valve then enters the evaporator, where the effect of cooling is obtained.

2.5. Water desalination system
Water desalination used is a single-stage flash system [15] consisting of 2 heat exchangers, a pump, expansion valve, and separation vessel (SV). First, the saltwater enters through pump 3 then enters HX7 for preheating, then is heated again in HX2. After that, it enters the expansion valve and then is separated through SV. Then, the separated steam is then condensed in HX7, and pure water is produced.
3. Research Methodology

The methodology is carried out with literature and simulation studies (modeling) using EES software. Figure 2 shows the entire thermodynamic simulation process of the geothermal MGS.

3.1. Energy and exergy analysis

The energy equations model used are:

(i) Mass balance equation:
\[ \sum_i \dot{m}_{in} = \sum_0 \dot{m}_{out} \] (1)

(ii) Concentration balance equation:
\[ \sum (\dot{m}_{out} Y) = \sum (\dot{m}_{in} Y) \] (2)

(iii) Energy balance equation:
\[ Q_{cv} - W_{cv} = \sum (\dot{m}_{out} H) - \sum (\dot{m}_{in} H) \] (3)

(iv) Mass extraction ratio (MER):
\[ \text{MER} = \frac{\dot{m}_5}{\dot{m}_4} \] (4)

The total exergy of a flowing stream of matter at component \( k \) (\( \dot{E}_x_k \)) is the sum of the physical exergy and chemical exergy associated with the stream’s workflow [16] [17]).

\[ \dot{E}^{PH}_k = \dot{m}e^{PH}_k = \dot{m}[(h_k - h_0) - T_0(s_k - s_0)] \] (5)
For chemical exergy can be seen in the equation below [18]:

\[
\dot{E}_k^{CH} = \dot{m}\left(\frac{e_{ch,NH_3}^{0}}{M_{NH_3}}Y + \frac{e_{ch,H_2O}^{0}}{M_{H_2O}}(1 - Y)\right)
\]  

(6)

\[
\dot{E}_k = \dot{E}_k^{PH} + \dot{E}_k^{CH}
\]  

(7)

An exergy rate balance between the exergy of the fuel, product, loss, and exergy destruction for the \(k\)-th component is:

\[
\dot{E}_{X_F,k} = \dot{E}_{X_P,k} + \dot{E}_{X_L,k} + \dot{E}_{X_D,k}
\]  

(8)

Exergy efficiency of MGS can be shown in the following equation:

\[
\eta_{ex} = \frac{W_{net} + (\dot{E}_{x_{30}} - \dot{E}_{x_{29}}) + (\dot{E}_{x_{58}} - \dot{E}_{x_{57}}) + (\dot{E}_{x_{62}} - \dot{E}_{x_{61}}) + \dot{E}_{x_{33}}}{(\dot{E}_{x_{22}} - \dot{E}_{x_{41}}) + (\dot{E}_{x_{35}} - \dot{E}_{x_{40}}) + \dot{E}_{x_{57}} + \dot{E}_{x_{61}}}
\]  

(9)

3.2. PEM modeling

The analysis of PEM can be carried out using this model’s equations [1] [19]:

\[
\Delta H = \Delta G + T\Delta S
\]  

(10)

\(\Delta G\) and \(T\Delta S\) are the Gibbs free energy and required thermal energy for specified control volume.

\[
\dot{N}_{H_2,\text{out}} = \frac{J}{2F} = \dot{N}_{H_2O,\text{out}}
\]  

(11)

\(J\) is the current density in A.m\(^{-2}\), \(F\) is Faraday constant in C.mol\(^{-1}\), \(\dot{N}_{H_2O,\text{out}}\) is the molar mass flow rate for the water that enters the PEM electrolyzer in mol.s\(^{-1}\), \(\dot{N}_{H_2,\text{out}}\) is the molar mass flow rate of hydrogen in mol.s\(^{-1}\).

\[
\dot{E}_{\text{elec}} = JV
\]  

(12)

\(\dot{E}_{\text{elec}}\) is the energy of PEM electrolyzer and \(V\) is the energy potential.

\[
V = V_O + V_{ohm} + V_{act,a} + V_{act,c}
\]  

(13)

\(V_O\) is the reversible potential, \(V_{act,c}\) is the cathode activation potential, \(V_{act,a}\) is the anode activation potential, and \(V_{ohm}\) is the ohmic potential.

\[
V_O = 1.229 - 8.5\times10^{-4}(T_{PEM} - 298)
\]  

(14)

\[
\sigma_{PEM}[\lambda(x)] = [0.5139\lambda(x) - 0.326]\exp\left[1268\left(\frac{1}{303} - \frac{1}{T_{PEM}}\right)\right]
\]  

(15)

\[
\lambda(x) = \frac{\lambda_a - \lambda_c}{D}x + \lambda_c
\]  

(16)

\(x\) refers to the measured depth of the cathode membrane, \(\lambda(x)\) is the membrane surface water, \(D\) is the membrane thickness, \(\lambda_a\) is the anode membrane surface water, \(\lambda_c\) is the cathode membrane surface water.

\[
R_{PEM} = \int_0^D \frac{dx}{\sigma_{PEM}[\lambda(x)]}
\]  

(17)
$R_{PEM}$ is the resistance of PEM. 

$$V_{ohm} = J R_{PEM}$$ \quad (18)

$$V_{act,i} = \frac{RT}{F} \sinh^{-1} \left( \frac{J}{J_{O,i}} \right), \quad i = a, c$$ \quad (19)

$J_{O,i}$ is the exchange current density.

$$J_{O,i} = J_{i}^{ref} \exp \left( -\frac{E_{act,i}}{RT} \right), \quad i = a, c$$ \quad (20)

$J_{i}^{ref}$ is the pre-exponential factor, $E_{act,i}$ is the activation energy.

$$\dot{Q}_{H2O} = \dot{m}_{H2O}(h_{out,HX6} - h_{in,HX6}) = \dot{m}_{H2O} \dot{q}_{HEAT,PEM}$$ \quad (21)

$\dot{m}_{H2O}$ is the water mass flow rate, $\dot{q}_{HEAT,PEM}$ is the specific heat provided.

$$\eta_{th,PEM} = \frac{LHV_{H2} \dot{N}_{H2}}{Q_{HEAT,PEM} + E_{elec}}$$ \quad (22)

$\eta_{th,PEM}$ is the thermal efficiency of PEM electrolyzer.

### 4. Result and Discussion

#### 4.1. Exergy analysis of system

The simulation result of exergy is shown in table 2. Table 2 shows the main parameters of thermodynamics, namely temperature, pressure, ammonia mass fraction, enthalpy, entropy, mass flow rate, total exergy, physical exergy, and chemical exergy. The highest exergy value is at stream 22, namely at the vapor generator input, where the system's highest temperature is reached. The mass flow rate of hydrogen at stream 33 is 0.0008 kg/s, the mass of natural gas (NG) at stream 40 is 1.252 kg/s, and the mass flow rate of pure water of water desalination is 0.3914 kg/s.

Table 1: Simulation results of exergy analysis

| Stream | T (K) | P (bar) | m (kg/s) | H (kJ/kg) | Y(-) | $s^*$ | Ex(kW) | ExpH (kW) | ExcH (kW) |
|--------|-------|---------|----------|-----------|-------|-------|---------|-----------|-----------|
| 1      | 433.2 | 30      | 10.01    | 890.6     | 0.45  | 2.88  | 2543    | 2451      | 92.27     |
| 2      | 433.2 | 30      | 2.916    | 1760      | 0.83  | 5.074 | 1615    | 1567      | 48.34     |
| 3      | 347.9 | 3       | 2.916    | 1418      | 0.83  | 5.184 | 523.8   | 475.5     | 48.34     |
| 4      | 433.2 | 30      | 7.093    | 533       | 0.29  | 1.977 | 902     | 858.1     | 43.94     |
| 5      | 433.2 | 30      | 2.128    | 533       | 0.29  | 1.977 | 270.6   | 257.4     | 13.18     |
| 6      | 368.6 | 4       | 2.128    | 533       | 0.29  | 2.075 | 209.7   | 196.5     | 13.18     |
| 7      | 368.6 | 4       | 0.3749   | 1704      | 0.82  | 5.835 | 102     | 95.87     | 6.112     |
| 8      | 276.4 | 4       | 0.3749   | -115      | 0.82  | -0.0178 | 63.32  | 57.21     | 6.112     |
| 9      | 268.8 | 3       | 0.3749   | -115      | 0.82  | -0.0161 | 63.13  | 57.02     | 6.112     |
| 10     | 287.2 | 3       | 0.3749   | 489.9     | 0.82  | 2.195 | 46.79   | 40.68     | 6.112     |
| 11     | 368.6 | 4       | 1.753    | 282.7     | 0.18  | 1.271 | 69.69   | 62.02     | 7.07      |
| 12     | 287.2 | 4       | 1.753    | -62.7     | 0.18  | 0.2125 | 8.081  | 1.011     | 7.07      |
| 13     | 287.2 | 4       | 1.753    | -62.7     | 0.18  | 0.2125 | 7.886   | 0.8169    | 7.07      |
| 14     | 433.2 | 30      | 4.965    | 533       | 0.29  | 1.977 | 631.4   | 600.6     | 30.76     |
| 15     | 315.4 | 30      | 4.965    | -2.26     | 0.29  | 0.5411 | 63.94   | 33.18     | 30.76     |
|   |     |     |     |     |     |
|---|-----|-----|-----|-----|-----|
| 16| 306.6| 30  | 4.965| -39.9| 0.29 |
| 17| 307.2| 3   | 4.965| -39.9| 0.29 |
| 18| 333.7| 3   | 10.01| 400.7| 0.45 |
| 19| 305.2| 3   | 10.01| -94.3| 0.45 |
| 20| 305.4| 30  | 10.01| -90.7| 0.45 |
| 21| 364.2| 30  | 10.01| 174.8| 0.45 |
| 22| 443.2| 9   | 30   | 719.3| 2.042|
| 23| 387.6| 9   | 30   | 480.6| 1.466|
| 24| 363.2| 9   | 30   | 377.6| 1.192|
| 25| 387.6| 9   | 15   | 480.6| 1.466|
| 26| 387.6| 9   | 15   | 480.6| 1.466|
| 27| 293.2| 1   | 118.4| 83.93| 0.2962|
| 28| 303.2| 1   | 118.4| 125.8| 0.4365|
| 29| 293.2| 1   | 2.794| 83.93| 0.2962|
| 30| 273.8| 1   | 2.794| 2.808| 0.0099|
| 31| 298.2| 1   | 0.013| 104.8| 0.3669|
| 32| 353.2| 1   | 0.013| 335  | 1.075 |
| 33| 353.2| 1   | 0.0008| 4723 | 55.81 |
| 34| 353.2| 1   | 0.0061| 50.5  | 0.1556|
| 35| 111.2| 1   | 1.252| -913  | -6.693 |
| 36| 112  | 25  | 1.252| -906  | -6.687 |
| 37| 172  | 25  | 1.252| -362  | -3.226 |
| 38| 358.6| 25  | 1.252| 122   | -1.274 |
| 39| 229.9| 3   | 1.252| -152  | -1.138 |
| 40| 298.2| 3   | 1.252| -2.93 | -0.5697|
| 41| 363.1| 9   | 30   | 377.5 | 1.192 |
| 42| 305.2| 3.8 | 5.38 | -96.6 | 0.49 |
| 43| 305.2| 12  | 5.38 | -95.4 | 0.49 |
| 44| 343.3| 12  | 5.38 | 76.87 | 0.49 |
| 45| 377.6| 12  | 4.108| 254.2 | 0.34 |
| 46| 326.9| 12  | 4.108| 28.49 | 0.34 |
| 47| 327.1| 3.8 | 4.108| 28.49 | 0.34 |
| 48| 311.8| 12  | 1.272| 1313  | 1   |
| 49| 305.2| 12  | 1.272| 151.3 | 1   |
| 50| 269.8| 3.8 | 1.272| 151.3 | 1   |
| 51| 270.2| 3.8 | 1.272| 1233  | 1   |
| 52| 363.2| 9   | 15   | 377.6 | 1.192 |
| 53| 293.2| 1   | 52.73| 83.93 | 0.2962|
| 54| 303.2| 1   | 52.73| 125.8 | 0.4365|
| 55| 293.2| 1   | 35.32| 83.93 | 0.2962|
| 56| 303.2| 1   | 35.32| 125.8 | 0.4365|
| 57| 280.2| 1   | 65.51| 29.51 | 0.1063|
| 58| 275.2| 1   | 65.51| 8.503 | 0.0306|
| 59| 363.2| 9   | 15   | 377.6 | 1.192 |
| 60| 303.2| 1   | 14.79| 125.8 | 0.4365|
| 61| 303.2| 1.2  | 14.79| 125.8 | 0.4365|
| 62| 318.2| 1.2  | 14.79| 188.5 | 0.6385|
| 63| 343.1| 1.2  | 14.79| 293   | 0.9546|

**Note:** The table represents data extract from the document.
Sensitivity analysis is conducted considering MER, \( Y_B \), and \( T_{GEO} \) parameters on thermodynamics performance, including exergy efficiency, net output power, coefficient of performance (COP) of ARS [20], and mass of NG.

\[
\begin{array}{cccccc}
64 & 328.2 & 0.2 & 14.79 & 293 & 0.9591 & 217.4 & 217.4 \\
65 & 328.2 & 0.2 & 0.3914 & 2600 & 7.99 & 102.1 & 102.1 \\
66 & 328.2 & 0.2 & 14.4 & 230.2 & 0.7679 & 115.4 & 115.4 \\
67 & 328.2 & 0.2 & 0.3914 & 230.2 & 0.7679 & 3.137 & 3.137 \\
68 & 293.2 & 1 & 4.269 & 83.93 & 0.2962 & 0 & 0 \\
69 & 303.2 & 1 & 4.269 & 125.8 & 0.4365 & 2.978 & 2.978 \\
70 & 346.6 & 12 & 1422 & 0.2962 & 0 & 0 \\
71 & 346.6 & 12 & 0.0292 & 92.09 & 0.49 & 0.8987 & 1.309 & 1.015 & 0.294 \\
\end{array}
\]

\( * \) is in (kJ kg\(^{-1}\) K\(^{-1}\)) unit.

**Figure 3.** The effect of MER on exergy efficiency, net output power, COP\(_{ARS}\) and Mass of NG of the system.

MER values vary from 0.15 to 0.5. If there is a decrease in efficiency, it will increase MER exergy if the increase in net power output will increase the MER value. The net output power has increased because of the increase in turbine 2 power. An increase in COP\(_{ARS}\) is also proportional to an increase in MER, while an increase in the mass of NG also automatically increases the MER value. The increase in COP\(_{ARS}\) is caused by the decrease in heat transfer of the desorber.

**Figure 4.** The effect of \( Y_B \) on exergy efficiency, net output power, COP\(_{ARS}\) and Mass of NG of the system.
$Y_B$ is varied from 0.38 to 0.48, and if you try to increase the efficiency of the net power, it will automatically increase the $Y_B$ value. The increase in net output power is caused by the increase in power of turbine 1. COP$_{ARS}$ increases with the increase in $Y_B$, while the mass of NG decreases with the increase in $Y_B$. COP$_{ARS}$ increases because of the decrease in the desorber’s heat transfer.

Figure 5. the effect of $T_{geo}$ on exergy efficiency, net output power, COP$_{ARS}$, and Mass of NG of the system

$T_{geo}$ varied from 150 to 174, and there was an increase in the exergy efficiency and net output power of the increase in $T_{geo}$. Net output power increased because of the increase in turbine 1 power. The decrease in COP$_{ARS}$ occurs with the increase in $T_{geo}$, while the reduction in mass of NG occurs with the rise in $T_{geo}$. COP$_{ARS}$ increases because of the decline in the desorber’s heat transfer.

5. Conclusions
In the present study, sensitivity analysis has been done to MER, $Y_B$, and $T_{GEO}$ parameters on thermodynamics performance, including exergy efficiency, net output power, coefficient of performance (COP) of ARS, and mass of natural gas (NG).

In the variation of MER, exergy efficiency was decreased, and the net output power increased. COP$_{ARS}$ and mass of NG increased in line with the variation of MER. There was an increase in exergy efficiency and net output power in $Y_B$ variation. The COP$_{ARS}$ increased while the mass of NG decreased in the variation of $Y_B$. $T_{geo}$ increases exergy efficiency and net output power while reducing COP$_{ARS}$ and the mass of NG occurs. IN the EES simulation, the thermal efficiency is 27.2%. The exergy efficiency is 35.89%. The net power output from turbine 1 is 997.8 kW. From turbine 2 is 343.2 kW. The hydrogen production of mass flow rate is 0.0008 kg/s, the NG mass flow rate that can be used is 1.252 kg/s, the COP of ARS is 0.8876, and the mass flow rate of pure water of water desalination system is 0.3914 kg/s.

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