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Performance Analyses of a Renewable Energy Powered System for Trigeneration

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Abstract: In this research, a novel trigeneration powered by a renewable energy (RE) source is developed and analyzed. The trigeneration system is designed to produce electricity, hot water, and cooling using two steam cycles, a gas cycle, hot water chamber, and an absorption cycle. The RE source considered in the scope of this study is biogas generated from chicken manure and maize silage. The energy and exergy analysis of the trigeneration system is performed with the aim to achieve higher efficiencies. The efficiencies are presented based on power generation, cogeneration (electricity and cooling) and trigeneration. The overall trigeneration energy and exergy efficiency for the system developed is 64% and 34.51%. The exergy destruction within the system is greatest in the combustion chamber.

Keywords: biogas; energy; exergy; trigeneration; renewables

1. Introduction

Renewable energy (RE) powered systems for electricity generation have been widely researched in literature [1–4]. The low energy efficiency of power cycles led to the use of multigeneration system for electricity production. Combined heat and power (cogeneration) systems were the first generation of commercialized multigeneration systems. Since then, trigeneration and multigeneration have been researched, developed and commercialized globally. RE powered multi-generation systems have been presented in different literature [5–8]. Multigeneration systems are generally powered by a thermal heat source and are designed to increase energy and exergy performances of an energy system. In the literature, sources like solar, biomass and geothermal have been used as thermal heat sources for multi-generation systems [9–11].

Generally, performance analysis of most multigeneration systems focuses more on the exergy and energy content in the system. In recent studies, the combination of different cycles to enhance energy and exergy performance have been presented. Hashemian and Noorpoor [12], presented a multigeneration system that comprised of a Rankine cycle, proton exchange membrane (PEM) electrolyzer, double effect absorption chiller, parabolic solar collector, and multi-effect desalination system. The thermodynamic analysis showed that the system has an exergy and energy efficiency of 14% and 82.4%, respectively [12]. In a similar study, Yilmaz et al. [13] studied a coal gasification process for multi-generation. The system uses a Rankine cycle, ORC, membrane distillation process, single absorption cycle, hydrogen liquefaction, and PEM electrolyzer to produce heating, electricity, cooling, fresh/hot water, liquefaction, and hydrogen production. The energy and exergy efficiencies for their system are calculated to be 58.47% and 55.72% respectively [13]. Ishaq et al. [14], presented a system that will produce hydrogen via thermal management. A steam cycle, double-stage Organic

Rankine Cycle (ORC), multi-effect desalination system, and Cu-Cl cycle with multistage compression. The overall systems' exergy and energy efficiencies are 38.1% and 36.5%, respectively [14].

Multigeneration systems are powered with different single thermal source inputs such as geothermal [15–18], solar [19–21], biogas [22–24], coal [13,25], solar-biomass [26,27], and geothermal-biogas [28,29]. However, more research is required in this field to improve the systems' over energy and exergy performance. In this research, a novel trigeneration configuration that is powered with biogas from plant and animal dungs is presented. The system is designed to produce electricity, cooling, and hot water using a gas cycle, two steam cycles, a hot water chamber, and a single effect absorption cycle. While the first steam cycle incorporates reheat and regeneration for better performance, the second steam cycle in this research only incorporates regeneration. Although research in the literature have used biomass for trigeneration [30–35], this research is novel as it considered the use of maize silage and chicken manure for the bio-gasification. Also, in comparison to research in the literature, the configuration presented in this study is novel as reheat and regeneration principles are applied to the steam cycles to improve the overall systems' (energy and exergy) performance.

Single effect absorption system is used in this research as it can be powered with low grade thermal energy and the hot water chamber is use to convert waste energy at the condenser stage. Maize silage and chicken manure are also considered for the bio-gasification process as they are readily available raw material that are unutilized in many communities. The thermodynamics (energy and exergy) and performance analysis of the biogas trigeneration system presented in this research will be studied with the aim of achieving better efficiencies compared to research in the literature. To our best understanding, this is the first research about biogas powered trigeneration system that applied reheat and regenerative principles within two steam cycles. The next section presents the system description and modelling detail while the results from this research is discussed in section three. Finally, conclusions from this study are highlighted in section four.

2. System Description and Modelling

The trigeneration systems' configuration in this research will produce electricity, hot water, and cooling. Priority is given to electricity production in this research as this is the most versatile form of energy. Three power cycles (one gas cycle and two steam cycles) are used for electricity production. The trigeneration system is powered by biogas generated from chicken manure and maize silage. This section gives the details of the design and modelling of the trigeneration system with reference to the state numbers in Figure 1.

The biogas used as thermal heat source is modeled based on research presented by Pfeifer et al. [36], and Eren et al. [37]. According to their studies, the mixture of chicken manure (70,000 kg) and maize silage (30,000 kg) was used to produce the biogas. Similarly, the chemical composition of the biomass mixture used in this research is presented in Table 1. The heating load for the biogas process is 66 kW while the temperature of the first and second digesters are 311 K and 309 K, respectively. The gas yield rate is 0.73 Nm^3/kg_{db}.

Chicken manure and maize silage are combined together (stage 1) in a mixer and then passed (stage 2) to a digester. The digestion process takes place in the two digesters (stage 3). After the biomass digestion process, the biogas produced is passed through a pre-heater (stage 4) to increase the combustion quality. Pre-heated biogas at stage 5 is combusted in the combustion chamber with compressed air at stage 6. This produces a gas with a high exergy and energy contents (stage 8) which is sent into the gas turbine (Turb 1) where electricity is generated. The exhaust gas at stage 9 passes through a heat exchanger (HEX 1) which serves as thermal energy source for the digestion process before being used in another heat exchanger (HEX 2). Pressurized liquid at stage 15 passes through HEX 2 where it receives thermal energy and turns to pressurized steam before being sent to a steam turbine (Turb 2) and electricity is generated. In steam cycle 1, reheat (stage 17/stage 18) and regeneration (stage 19/stage14) principles are applied to further enhance the energy performance of the cycle.

As mentioned in the preceding section, two steam cycles are used in this trigeneration design. Ninety percent of the steam that enters into Turb 3 is designed to bleed out (stage 19) and it serves as thermal heat source for steam cycle 2. Regeneration principle (stage 34 and stage 35) is applied in steam cycle two and the condenser is replaced with a heat exchanger (HEX 4). To ensure the thermodynamic balance of the trigeneration system, two steam traps (ST1 and ST2) and three feedwater heaters (CFWH1, CFWH2 and OFWH) are incorporated in the design. The heat exchanger (HEX 4) serves as heat energy input source for the absorption cycle. Low grade heat at the condenser stage of steam cycle 1 is used to produce hot water, thereby increasing the overall performance of the trigeneration system.

Lithium bromide solution (LiBrH2O) is used as the working fluid for the absorption cycle. While water (H2O) is the refrigerant, Lithium bromide (LiBr) is the absorber. Water refrigerant mixes with strong LiBr solution to form a weak solution in the absorber. This (stage 39) is passed through a pump and then (stage 40) sent into a solution heat exchanger. The weak solution is preheated in the solution heat exchanger (S. EX1) and then (stage 41) sent into the generator where more heat is added. The refrigerant and the absorber are separated in the generator and the refrigerant flows (stage 42) into a condenser. The refrigerant is condensed and passed through an expansion valve (V1) into (stage 44) the evaporator. Heat from the cooling space is absorbed by the evaporator and the refrigerant is used to cool the space.

Table 1. Biogas Chemical Components [36].

Definition	Poultry Litter	Maize Silage	Digestate
C [wt% kg d.b.]	37.50	33.71	35.34
O [wt% kg d.b.]	29.40	16.86	24.36
A [wt% kg d.b.]	21	33.80	30.38
H [wt% kg d.b.]	5.5	4.47	4.53
N [wt% kg d.b.]	4.7	11.16	5.35

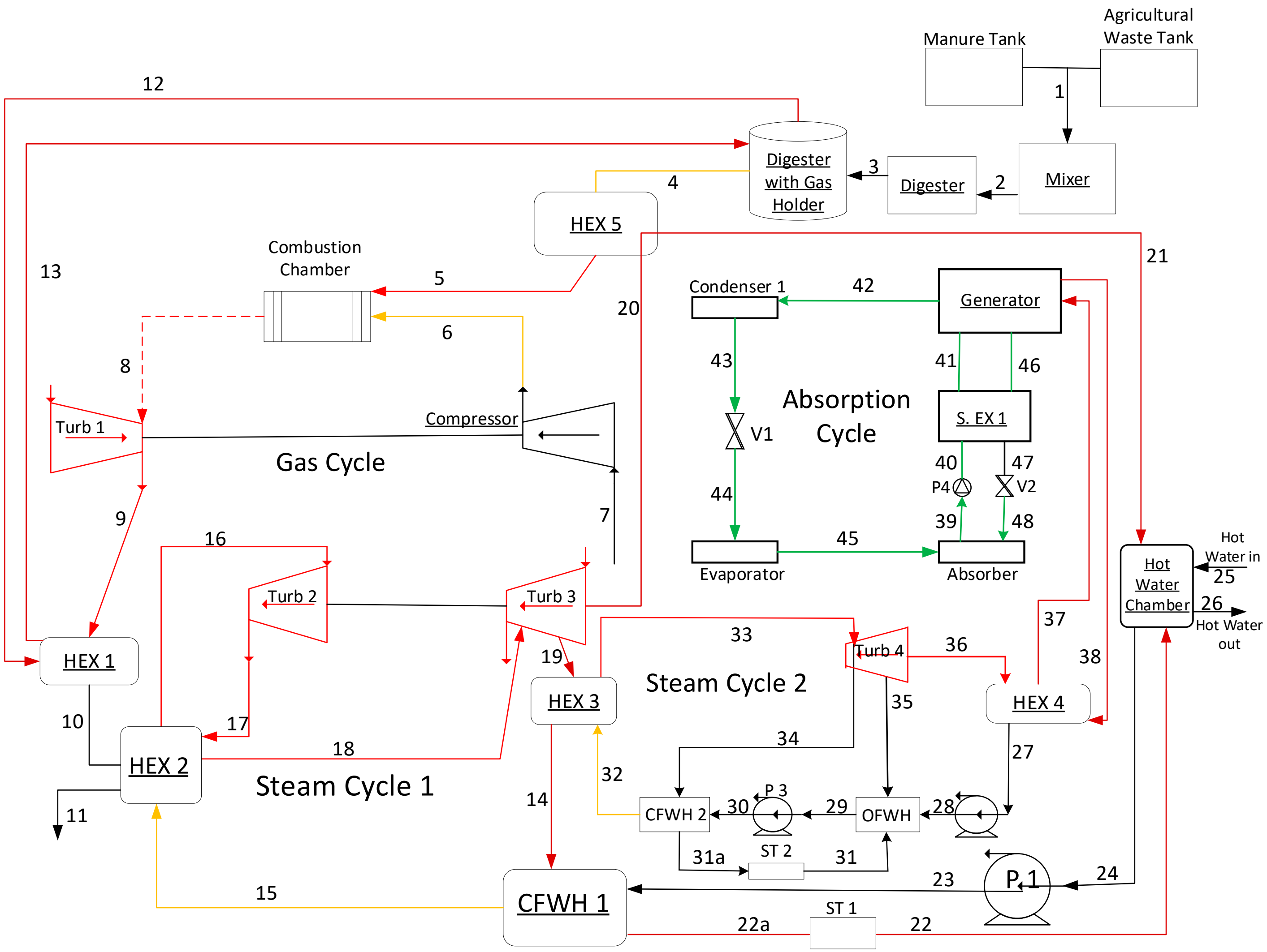

Figure 1. Biogas powered trigeneration configuration layout.

The input parameters used for the simulation are summarized in Table 2. The energy and exergy analysis of the system developed is performed with several assumptions such as:

- Atmospheric temperature and pressure (dead state properties) are assumed to be 101 kPa and 298 K, respectively.
- The turbine and pumps are considered adiabatic.
- The system operates on steady state conditions.
- The idea gas properties are chosen for air to perform the analysis.
- Potential and kinetic energy changes are negligible.
- Total combustion in gas cycle is assumed with an 80% combustion efficiency.

Engineering Equation Solver (EES) program is used to solve the mathematical model for the trigeneration system. The exergy and energy performance analysis are done with inputted parameters in Table 2. The overall energy and exergy efficiency of the trigeneration system is calculated with Equation (1) and Equation (2) respectively. The other key equations used for the mathematical modeling of the trigeneration are given in Table 3.

$$\eta_{en,tri} = \frac{W_{power} + \dot{Q}_{abs,\ E} + W_{en,HW}}{Q_{in}} \tag{1}$$

$$\eta_{ex,tri} = \frac{W_{power} + \left(1 - \frac{T_0}{T_{hi}}\right)\dot{Q}_{abs,\ E} + \left(1 - \frac{T_0}{T_{hj}}\right)W_{en,HW}}{Q_f} \tag{2}$$

Table 2. Trigeneration system input parameters [6,9,38,39].

Gas Cycle	
Mass flow rate (kg/s)	3.256
Turbine efficiency	87%
Compression Ratio	3
Rated Pressure	304 kPa
Combustion chamber efficiency	80%
Rated Temperature	1100 K
Steam Cycles	
Turbine efficiency	85%
Pump Efficiency	95%
Heat Exchanger Efficiency	90%
Rated Temperature for Turb 1 and Turb 2	800 K
Rated Temperature for Turb 3	573 K
Rated Pressure for Turb 1	5000 kPa
Rated Pressure for Turb 2	1200 kPa
Rated Pressure for Turb 3	8000 kPa
Absorption Cycle	
Minimum Temperature	279.1 K
Atmospheric Pressure (P_0)	101 kPa
Rated Pressure	4.82 kPa
Refrigerant	LiBrH2O

Table 3. Mathematical model equation summary.

Definition	Mathematical Model
Total work output	$W_{net} = W_{power} + \dot{Q}_{abs,\ E} + W_{en,HW}$
Total power produced	$W_{power} = \left(W_{out,\ T,1} + W_{out,\ T,2} + W_{out,\ T,3} + W_{out,\ T,4}\right) - \left(W_{in,comp} + W_{in\ P,1} + W_{in,\ P,2} + W_{in,\ P,3}\right)$
Pump/compressor Work input	$W_{in,\ P} = \left(\dot{m_{out}} h_{out} - \dot{m_{in}} h_{in}\right)\eta_P$
Turbine work output	$W_{out,\ T} = \left(\dot{m_{in}} h_{in} - \dot{m_{out}} h_{out}\right)\eta_T$
Evaporator work output	$\dot{Q}_{abs,\ E} = \dot{m_{45}} h_{45} - \dot{m_{44}} h_{44}$
Work equivalence of the hot water produced	$W_{en,HW} = \left(\dot{m_{22}} h_{22} + \dot{m_{21}} h_{21} - \dot{m_{23}} h_{23}\right)\eta_{en,HW}$
Power Energy Efficiency	$\eta_{en,el} = \frac{W_{power}}{Q_{in}}$
Biogas Energy Input	$\dot{Q}_{in} = \dot{m_{bio}} \times LHV$
The biogas LHV is the Lower Heating Value of the digestate and is 17.52 MJ [37].	
Cogeneration energy efficiency	$\eta_{en,cog} = \frac{W_{power} + \dot{Q}_{abs,\ E}}{Q_{in}}$
Exergy at each point	$Ex = \dot{m}(h - h_0) - T_0(S - S_0)$
Biomass process total exergy rate	$Ex_{total} = Ex^{PH} + Ex^{CH}$
Physical exergy per mass flow rate [40]	$Ex^{PH} = (h - h_0) - T_0(S - S_0) + \frac{V^2 + V_0^2}{2} + g(z - z_0)$
Chemical exergy rate per mass flow [40]	$Ex^{CH} = M\left(x\overline{Ex}^{CH} + RT_0 x ln(x)\right)$
Where h, S, V, g, z, M, R and x are enthalpy, entropy, velocity, gravity, elevation, molecular weight, universal gas constant and molar concentration respectively at different state point. $\overline{Ex}^{CH}$ is the molecular weight.	
Exergy destruction	$\dot{X}_{destroyed} = W_{rev,out} - \dot{W}_{out}$
Exergy destruction	$\dot{X}_{destroyed} = \dot{W_{PI,in}} - \dot{W}_{rev,in}$
Reversible work output	$W_{rev,out} = \dot{m}(\psi_{in} - \psi_{out})$
Reversible work input	$W_{rev,in} = \dot{m}(\psi_{out} - \psi_{in})$
Power exergy efficiency	$\eta_{ex,el} = \frac{W_{power}}{Q_f}$
Cogeneration exergy efficiency	$\eta_{ex,cog} = \frac{W_{power} + \left(1 - \frac{T_0}{T_{hi}}\right)\dot{Q}_{abs,\ E}}{Q_f}$

3. Results and Discussions

In this study, a trigeneration system designed to produce cooling effect, electricity, and hot water is presented. One gas cycle, two steam, a hot water chamber, and one absorption cycle has been used in the development of the trigeneration system. The performance analysis of this system is done with energy and exergy approach. Based on the simulation outputs, the thermodynamic properties (fluid type, pressure, mass flowrate, temperature, enthalpy) at each stage (as in Figure 1) of the novel trigeneration system presented in this research are tabulated in Table 4.

The performance analysis shows that the trigeneration system is capable of producing 1460 kW worth of electricity. This is equivalent to 43.96% and 33.34% power energy and exergy efficiency, respectively. The cogeneration total production of the system considering electricity production and cooling effect is 1740.8 kW. This will increase the systems energy and exergy efficiency from 43.96% and 33.34% to 52.41% and 34.26%, respectively. The trigeneration system uses 2173.6 kW of the 3322 kW worth of energy input from biomass. This gives a trigeneration efficiency of 64% and 35.41% for energy and exergy efficiency, respectively. The result from this system is similar to research in the literature, as their system was able to achieve 66% energy efficiency [26]. The increase in their energy efficiency can be attributed to the use of a solar-biomass hybrid system. Their research also presented a multi-generation system as against the trigeneration configuration presented in this research. A detailed summary of the multi-generation system performance is tabulated in Table 5.

The performance of different cycles in the trigeneration system is a progress in science compared to the typical performances of such system. The energy efficiency of the gas cycle is 23.03% and this is greater than the average performance of most gas cycles (14%) [39]. The 25.76% and 32.99% energy efficiency recorded by the two steam cycles is a reflection of the advantage of reheat and regeneration process applied in the two cycles. This is reflected in the good exergy efficiency (16.17% for steam cycle 1 and 15.83%) recorded. The application of regeneration principles only in steam cycle 2 resulted in a higher energy efficiency while application reheat and regeneration principles in steam cycle 1 produced a better exergy performance. It should be noted that the turbine bleeding process applied in steam cycle 1 is a disadvantage to the cycle but an advantage to the overall performance of the trigeneration system. The energy performance of steam cycle 1 will increase more if there is no turbine bleeding process in Turb 2. The performance of the single effect absorption cycle and hot water system for this trigeneration system is similar to results in the literature, but its overall effect on the trigeneration performance is an improvement to the literature.

Exergy destruction for trigeneration systems is generally due to irreversibilities. For this research, exergy destruction is greatest in the combustion chamber of the gas cycle followed by the hot water production chamber. The exergy destruction in major component is shown in Figure 2.

Table 4. Thermodynamics properties of each state in the multi-generation system.

State No	Fluid Type	P (kPa)	M (kg/s)	T (K)	h (kJ/kg)
0		101		298	104.2
4	Biogas	101.3	0.1896	304.5	10.85
5	Biogas	303.9	0.1896	313	21.11
6	Air	304	3.066	337.4	338
7	Air	101	3.066	298	298
8	Air/Biogas	304	3.256	1100	1168
9	Air/Biogas	101.3	3.256	886.1	895.7
10	Air/Biogas	101.3	3.256	847.8	875.3
11	Air/Biogas	101.3	3.256	300	300.3
12	-	-	-	-	-
13	-	-	-	-	-
14	Water	300	0.3016	406.7	561.6
15	Water	5000	0.5027	379.3	448.5
16	Water	5000	0.5027	800	3496
17	Water	1200	0.5027	573	3045
18	Water	1200	0.5027	800	3535
19	Water	300	0.3016	573	3069
20	Water	20	0.2011	363	2666
21	Water	20	0.2011	358	2657
22a	Water	300	0.3016	331	242.4
22	Water	20	0.3016	331	242.2
23	Water	20	0.5027	333.2	251.4
24	Water	5000	0.5027	333.5	257
25	-	-	-	-	-
26	-	-	-	-	-

Table 4. *Cont.*

27	Water	40	0.2798	349	317.6
28	Water	600	0.2798	349	318.2
29	Water	600	0.3614	432	670.4
30	Water	8000	0.3614	432.9	679
31a	Water	1200	0.02538	461.1	798.3
31	Water	600	0.02538	432	798.3
32	Water	8000	0.3614	460.4	798.3
33	Water	8000	0.3614	573	2786
34	Water	1200	0.02538	461.1	2498
35	Water	600	0.0563	432	2362
36	Water	40	0.2798	349	2038
37	-	-	-	-	-
38	-	-	-	-	-
39	LiBrH2O	0.93	1.1418	308.7	85.3
40	LiBrH2O	4.82	1.1418	308.9	85.31
41	LiBrH2O	4.82	1.1418	328	124.7
42	LiBrH2O	4.82	0.1181	338	2621
43	LiBrH2O	4.82	0.1181	305.4	135
44	LiBrH2O	0.93	0.1181	279.1	135
45	LiBrH2O	0.93	0.1181	279.4	2512
46	LiBrH2O	4.82	1.3	348	184.5
47	LiBrH2O	4.82	1.3	316.7	124.6
48	LiBrH2O	0.93	1.3	318.7	124.6

Table 5. Trigeneration energy and exergy performance summary.

Power Cycle	**Work Input [kW]**	**Net Work Output [kW]**	**Energy Efficiency [%]**	**Exergy Efficiency [%]**
Gas Cycle	3322	765	23.03	18.08
Steam Cycle 1	1778	458.2	25.76	16.17
Steam Cycle 2	718.3	237	32.99	15.83
Cooling Effect	**Work Input [kW]**	**Net Work Output [kW]**	**COP_{en}**	**COP_{ex}**
Single Effect Absorption cycle	372.6	280.8	0.7537	0.3492
Hot Water Production	**Work Input [kW]**	**Net Work Output [kW]**	**Energy Efficiency [%]**	**Exergy Efficiency [%]**
Hot Water	481	384.7	80	53.36
Overall System	**Work Input [kW]**	**Net Work Output [kW]**	**Energy Efficiency [%]**	**Exergy Efficiency [%]**
Power	3322	1460	43.96	33.34
Cogeneration	3322	1740.8	52.41	34.26
Trigeneration	3322	2173.6	64	35.41

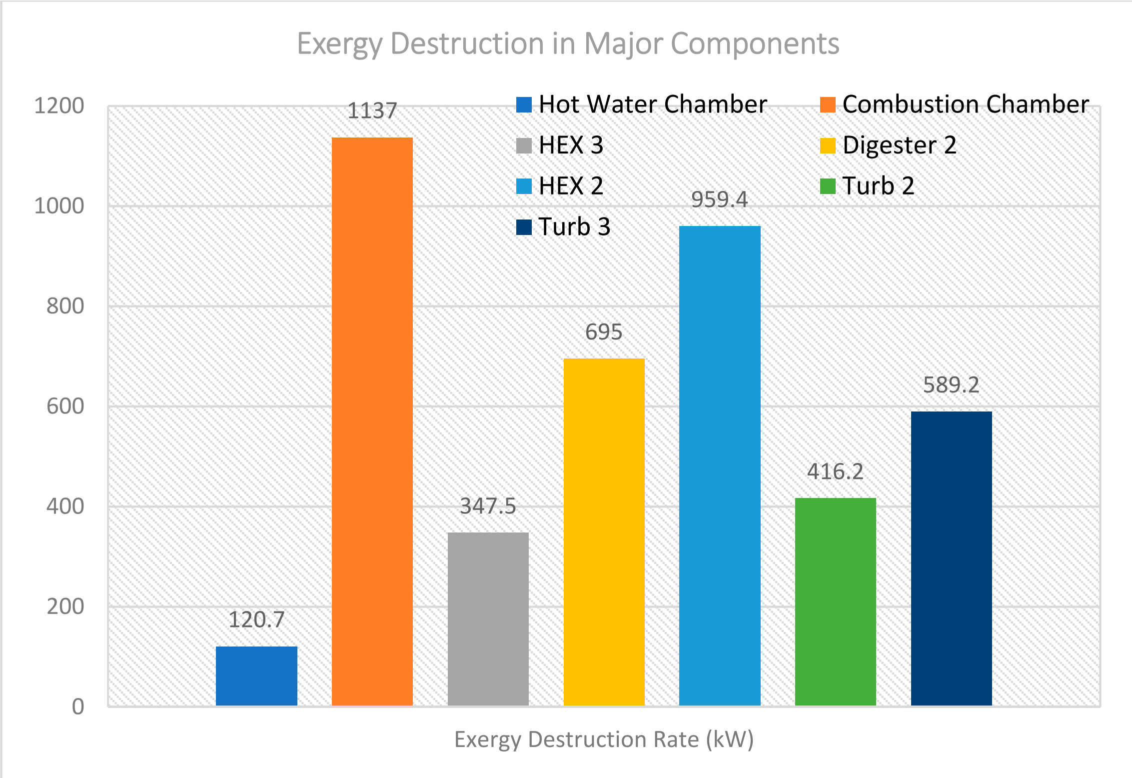

Figure 2. Trigeneration system exergy destruction summary in major components.

Ambient temperature is one factor that affects the exergy efficiencies of a trigeneration system in general. It also affects the exergy destruction within a system. A parametric study is done to check the effect of ambient temperature on exergy destruction and exergy efficiencies. A rise in ambient temperature from 280 K to 320 K reduces the exergy efficiencies (Figure 3). This shows that as the trigeneration system moves closer to dead state, the exergetic performance decreases. Increase in ambient temperature also has an impact on the exergy destruction in some of the components. While the exergy destruction increases for HEX 2, it decreases for other components (Figure 4).

Power generation is from the turbines in this trigeneration system. Since the biogas input is fixed, the temperature of the first turbine is designed according to the input conditions. The effect of increasing the inlet temperature of Turb 2 on mass flow rate, work output and energy efficiency is studied parametrically. While the mass flow of the two steam cycles and absorption cycle reduces as the temperature of Turb 2 increases, the reduction in mass flow rate is more evident on the absorption cycle (Figure 5). This also increases the power output from SC 1 and reduces the production of the other cycles (Figure 6). When the effect of change in Turb 2 is checked against the energy efficiencies performance, it is most evident on the energy efficiency of SC 1. There is a slight increase in the power, cogeneration, and trigeneration efficiency. The energy efficiency of SC 2 remains the same (Figure 7) but the work output reduces (Figure 6).

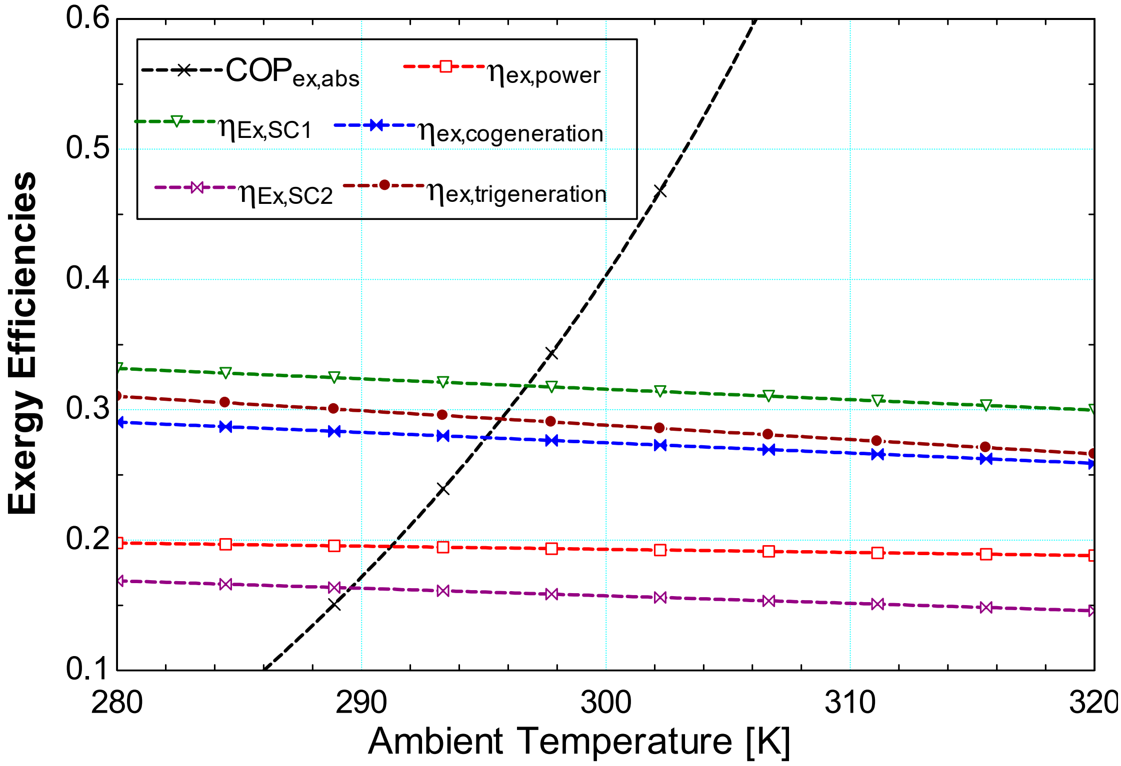

Figure 3. Effect of ambient temperature on exergy efficiency.

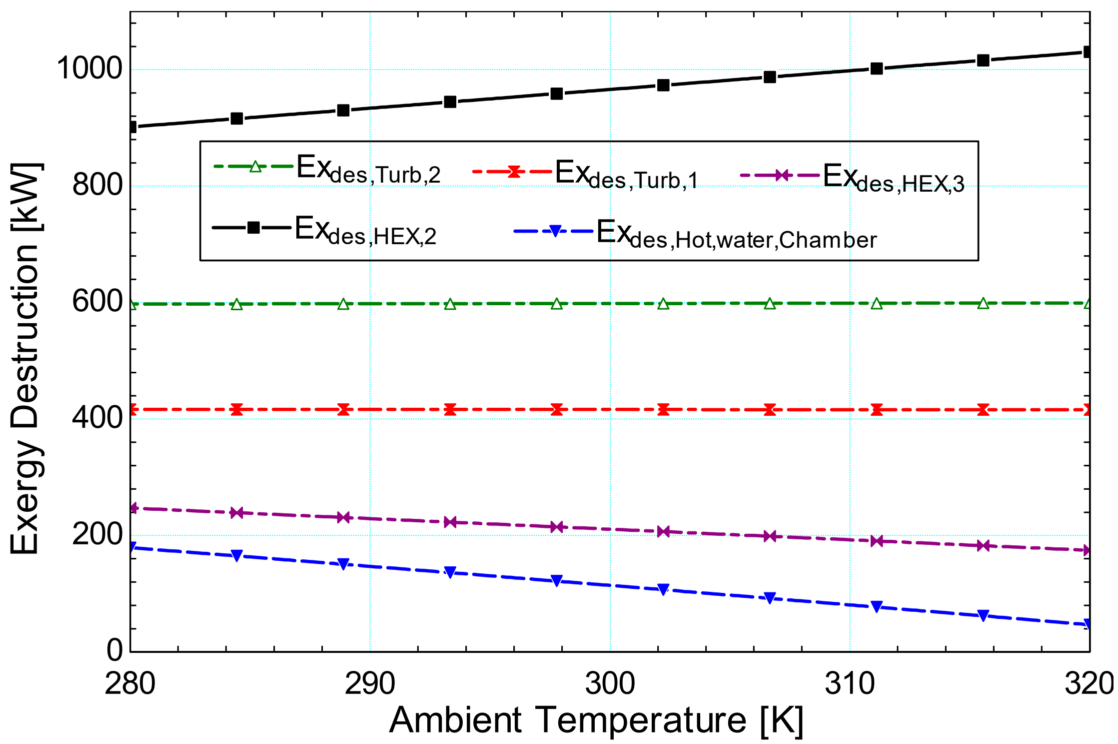

Figure 4. Effect of ambient temperature on exergy destruction.

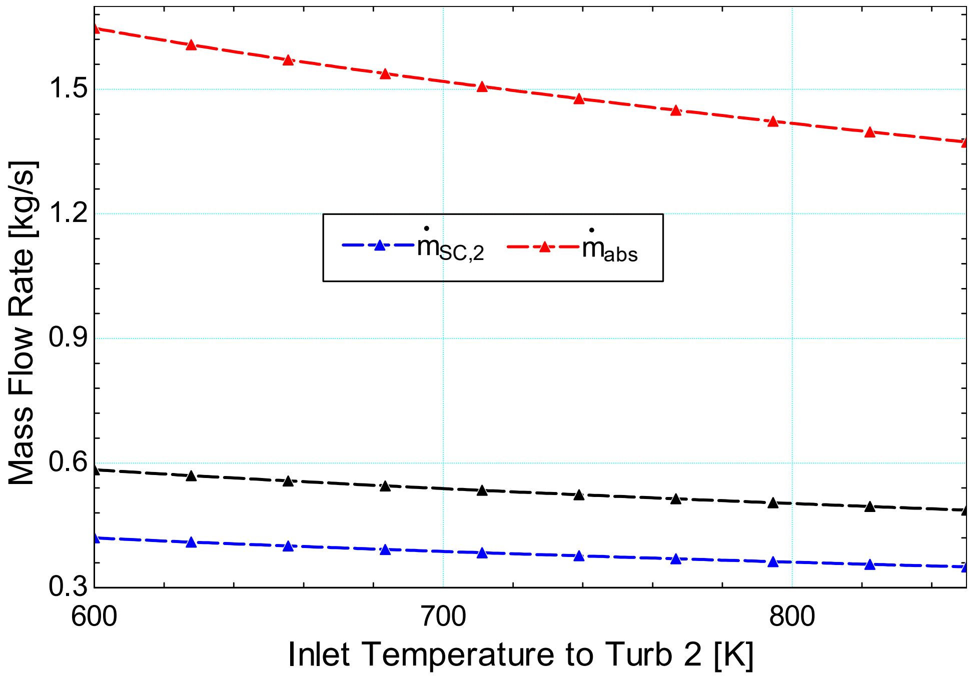

Figure 5. Effect of inlet temperature to Turb 2 on mass flow rate.

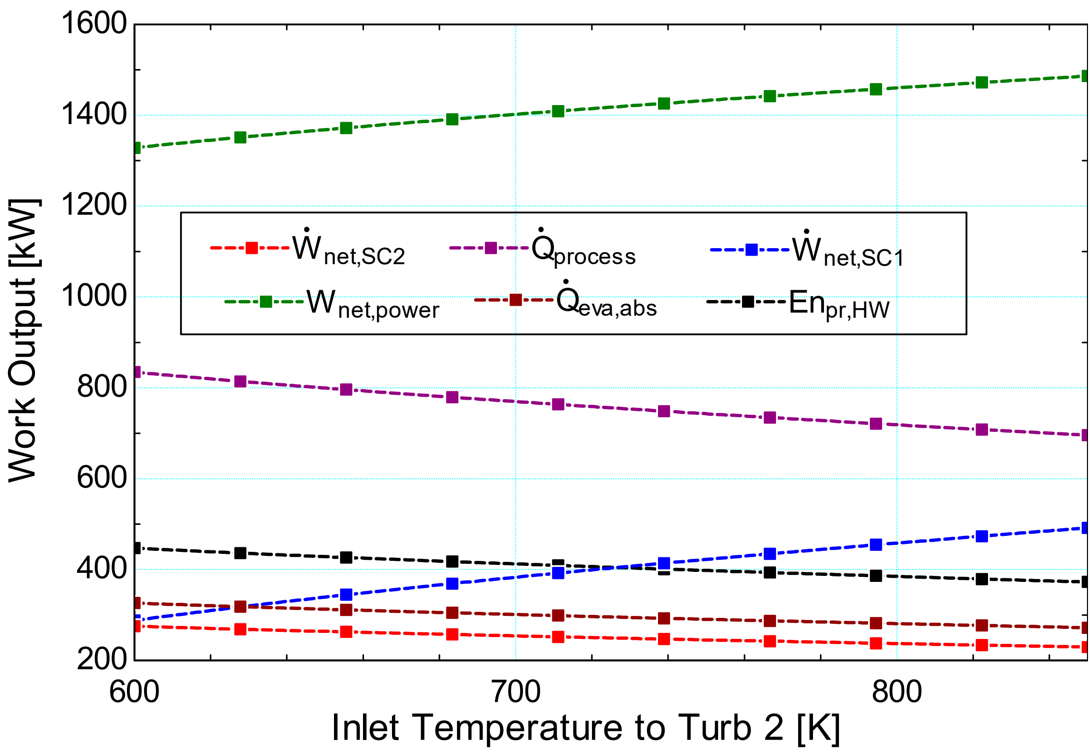

Figure 6. Effect of inlet temperature to Turb 2 on work output.

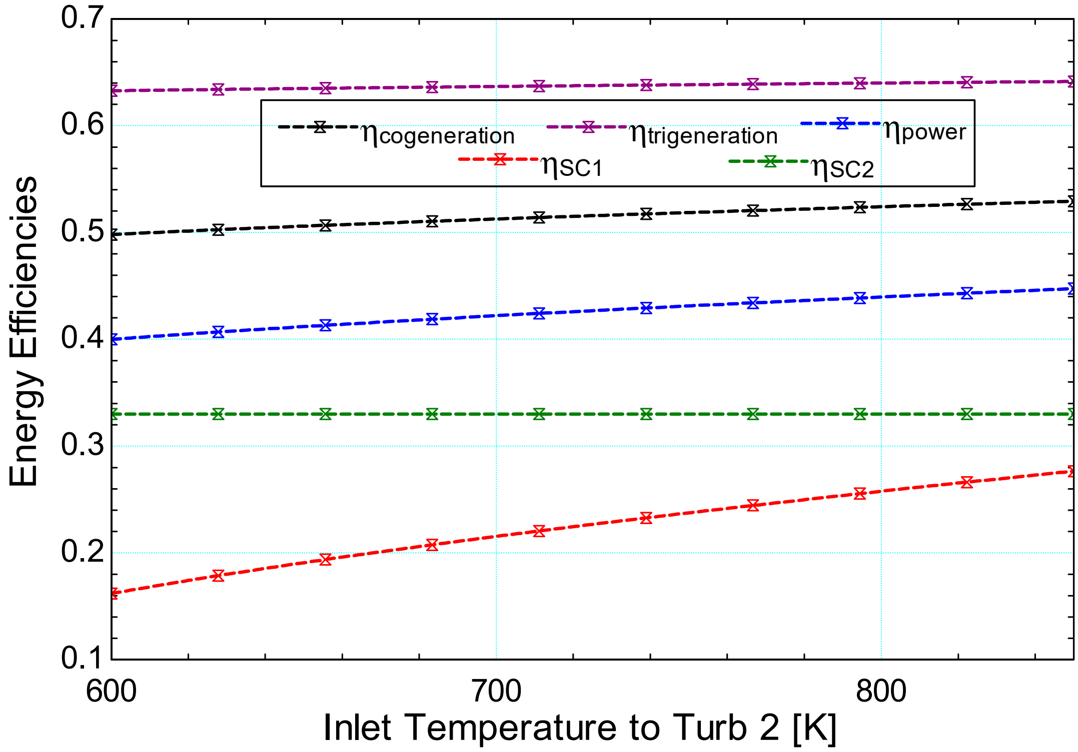

Figure 7. Effect of inlet temperature to Turb 2 on energy efficiencies.

4. Conclusions

Energy and exergy analyses of a trigeneration system driven by biogas is done in this study. A parametric study is done to check the system's performance with varying ambient temperature and turbine inlet temperature. The main concluding points in this study include:

- Biogas production is from 70,000 kg and 30,000 kg of chicken manure and maize silage respectively.
- Trigeneration system produces 1460 kW of electrical energy, 280.8 kW of cooling and 122.6 L/mins of hot water.
- The systems energy and exergy performance increase as more useful outputs are produced. The energy and exergy efficiency of the system respectively increases from 43.96% and 33.34% when generating electrical energy only to 64% and 34.51% when used for trigeneration.
- Exergy destruction is greatest in the combustion chamber in the multi-generation system.
- This trigeneration system will be suitable for developed and developing countries, where the biogas raw materials are readily available.

One of the main constraints in using biogas for trigeneration is production of the biogas itself. The critical detail in terms of raw material specifications and the large amount of raw materials required can be a source of drawback for the commercialization of such technology at present. In future research, the life cycle analysis of this system and raw materials demand/supply possibilities will be researched. Also, the control and power electronics of the developed trigeneration system will be considered.

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Abbreviations

abs	Absorption
CFWH	Closed Feedwater Heater
COP	Coefficient of Performance
E	Evaporator
HEX	Heat Exchanger
HW	Hot Water
OFWH	Open Feedwater Heater
P	Pump
S. EX	Solution Heat Exchanger
ST	Steam Trap
Turb	Turbine
V	Valve

Nomenclatures

ex	Exergy
h	Enthalpy
m	Mass flowrate
P	Pressure
Q	Useful Energy
S	Entropy
T	Temperature
u	Velocity
W	Work

Greek Letters

η	Efficiency
Ψ	Exergy

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