**INTRODUCTION**

This world has been experiencing a diversification in the use of various forms of energy owing to the technological advancement and ceaseless growth of population. Highest share of this energy production still attributes to fossil fuels. However, the use of such fuels is constrained by their limited reserve. Therefore, attention to efficient consumption of these natural energy resources has become a matter of immense importance and that necessitates establishing proper methods of performance evaluation of the energy systems. Conventionally, performance assessment of thermal power plants is carried out through energetic performance criteria based on the first law of thermodynamics. In recent times, the researchers, however, become equally interested in the exergetic performance analysis due to its capability of providing more detailed information regarding the performance of power systems.
generation systems. Exergy analysis combines the conservation of mass and conservation of energy principle together with the second law of thermodynamics and thus enables determination of locations, types, and true magnitudes of wastes and losses in the system. Carrying out energy and exergy analysis together can provide a better understanding of the performance characteristics of the concerning system. As a result, this type of comprehensive analysis has become a tangible approach toward performance evaluation and determination of steps for improvement.

As the energy and exergy analysis is performed aiming efficient utilization of energy resources, this implicates environment and sustainability as well. Higher resource utilization efficiency vouches for reduced quantity of fuel requirement for the production of same products and services. Reduced fuel consumption lessens the carbon emission quantity and hence subsides negative environmental impact. Furthermore, lower fuel usage reduces the depletion rate of fuel resources, preserving the resources for the future generation. Therefore, a confluence of energy, exergy (as the useful part of energy), environment and sustainability is suggested. It was observed that, as the efficiency increases, sustainability increases and environmental impact decreases.

One of the proper methods for increasing the productivity and efficiency of any electricity generation unit is to extend it to a combined heat and power (CHP) or combined cooling, heating and power (CCHP) systems. These systems have been proven as major alternatives for traditional approaches, like old power plants, in terms of energy saving, efficiency and environmental issues. In a CHP system, cogeneration of more than one useful form of energy (usually electricity and heat) occurs from a single energy source. The CHP system is capable of achieving up to 65%-70% fuel efficiency, compared to less than 50% of that by separate production of heat and power. A case study of “Pfizer Inc”, a US-based pharmaceutical company revealed, use of CHP system reduced the carbon dioxide emission by 38%, sulfur dioxide by 52% and nitrogen oxide by 41%.

Performance evaluation of CHP systems has been a matter of tremendous importance, and lots of studies are done as found in the literature. One of the essential investigations in that case was done by Balli and Aras in 2007. They performed energetic and exergetic performance evaluation of a CHP system run by microgas turbine in Turkey by quantitative assessment of each component and the overall system. In recent times, Ahamadi et al. analyzed an existing CHP system in a petrochemical plant in terms of energy, exergy and environmental aspects. Based on their results, the main exergy destruction occurs in the boilers of the system. Braimakis et al investigated the performance of biomass fueled CHP plant. They found most of the exergy destruction occurred during combustion and steam generation process, corresponding to 67%-70% and 13%-16%, respectively. Catalano et al modeled and assessed the performance of a CHP system in a frozen food processing factory. Energy, exergy and economic analysis was carried out, and multi-objective analysis was performed to find the best trade-off solution. Ziolkowski et al. analyzed the energetic, exergetic, and environmental aspects of a combined gas-steam cycle CHP system and found that highest exergy losses occurred in the combustion chamber. Taie and Hagen performed first and second law analysis of a residential ICE micro-CHP system and found an exergy efficiency of 33.7%. Gill et al. performed energy, exergy, and exergo-environmental and exergo-economic analysis of a solar-assisted multi-generation system. The system corresponds to a thermal efficiency of 41.08% and exergetic efficiency of 23.26%. Wang et al. carried out a performance investigation of a solar-assisted hybrid CCHP system based on energy, exergy, exergo-economic, and exergo-environmental analyses. The system consisted of a natural gas-fueled IC engine, solar heat collector, absorption heat pump, a heat exchanger, and a thermal storage tank. The system achieved an annual energy efficiency of 76.3% and exergy efficiency of 22.4%.

Based on the literature review, it is evident that energy, exergy, exergo-environmental, and exergetic sustainability aspects are rarely investigated for a natural gas engine-driven CHP system. This gap is aimed to be filled with this study. This sort of analysis is quite crucial for Bangladesh as well given the energy situation here. Under the influence of the above-mentioned facts, this study considers performance evaluation of a natural gas engine-driven CHP system installed at the Rajshahi feed mill of ACI Godrej Agrovet Private Limited in Bangladesh. The main contributions of this study are as follows:

- A comprehensive methodology for energetic and exergetic analysis for natural gas engine-driven CHP system is prepared, and performance is assessed based on actual data.
- In addition to the energy and exergy analysis, the methodology is prepared to understand the environmental effect the CHP system causes through exergo-environmental analyses.
- The sustainability of the CHP system is determined and discussed.
- Along with the entire CHP system, performance of the individual components of the CHP system is analyzed which will pave the way for operational and design improvement in specific locations.
2 | SYSTEM DESCRIPTION

A combined heat and power plant of $2 \times 2$ MW capacity installed at the Rajshahi feed mill of ACI Godrej Agrovet Private Limited is selected to be studied. The plant has two CAT G3520C model reciprocating gas engine (RE), each of which is coupled with a CAT SR4B generator (G). Each gas generator set has a rated electrical power output of 2 MW. For heat recovery steam generator (HRSG), the plant has an ENERGEN ENSG7 model boiler. The plant generates electrical power and heat to meet the demand of the factory. To analyze the system performance, data from one of the gas generator set are collected. Other components of the plant include a turbo charger (TC), an after cooler (A/C), an after cooler heat exchanger (A/C HE), a jacket water heat exchanger (JW HE), a lube oil cooler (LOC), a lube oil filter (LOF), a water reservoir pump (WRP), a feed water pump (FP), and two cooling towers. The schematic of the plant is illustrated in Figure 1.

The air and natural gas from air inlet and gas inlet, respectively, are mixed in a venturi mixer and enter the turbocharger compressor at 319.25 K temperature and 132.85 kPa pressure. The mass flow rates of air and gas are 1.45 and 0.09 kg/s, respectively. The mixture gets compressed to 169.32 kPa pressure in there, while the temperature increases to 371.15 K. After leaving the turbocharger, the mixture enters the after cooler where it is cooled to a temperature (327.15 K) suitable for further operations. From after cooler, the mixture enters the inlet manifold of the engine and subsequently into the engine cylinders. After the four-stroke cycle operation of the engine, the exhaust gas from the left and right bank (at 892.15 K and 688.24 kPa) exhaust ports combines and expands (to 540 kPa) at the turbocharger. The exhaust gas then enters the boiler where heated water is turned into steam by utilizing the heat from it. The exhaust gas then enters the economizer where more heat is extracted from it to preheat the boiler feed water. Finally, the exhaust gas leaving the economizer is rejected (at 402.65 K and 130 kPa) to the environment. At 48% load, the engine generates 957 kW electrical power of which 818.75 kW is available for use in the factory. The steam generator system produces 384.92 kW of heat for meeting the heating demand of the feed mill.

3 | MATHEMATICAL MODELING

In this study, an existing combined heat and power plant consisting of two CAT G3520C model reciprocating gas engine (RE) installed and operated at the Rajshahi feed mill of ACI Godrej Agrovet Private Limited in Bangladesh is studied. Performance analysis is carried out experimentally by collecting actual data from the site. The mathematical formulations necessary for the analysis are adopted from available literature and presented in the following subsections. Therefore, the present study plans not to redevelop (untested) thermodynamic model of a new system, rather to use accepted formulae to examine energetic, exergetic, exergo-environmental performance, and sustainability of an existing system. A comprehensive methodology is prepared, and with that, the thermodynamic performance of the system is assessed under its normal operating conditions using on-site data available from the gauges and the Supervisory Control and Data Acquisition (SCADA) system installed at the plant.

This section includes formulations necessary for thermodynamic analysis, ie, energy analysis and exergy analysis, and the associated performance parameters necessary for the condition assessment of the CHP system in study. The analysis involves some assumptions which are listed below:

- The CHP system operates in a steady-state condition.27
- The ideal gas principles are applied to air and combustion gases.27
- The energies and exergies of kinetic and potential are neglected.28
- The energetic and exergetic analyses are made on the CHP system.29
- The temperature and pressure of the dead (environmental) state are 298.15 K and 101.325 kPa, respectively.29

3.1 | Energy analysis

The general form of mass and energy balance equation for a control volume considering the above-mentioned assumptions is expressed by Equation (1)\(^30\) and Equation (2),\(^29\) respectively:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} \epsilon_{in} - \sum \dot{m}_{out} \epsilon_{out} = 0 \quad (2)$$

where $\dot{m}$ refers to mass flow rate, $\dot{Q}$ and $\dot{W}$ denote the net energy transfer rate by heat and mass, respectively, and $\epsilon$ refers to the specific energy. The subscripts “in” and “out” indicate the inlet and outlet stream of the control volumes.

Specific energy in general comprises of four components: specific kinetic energy, specific potential energy, specific physical energy, and specific chemical energy.\(^31\) Specific kinetic energy depends on the velocity, and specific potential energy depends on the height of the system or components. Since there are negligible changes
FIGURE 1 Schematic of the CHP system
in velocity and height, these two components are often excluded from the analysis and specific energy is calculated as expressed in Equation (3).

\[ e = e_{ph} + e_{ch} \] (3)

Since ideal gas behavior is assumed for air and combustion gas in this study, the specific physical energy for these two substances can be calculated by Equation (4).33

\[ e_{ph} = C_P(T)T - C_P(T_0)T_0 = h(T) - h(T_0) \] (4)

where \( C_P(T) \) and \( C_P(T_0) \) refer to the specific heat capacity at temperatures \( T \) and \( T_0 \), respectively. Also, \( h \) indicates to the enthalpy. The values of specific heat capacity of different substances are illustrated in Table 1.

The specific chemical energy of hydrocarbon fuels is equal to the fuel’s lower heating value (LHV) or higher heating value (HHV). This study considers the lower heating value of the fuel (mentioned in the assumptions); therefore, the specific chemical exergy is calculated by Equation (5).29

\[ e_{ch,\text{Fuel}} = \text{LHV} \] (5)

The lower heating value of natural gas used in the CHP system is 44 661 kJ/kg.29

Energy efficiency of a CHP system is defined as the ratio of useful output energy (electricity and heat) to the total energy input by fuel into the system. Thus, the energy efficiency of a CHP system can be determined by following Equation (6).36

\[ \eta_{\text{CHP}} = \frac{E_{\text{elec}} + E_{\text{heat}}}{E_{\text{Fuel}}} \] (6)

Energy efficiency for the cooler, heat exchanger, and heat recovery steam generator can be calculated by Equation (7).29

\[ \eta = \frac{E_{\text{cs,\text{out}}} - E_{\text{cs,\text{in}}}}{E_{\text{hs,\text{out}}} - E_{\text{hs,\text{out}}}} \] (7)

For compressor and pump, energy efficiency can be determined as29:

\[ \eta = \frac{E_{\text{out}} - E_{\text{in}}}{W} \] (8)

For turbine and expander, energy efficiency is calculated as29:

\[ \eta = \frac{W}{E_{\text{out}} - E_{\text{in}}} \] (9)

Any component other than these, the energy efficiency is determined considering the energy of the streams entering and exiting the respective component. For any component \( k \), it can be calculated by Equation (10) as follows26:

\[ \eta_k = \frac{\dot{E}_{\text{out},k}}{\dot{E}_{\text{in},k}} \] (10)

### 3.2 Exergy analysis

The general form of exergy balance equation for a control volume is expressed by Equation (11).37

\[ \dot{E}_X = \dot{E}_W + \sum \dot{m}_i e_X - \sum \dot{m}_o e_X = \dot{E}_D \] (11)

where \( \dot{m} \) and \( e_X \) refer to the mass flow rate and specific exergy, respectively, and \( \dot{E}_D \) refers to the exergy destruction rate. \( \dot{E}_X \) and \( \dot{E}_W \) refer to the exergy transfer rate by heat and work and can be expressed by Equations (12) and (13) as follows38:

\[ \dot{E}_X = \dot{Q}_m \left( 1 - \frac{T_0}{T_m} \right) \] (12)

\[ \dot{E}_W = W \] (13)

where \( \dot{Q}_m \) represents the heat transfer from the boundary of system components and \( T_m \) refers to the temperature at which heat transfer occurs. Also, \( T_0 \) represents the temperature of the environment. Exergy balance equations of CHP system and its components are given in Appendix A.

| Substance          | Unit       | Equation/value |
|--------------------|------------|----------------|
| Air                | kJ/kg K    | \( C_{P,A(T)} = 1.04841 - 0.000383719T + \frac{2.45787}{10^4} - \frac{4.93513}{10^6} + \frac{2.92647}{10^9} \) |
| Combustion gas     | kJ/kg K    | \( C_{P,EG(T)} = 0.93750 + \frac{0.01237}{10^3} - \frac{0.01629}{10^4} + \frac{0.97164}{10^7} \) |
| Lube oil           | kJ/kg K    | 2.10-2.16a     |

*Value varies in this range for different temperature encountered.*

**Table 1** Specific heat capacity of different substance
Irreversibilities within a component or a system cause exergy destruction and the exergy quantity that is emitted to the environment accounts for exergy loss of the system. These two terms sum up to account for the total exergy consumption of a system and is expressed by Equation (14)\(^39\) as follows:

\[
\dot{E}_C = \dot{E}_D + \dot{E}_L
\]  

(14)

The subscripts “C” and “L” refer to consumption and loss, respectively.

The physical exergy of combustion gas and air can be calculated by the expression in Equation (15)\(^40\) and that of solids and liquids can be calculated by Equation (16),\(^41\) whereby \(C_p, R, T, P, \text{ and } v\) refer to the specific heat at constant pressure, universal gas constant, temperature, pressure, and specific volume, respectively.

\[
ex_{ph} = C_p(T) \left[ T - T_0 - T_0 \ln \left( \frac{T}{T_0} \right) \right] + RT \left( \frac{P}{P_0} \right)
\]  

(15)

\[
ex_{ph} = C_p(T) \left[ T - T_0 - T_0 \ln \left( \frac{T}{T_0} \right) \right] - v \left( P - P_0 \right)
\]  

(16)

Furthermore, the chemical exergy of gaseous hydrocarbon fuel in the form \(\text{C}_a\text{H}_b\) on a mass unit basis can be calculated by Equation (17),\(^42\) whereby \(\gamma\) is the exergy grade function of fuel.

\[
ex_{ch,\text{Fuel}} \text{ LHV} = \gamma \cong 1.033 + 0.0169 \frac{b}{a} - 0.0698 \frac{a}{b}
\]  

(17)

The energy efficiency of a CHP system can be determined by following Equation (18).\(^36\)

\[
\psi_{\text{CHP}} = \frac{\dot{E}_{\text{elec}} + \dot{E}_{\text{heat}}}{\dot{E}_{\text{Fuel}}}
\]  

(18)

The exergy efficiency for the cooler, heat exchanger, and heat recovery steam generator can be calculated by Equation (19).\(^29\)

\[
\psi = \frac{\dot{E}_{\text{cs, out}} - \dot{E}_{\text{cs, in}}}{\dot{E}_{\text{hs, out}} - \dot{E}_{\text{hs, out}}}
\]  

(19)

For compressor and pump, exergy efficiency can be determined as\(^29\):

\[
\psi = \frac{\dot{E}_{\text{out}} - \dot{E}_{\text{in}}}{W}
\]  

(20)

For turbine and expander, exergy efficiency is calculated as\(^29\):

\[
\psi = \frac{W}{\dot{E}_{\text{out}} - \dot{E}_{\text{in}}}
\]  

(21)

Any component other than these, the exergy efficiency is determined considering the exergy of the streams entering and exiting the respective component. For any component \(k\), it can be calculated by Equation (22) as follows\(^26\):

\[
\psi_k = \frac{\dot{E}_{\text{out,k}}}{\dot{E}_{\text{in,k}}}
\]  

(22)

### 3.3 Thermodynamic performance parameters

The thermodynamic performance of the system and its components are assessed by the following parameters:

- **Improvement potential**: Improvement directly depends on the quantity of loss encountered and maximum improvement is achieved when the loss is minimized. Therefore, employing the concept of “improvement potential” is suggested as a part of performance analysis both for energetic\(^43\) and exergetic\(^44\) point of view and can be determined by Equations (23) and (24) for energy terms and exergy terms, respectively.

\[
IP_E = (1 - \eta) \dot{E}_L
\]  

(23)

\[
IP_{Ex} = (1 - \psi) \dot{E}_C
\]  

(24)

where \(IP\) is improvement potential in kW, and \(\dot{E}_L\) and \(\dot{E}_C\) are the energy loss (exergy consumption) of the system or the component, respectively.

- **Fuel depletion ratio**: The fuel depletion ratio is defined as the ratio of the energy loss (exergy consumption) of the \(k\)th component to the total fuel energy rate (fuel exergy rate) entering the system. For energy and exergy terms, this parameter is calculated by Equations (25) and (26), respectively\(^45\).

\[
\phi = \frac{\dot{E}_{L,k}}{\dot{E}_{Fuel}}
\]  

(25)

\[
\alpha = \frac{\dot{E}_{C,k}}{\dot{E}_{Fuel}}
\]  

(26)

- **Productivity lack ratio**: The productivity lack ratio is defined as the ratio of energy loss (exergy consumption) of the \(k\)th component of the system to total useful output energy (output exergy) of the system. Since the output
of a CHP system is electricity and heat, the parameter is expressed for energy and exergy terms by Equations (27) and (28), respectively.46

\[ \xi = \frac{\dot{E}_{L,k}}{\dot{E}_{\text{elec}} + \dot{E}_{\text{heat}}} \]  

\[ \beta = \frac{\dot{E}_{\text{C},k}}{\dot{E}_{\text{C,elec}} + \dot{E}_{\text{C,heat}}} \]  

• Relative loss/consumption ratio: Relative energy loss ratio is expressed as the ratio of the energy loss of \( k \)th component of the system to the total energy loss in the system. It is determined by Equation (29).43

\[ \omega = \frac{\dot{E}_{L,k}}{\dot{E}_{\text{L,CHP}}} \]  

Similarly, relative exergy consumption ratio is expressed as the ratio of exergy consumption of \( k \)th component of the system to the total exergy consumption of the system and can be calculated by Equation (30).43

\[ \chi = \frac{\dot{E}_{\text{C},k}}{\dot{E}_{\text{C,CHP}}} \]  

3.4 | Exergo-environmental analysis

Exergo-environmental analysis of a system combines the exergetic and environmental assessments and explains the effect of the system and its different components on the surrounding. The exergo-environmental factor (\( f_{el} \)) is directly related to exergy consumption and can be calculated by Equation (31)47 as follows:

\[ f_{el} = \frac{\dot{E}_{\text{C}}}{\dot{E}_{\text{in}}} \]  

The exergo-environmental impact coefficient (\( C_{el} \)) is another important parameter to assess the performance of a system. This parameter depends on the exergetic efficiency (\( \psi \)) of the system and can be determined by Equation (32).47

\[ C_{el} = \frac{1}{\psi} \]  

Environmental damage factor (\( \theta_{el} \)) is used to express the damaging effect of a system or a component on the environment, and it can be obtained from Equation (33).48

\[ \theta_{el} = f_{el}C_{el} \]  

Finally, by the environmental benign index (\( \theta_{ebi} \)), the positive effect of the system or the components is expressed and is determined by Equation (34).49

\[ \theta_{ebi} = \frac{1}{\theta_{el}} \]  

3.5 | Exergetic sustainability

Sustainability can be defined as protecting resources for the requirement of next generation while supplying requirements of the present generation.50 Therefore, the more efficiently the energy consumption occurs in a system, the more sustainability can be achieved. The exergetic sustainability index (SI) is adopted for this study to assess the sustainability of the system, and it is calculated as a function of exergy efficiency (\( \psi \)) as shown in Equation (29).50-52

\[ \text{SI} = \frac{1}{1 - \psi} \]  

4 | THERMODYNAMIC PROPERTIES ON THE STATIONS OF THE CHP SYSTEM

The thermodynamic properties of different stations of the CHP system are presented in Table 2. The data collection was carried out according to the schematic diagram of the CHP system illustrated in Figure 1 for every selected location of the system. At the time of data collection, the load factor of the engine under study was 48% and the engine was running at constant 1500 rpm speed. The corresponding energy rate and exergy rate of every station were calculated according to the formulations presented in Sections 3.1 and 3.2. The data were measured several times with a view to minimizing any possibilities of error. Most of the data were measured on the spot from different temperature and pressure gauges installed throughout the plant. The mass flow rate values were determined from the sensor reading displayed in the Supervisory Control and Data Acquisition (SCADA) system.

5 | RESULTS AND DISCUSSION

5.1 | Thermodynamic performance

In this study, thermodynamic performance of the CHP system and its components are determined principally based on energy and exergy efficiency. Furthermore, several performance parameters such as improvement potential, fuel depletion ratio, productivity lack ratio,
relative loss, or consumption ratio are calculated for both the system and components as well. In the following sections, the performance of the individual components is discussed first followed by the discussion of overall system performance.

### 5.1.1 Thermodynamic performance of CHP system components

Energy and exergy input rate, output rate, loss or destruction rate, and energetic and exergetic efficiency of the components are summarized in Tables 3 and 4.

Figure 2 reports the energy input rate, output rate, and energy loss rate of the CHP system components. Higher energy loss is seen to be occurring in RE, HRSG, JW HW, A/C, and A/C heat exchangers with values of 656.54 kW, 465.51 kW, 234.99 kW, 206.82 kW, and 169.34 kW, respectively. Additionally, a significant amount of energy (181.38 kW) is lost through the exhaust gas as reported in Table 3. Considering losses with respect to individual componentwise energy input, it can be seen the maximum percentage of energy input loss corresponds to the HRSG (58.78%), followed by A/C (44.80%), A/C HE (36.44%), and JW HE (20.91%). This percentage is lower in G (1.46%), LOF (5.95%), LOC (8.61%), TC (10.19%), and RE (16.19%).

### Table 2 Thermodynamic properties on the stations of the CHP system

| Station No. | Fluid/power | Temperature $T$ (K) | Pressure $P$ (kPa) | Mass flow rate $\dot{m}$ (kg/s) | Energy rate $\dot{E}$ (kW) | Exergy rate $\dot{Ex}$ (kW) |
|-------------|-------------|---------------------|-------------------|-------------------------------|--------------------------|---------------------------|
| 0           | Air         | 298.15              | 101.325           | -                             | -                        | -                        |
| 1           | Natural gas | 316.15              | 126               | 0.09                          | 4019.49                  | 4143.29                  |
| 2           | Air         | 324.85              | 139.7             | 1.45                          | 44.79                    | 172.77                   |
| 3           | Air gas mixture | 319.25 | 132.85            | 1.54                          | 4054.34                  | 4307                     |
| 4           | Air gas mixture | 371.15 | 169.32            | 1.54                          | 4207.63                  | 4425.74                  |
| 5           | Air gas mixture | 327.15 | 160.85            | 1.54                          | 4053.05                  | 4346.77                  |
| 0'          | Lube oil    | 298.15              | 101.325           | -                             | -                        | -                        |
| 6           | Lube oil    | 369.15              | 506               | 2.67                          | 640.33                   | 40.84                    |
| 7           | Lube oil    | 354.65              | 499               | 2.67                          | 585.17                   | 35.15                    |
| 8           | Lube oil    | 363.65              | 467               | 2.67                          | 550.35                   | 34.09                    |
| 0"          | Water       | 298.15              | 101.325           | -                             | -                        | -                        |
| 9           | Jacket water | 360.45 | 244               | 11.2                          | 3099.44                  | 267.79                   |
| 10          | Jacket water | 340.15 | 235               | 11.2                          | 1646.40                  | 121.04                   |
| 11          | Cooling water | 321.55 | 172.4             | 18.5                          | 1809.52                  | 66.23                    |
| 12          | Cooling water | 310.25 | 160               | 18.5                          | 920.75                   | 16.84                    |
| 13          | Cooling water | 324.25 | 190               | 7.84                          | 857.85                   | 34.65                    |
| 14          | Cooling water | 310.15 | 181               | 7.84                          | 393.25                   | 7.11                     |
| 15          | Cooling water | 313.95 | 172.4             | 18.5                          | 1216.01                  | 29.97                    |
| 16          | Cooling water | 308.45 | 101.325           | 18.5                          | 905.57                   | 9.51                     |
| 17          | Combustion gas | 892.15 | 688.24            | 1.54                          | 1235.35                  | 1401.23                  |
| 18          | Combustion gas | 819.15 | 540               | 1.54                          | 1064.43                  | 1104.18                  |
| 19          | Combustion gas | 782.15 | 500               | 1.54                          | 973.32                   | 1004.23                  |
| 20          | Combustion gas | 402.65 | 130               | 1.54                          | 181.38                   | 192.65                   |
| 21          | Hot water   | 368                | 1102              | 1.60                          | 487                      | 46.18                    |
| 22          | Hot water   | 368.15             | 1200              | 1.60                          | 488.52                   | 47.18                    |
| 23          | Steam       | 443.15             | 900               | 1.60                          | 873.44                   | 186.24                   |
| 24          | Electrical power | -           | -                 | -                             | 957                      | 957                      |
| 25          | Electrical power | -           | -                 | -                             | 943                      | 943                      |
| 26          | Electrical power | -           | -                 | -                             | 39.25                    | 39.25                    |
| 27          | Electrical power | -           | -                 | -                             | 85                       | 85                       |
| 28          | Electrical power | -           | -                 | -                             | 818.75                   | 818.75                   |
Figure 3 illustrates the calculated energy efficiency of the components of the CHP system. The components G, LOF, LOC, TC, and RE have higher energetic efficiency being 98.54%, 94.05%, 91.39%, 89.65%, and 83.20% efficient, respectively. Among all the components, HRSG exhibited the lowest energy efficiency (48.83%) due to higher irreversibility associated with the steam generation process. In addition to that, FP, WRP, and A/C have energy efficiencies in the lower ranges with values of 50.60%, 50.67%, and 55.20%, respectively.

The values of the considered performance parameters for energetic performance assessment are presented graphically in Figure 4. The yellow marker indicates the values of energetic improvement potential. The highest improvement potential is associated with HRSG (207.50 kW) followed by RE (106.36 kW), A/C (92.66 kW), and A/C HE (61.72 kW). As reported in Table 3, these are the components with values of energy losses in the higher range. The components with higher energetic efficiency and moderate amount of energy loss, such as G, LOF, LOC, exhibit lower improvement potential (0.21 kW, 2.07 kW, and 4.75 kW, respectively). These components require less attention than the other ones while adjusting for improvement. However, the results indicate lower improvement potential is not able to sufficiently indicate that the condition of the component is satisfactory. As it can be seen for FP and WRP, these components have lower improvement potential (0.73 kW and 7.32 kW), but their lower energy efficiency value indicates that there are room for improvements. Higher fuel depletion ratio

| Components | $\dot{E}_{\text{in}}$ (kW) | $\dot{E}_{\text{out}}$ (kW) | $\dot{E}_L$ (kW) | $\eta$ (%) | $IP_E$ (kW) | $\phi$ (%) | $\xi$ (%) | $\omega$ (%) |
|------------|-----------------|-----------------|-------------|--------|-------------|--------|--------|-------|
| RE         | 4053.05         | 3396.51         | 656.54      | 83.80  | 106.36      | 16.33  | 54.54  | 23.32 |
| HRSG       | 791.94          | 386.43          | 465.51      | 48.83  | 207.50      | 11.58  | 38.67  | 16.53 |
| TC         | 170.92          | 153.49          | 17.43       | 89.65  | 1.81        | 0.43   | 1.45   | 0.2   |
| AC         | 461.60          | 254.78          | 206.82      | 55.20  | 92.66       | 5.14   | 17.18  | 7.34  |
| AC HE      | 464.60          | 295.26          | 169.34      | 63.55  | 61.72       | 4.21   | 14.07  | 6.01  |
| JW HE      | 1123.76         | 888.77          | 234.99      | 79.17  | 48.94       | 5.85   | 19.52  | 8.35  |
| LOC        | 640.33          | 585.17          | 55.16       | 91.39  | 4.75        | 1.37   | 4.58   | 1.96  |
| LOF        | 585.17          | 550.35          | 34.82       | 94.05  | 2.07        | 0.87   | 2.89   | 1.24  |
| FP         | 3.00            | 1.52            | 1.48        | 50.67  | 0.73        | 0.04   | 0.12   | 0.05  |
| WRP        | 30.00           | 15.18           | 14.82       | 50.60  | 7.32        | 0.36   | 1.23   | 0.53  |
| G          | 957             | 943             | 14          | 98.54  | 0.21        | 0.35   | 1.16   | 0.50  |
| Exhaust gas|                 |                 |             |        |             |        |        |       |
| Utilized power |         |                 |             |        |             |        |        |       |

| Components | $\dot{E}_{X_{\text{in}}}$ (kW) | $\dot{E}_{X_{\text{out}}}$ (kW) | $\dot{E}_{X}$ (kW) | $\psi$ (%) | $IP_{X}$ (kW) | $\alpha$ (%) | $\beta$ (%) | $\chi$ (%) |
|------------|-----------------|-----------------|-------------|--------|-------------|--------|--------|-------|
| RE         | 4346.77         | 2511.72         | 1835.04     | 57.74  | 775.49      | 44.29  | 191.59 | 57.61 |
| HRSG       | 811.58          | 140.07          | 671.51      | 17.26  | 555.61      | 16.21  | 70.11  | 21.08 |
| TC         | 297.05          | 118.74          | 178.31      | 40.0   | 106.99      | 4.30   | 18.62  | 5.60  |
| AC         | 78.97           | 27.54           | 51.43       | 34.87  | 33.50       | 1.24   | 5.37   | 1.62  |
| AC HE      | 27.54           | 13.13           | 14.41       | 47.68  | 7.54        | 0.35   | 1.50   | 0.45  |
| JW HE      | 146.75          | 49.39           | 97.36       | 33.66  | 64.59       | 2.35   | 10.16  | 3.06  |
| LOC        | 40.84           | 35.51           | 5.33        | 86.95  | 0.70        | 0.13   | 0.56   | 0.17  |
| LOF        | 35.51           | 34.09           | 1.42        | 96.0   | 0.06        | 0.03   | 0.15   | 0.05  |
| FP         | 3.00            | 1.00            | 2.00        | 33.33  | 1.33        | 0.05   | 0.21   | 0.06  |
| WRP        | 30.00           | 7.33            | 22.62       | 24.43  | 17.13       | 0.55   | 2.36   | 0.71  |
| G          | 957             | 943             | 14          | 98.54  | 0.20        | 0.34   | 1.46   | 0.44  |
| Exhaust gas| 192.65          |                 |             | 4.65   | 20.11       | 6.05   |        |       |
| Utilized power | 124.25        |                 |             | 3.00   | 12.97       | 3.90   |        |       |
was seen in RE (16.33%), HRSG (11.58%), JW HE (5.85%), A/C (5.14%), and exhaust gas (4.51%). The corresponding percentage indicates they deplete the input fuel by that percentage. These components have higher productivity lack ratio with values of 54.54%, 38.67%, 19.52%, 17.18%, and 15.07% for RE, HRSG, JW HW, A/C, and exhaust gas, respectively. Furthermore, these are the components that show maximum values of relative energy loss throughout the system where RE lost 23.32%, HRSG 16.53%, JW HW 7.34%, A/C 6.01%, and through exhaust gas 6.44% energy is lost. So based on the energetic performance assessment, taking provisions to improve the performance of HRSG, RE, A/C, A/C HE, and JW HE among other components, the performance of the plant can be improved.

The exergetic performance results of the CHP system components are summarized in Table 4. Based on these results, exergy input rate, exergy output rate, exergy destruction rate of different CHP components are illustrated in Figure 5. As observed, higher exergy destruction occurs in RE (1835.04 kW), HRSG (671.51 kW), TC (178.31 kW), and JW HE (97.36 kW). Further observation reveals that the components HRSG cause destruction of larger portion of its input exergy by 82.74%. For TC, this percentage is 60.02%, for JW HE 66.34%, and for RE 42.21%. The
The individual exergy efficiencies of the CHP system components are reported in Figure 6. The components with higher exergetic efficiencies are the G (98.54%), LOF (96%), and LOF (86.95%). Lower exergetic efficiencies are observed in WRP (24.43%), FP (33.33%), JW HE (33.66%), A/C (34.87%), and TC (40%). However, the lowest exergetic efficiency has been exhibited in the HRSG (17.26%). The components RE and A/C HE have moderately lower efficiency, 57.74% and 47.68%, respectively.

Although the exergetic performance of the system components can be assessed with the values of their calculated exergy efficiency, for a deeper understanding, several performance parameters with exergy values are calculated, as presented in Figure 7. The exergetic improvement potential is an indicator of how much the performance of the component can be improved. It can be seen that the highest improvement potential is in RE by 775.49 kW owing to the highest exergy destruction rate in the components. The following rank is occupied by HRSG (555.61 kW). Although the exergy destruction in HRSG is about 63%...
lower than RE, this higher improvement necessity is due to its very low exergy efficiency. Other components with comparatively higher improvement potential are TC (106.99 kW), JW HE (64.59 kW), and A/C (33.50 kW). The values of fuel depletion ratio indicate that RE depletes 44.29%, HRSG 16.21%, and exhaust gas 4.65% of the fuel input. Other components like A/C and JW HE deplete 1.24% and 2.35%, respectively, which are slightly higher than the rest of the components like A/C HE (0.35%), LOC (0.70%), LOF (0.03%), FP (0.05%), and WRP (0.55%). Relative exergy destruction ratio is obviously higher in RE, where 57.61% exergy is destroyed, followed by HRSG with 21.08%. While other components contribute lesser percentage, exhaust gas (6.05%), TC (5.60%), JW HE (3.60%), and A/C (1.62%) draw attention with their higher values.

As revealed in exergy analysis, the components that performed unsatisfactorily in terms of energy, still perform in the same way, except for the TC, the performance of which is lesser than that of energetic. In both cases, however, performance of HRSG is the least satisfactory of all and therefore requires immediate attention.

5.1.2 | Thermodynamic performance of overall CHP system

The energetic and exergetic performance results of the overall CHP system are illustrated in Figures 8 and 9, respectively. The CHP system has an energy efficiency of 29.95%. The system produces 818.75 kW electrical energy
and 384.92 kW heat energy for meeting the demand of the factory from 4019.19 kW fuel energy input. Total energy loss in the system is 2815.82 kW. The system has an electrical energy efficiency of 20.37% and heat energy efficiency of 9.58% with a power to heat ratio of 2.13. The overall CHP system depletes 70% of the fuel energy input which is calculated by the fuel depletion ratio. Furthermore, the system has energetic productivity lack ratio of 2.34 and energetic improvement potential of 1972.48.

As reported in Figure 9, the overall exergy efficiency of the CHP system is 23.12%, with electrical exergy efficiency of 19.76% and heat exergy efficiency of 3.36%. The electrical exergy output is same as electrical energy output, but the heat exergy output is reduced to 139.06 kW, about 64%
lower than energy output quantity. Consequently, an increase in the power to heat ratio is seen, where the exergetic power to heat ratio is 5.89. Exergetic fuel depletion ratio indicates that the system depletes 77% of the input fuel exergy (4143.29 kW). The total exergy consumption of the system is 3185.48 kW. The system has exergetic improvement potential of 2448.90 kW and a productivity lack ratio of 3.33.

5.2 Exergo-environmental performance and exergetic sustainability

Exergo-environmental analysis is carried out in order to understand the environmental impact of the exergy destruction in the CHP system and its components. Furthermore, since environment and sustainability go hand in hand with exergy, exergetic sustainability index of the CHP system is determined as part of the sustainability analysis. Exergo-environmental performance results of the CHP system components are summarized in Table 5.

Graphical representation of the exergo-environmental performance results can be seen in Figure 10. The bars represent the values of the factors that indicate the negative impact of the components on the environment (exergo-environmental factor, exergo-environmental impact coefficient, and environmental damage factor), whereas the marker indicates the value of positive impact factor (environmental benign index). The values of exergo-environmental factor are higher in HRSG (0.827), WRP (0.754), FP (0.754), JW HE (0.663), A/C (0.651), TC (0.600), and A/C HE (0.523). This reflects in the values of the exergo-environmental impact coefficient as well with values of 5.794, 4.093, 3.001, 2.971, 2.878, 2.500, and 2.097, respectively. The values of exergo-environmental damage factor are also higher in case of these components. As a result, the value of environmental benign index is lower for these components. The maximum value of environmental benign index is seen in G (67.359), and the minimum is for HRSG (0.209). Moderately higher value of the negative impact factors and lower value of positive impact factors are observed for RE. On the other hand, LOC and LOF exhibit very lower value of negative impact factors and consequently higher value of the positive impact factor.

Exergo-environmental performance results of the overall CHP system are reported in Figure 11. It can be seen from the results the system has more negative impact than positive impact on the environment. The lower exergy efficiency and high amount of exergy consumption attribute to these patterns in the result. The values of negative impact factors such as exergo-environmental factor, exergo-environmental impact coefficient, and environmental damage factor are found to be 0.77, 4.33, and 3.33, which are very high. Consequently, the value of environmental benign index is very low, only 0.30. The expected values of these factors can be understood from the values of the components that show better performance in terms of exergo-environmental analysis.

As for the exergetic sustainability index, it was found to be very low (1.30). This value corresponds to the value of fuel depletion ratio and exergetic efficiency of the system. It was already mentioned that fuel depletion ratio was found to be 0.77 for the overall system, which indicates the system depletes 77% of the fuel reserve and therefore is proven to be much less sustainable than needed.

6 CONCLUSIONS

The current energy situation in Bangladesh indicates that there is no way around than taking the immediate steps to improve the productivity of the currently employed energy generation systems. To materialize that, the current performance characteristics of the generation systems must be assessed properly. With a view to contributing to that measure, this study provides a performance evaluation procedure based on the first law and second law of thermodynamics for a natural gas engine-driven combined heat and power system in Bangladesh. As a widely accepted and proven method of analysis, a complete picture of the performance of the system and its components can be obtained through this. For performance assessment, energy and exergy efficiency along with some performance parameters such as improvement potential, fuel depletion ratio, productivity lack ratio, and relative loss or consumption ratio are adopted. Apart from energetic and exergetic evaluation, the effect of the CHP system performance on environment is assessed through an effective exergo-environmental analysis. Furthermore, exergetic
sustainability of the CHP system is also measured. The outcomes of this study are listed as follows:

- Energetic performance analysis of the components of the CHP system reveals maximum energy loss occurs in RE (656.54 kW) followed by HRSG (465.51 kW). HRSG has the lowest energy efficiency of all the components (48.83%). The energetic improvement potential, fuel energy depletion ratio, energetic productivity lack ratio of HRSG are found to be 207.50 kW, 11.58%, 38.67%, and 16.53%, respectively.

- Exergetic performance analysis of the components reveals maximum exergy destruction occurs in RE (1835.04 kW) followed by HRSG (671.51 kW). Similar to energetic performance, HRSG has the lowest exergy efficiency as well (17.26%). The exergetic improvement potential, fuel exergy depletion ratio, exergetic productivity lack ratio of HRSG are found to be 555.61 kW, 16.21%, 70.11%, and 21.08%, respectively.

- It is evident from combined energy and exergy analysis of the components that, in addition to RE and HRSG, the performance of the components A/C, A/C HE, JW HE needs to be improved as well in order to make the system more productive and thus efficient.

- The CHP system has an overall energy efficiency of 29.95% and an exergy efficiency of 23.12%. The energetic and exergetic fuel depletion ratio of the system is 0.70 and 0.77, respectively. The system has an energetic improvement potential of 1972.58 kW and an exergetic improvement potential of 2448.90 kW.

- Exergetic-sustainability analysis of the CHP system shows that the system has higher values of the negative impact factors and quite low value of the positive impact factors. This makes the system less environment friendly. The components analysis resonates the energy and exergy analysis and shows the HRSG is least environmentally friendly component of the system. The energetic sustainability index of the CHP system is found to be very low (1.30).

The results obtained from this study can be utilized effectively in order to boost the performance of the CHP system. Furthermore, the methodology is comprehensive and can be adopted to investigate the performance of any
thermal power plant. Energy and exergy analysis, being a universal method of performance assessment, is capable of evaluating the performance of any power generating system. In that regard, further research is warranted to investigate the performance of the diesel engine fueled plants, coal fired plants, and even the renewable systems that are currently meeting the electricity demand of the country. Future analyses are required to include parametric analysis of the system by measuring data at varying conditions of the key parameters. Moreover, in addition to conventional analysis, future works must consider advanced exergy analysis where the exergy destruction of any component can be found divided into avoidable and unavoidable parts, thus leading to ways of effectively reducing the exergetic shortcomings. Resource indicators, economic indicators, social indicators are recommended to be included in the sustainability analysis for more comprehensive manner of analysis. These steps leading to a more efficient power generation sector will certainly pave the way of a better future where a sustainable and enhanced living standard with energy security will prevail.

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NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| $C_p$  | Specific heat (kJ/kg K) |
| $E$    | Energy rate (kW) |
| $\dot{E}_x$ | Exergy rate (kW) |
| $e$    | Specific energy (kJ/kg) |
| $ex$   | Specific exergy (kJ/Kg) |
| $G$    | Generator |
| $h$    | Enthalpy (kJ/kg) |
| $IP$   | Improvement potential (kW) |
| $\dot{m}$ | Mass flow rate (kg/s) |
| $P$    | Pressure (kPa) |
| $R$    | Universal gas constant (kJ/kg K) |
| $T$    | Temperature (K) |
| $Q$    | Energy transfer rate by heat (kW) |
| $W$    | Energy transfer rate by work (kW) |
| $f_{el}$ | Exergo-environmental factor |
| $C_{ei}$ | Exergo-environmental Impact coefficient |

GREEK LETTERS

| Symbol | Description |
|--------|-------------|
| $\alpha$ | Exergetic fuel depletion ratio |
| $\beta$ | Exergetic productivity lack ratio |
| $\gamma$ | Exergy grade function of gaseous fuel |
| $\eta$ | Energy efficiency (%) |
| $\eta_{el}$ | Environmental damage factor |
| $\eta_{ebi}$ | Environmental benign index |

SUBSCRIPTS

| Symbol | Description |
|--------|-------------|
| $A$ | Air |
| $a$ | Number of carbon atoms |
| $b$ | Number of hydrogen atoms |
| $C$ | Consumption |
| $ch$ | Chemical |
| $cs$ | Cold side |
| $D$ | Destruction |
| $E$ | Energetic |
| $EG$ | Exhaust gas |
| $Ex$ | Exergetic |
| $elec$ | Electrical |
| $hs$ | Hot side |
| $in$ | Input |
| $k$ | Index for CHP components |
| $m$ | Boundary of system components |
| $out$ | Output |
| $ph$ | Physical |
| $Q$ | Heat |
| $W$ | Work |

ABBREVIATIONS

AI, Air inlet; A/C, After cooler; CHP, Combined heat and power; CT, Cooling Tower; FP, Feed pump; GF, Gas filter; HE, Heat exchanger; HRS, Heat recovery steam generator; JW, Jacket water; LHV, Lower heating value (kJ/kg); LOC, Lube oil cooler; LOF, Lube oil filter; NGI, Natural gas inlet; PR, Pressure regulator; RE, Reciprocating engine; RPM, Revolution per minute; SCADA, Supervisory Control and Data Acquisition; SI, Sustainability index; TC, Turbocharger; VM, Venturi mixer; WRP, Water reservoir pump.

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## APPENDIX A

### Control volume and balance equations of the CHP system components

Energy and exergy balance equations for the components of the CHP system are presented in Table A1.

| No. | Component | Control volume | Balance equation |
|-----|-----------|----------------|------------------|
| 01  | CHP unit  | 1 → 28         | \( (E_1 + E_2) - (E_{28,W} + E_{Q_{uo}}) = E_{21,CHP}E_{Q_{uo}} = E_{23} - E_{22} \) |
|     |           | 2 → \( Q_{Net} \) |                  |
| 02  | Reciprocating engine | 5 → 6           | \( E_6 - (E_6 - E_3) + (E_9 - E_{10}) + E_{17} + E_{24} = E_{L,RE} \) |
|     |           | 8 → 9           | \( E_{x_1} - (E_{x_1} - E_{x_2}) + (E_{x_9} - E_{x_{10}}) + (E_{x_{17}} + E_{x_{24}}) = E_{X,RE} \) |
| 03  | Heat recovery steam generator | 19 → 20       | \( (E_{19} - E_{20}) - (E_{23} - E_{22}) = E_{L,HRSG} \) |
|     |           | 22 → 23        | \( E_{x_19} - E_{x_{20}} - (E_{x_{23}} - E_{x_{22}}) = E_{X,HRSG} \) |
| 04  | Turbocharger | 3 → 4          | \( (E_{17} - E_{14}) - (E_4 - E_{13}) = E_{L,TC} \) |
|     |           | 17 → 18        | \( E_{x_{17}} - E_{x_{14}} - (E_{x_4} - E_{x_{13}}) = E_{X,TC} \) |
| 05  | After cooler | 4 → 5          | \( (E_4 - E_3) - (E_{11} - E_{14}) = E_{L,AC} \) |
|     |           | 14 → 13        | \( E_{x_4} - E_{x_3} - (E_{x_{11}} - E_{x_{14}}) = E_{X,AC} \) |
| 06  | After cooler HE | 13 → 14       | \( (E_{13} - E_{14}) - (E_{15} - E_{12}) = E_{L,AC/HE} \) |
|     |           | 12 → 15        | \( E_{x_{13}} - E_{x_{14}} - (E_{x_{15}} - E_{x_{12}}) = E_{X,AC/HE} \) |
| 07  | Jacket water HE | 9 → 10        | \( (E_9 - E_{10}) - (E_{11} - E_{12}) = E_{L,J/WHE} \) |
|     |           | 12 → 11        | \( E_{x_9} - E_{x_{10}} - (E_{x_{11}} - E_{x_{12}}) = E_{X,J/WHE} \) |
| 08  | Lube oil cooler | 6 → 7         | \( (E_6) - (E_7) = E_{L,LOC}(E_{x_6}) - (E_{x_7}) = E_{X,LOC} \) |

(Continues)
| No. | Component                  | Control volume | Balance equation                                      |
|-----|---------------------------|----------------|-------------------------------------------------------|
| 09  | Lube oil filter           |                | \((E_7) - (E_8) = E_{LOF}(E_x) - (E_x) = E_{LOF}\)   |
| 10  | Feed pump                 |                | \(E_{26,FF} - (E_{22} - E_{21}) = E_{FF}E_{26,FF} - (E_{22} - E_{21}) = E_{FF}\) |
| 11  | Water reservoir pump      |                | \(E_{26,WRP} - (E_{12} - E_{16}) = E_{WRP}E_{26,WRP} - (E_{12} - E_{16}) = E_{WRP}\) |
| 12  | Generator                 |                | \((E_{24}) - (E_{25}) = E_{G}(E_x) - (E_x) = E_{G}\)  |
| 13  | Electrical power distribution |              | \((E_{28}) - (E_{26} + E_{27}) = E_{ph}(E_x) - (E_{26} + E_{27}) = E_{ph}\) |