An innovative integrated CCHP system with water scrubbing-based biogas upgrading unit and molten carbonate fuel cell

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Abstract

The main purpose of this study is to develop an integrated structure of simultaneous generation of electricity and refrigeration as the main product and hot water as a by-product. This proposed structure consists of a water scrubbing biogas upgrading process, molten carbonate fuel cell (MCFC) unit, gas/steam power (GSP) cycle, and absorption refrigeration (AR) system. In this regard, 10.71 kg/s untreated biogas enters the integrated system and 158,351 kW net power is produced. Wasted heat of the structure is utilized to generate cooling of 253.9 kW at a temperature of 243.6 K by applying the AR system and the rest of the heat is used to generate 8.391 kg/s hot water as the system byproducts. The process integration between the different parts has led to an increase in the thermal efficiency of the whole system so that the electrical and overall efficiencies are 78.68% and 79.86%, respectively. The investigation of the exergy study demonstrates that the exergy destruction of the entire structure is 71,859 kW, of which the turbine/compressor/pump section with 24,700 kW (with a share of 34.37% of the total) and MCFC/reformer section with 22,285 kW (with a share of 31.01% of the total) have the most irreversibility. The exergy efficiency of the hybrid structure is 71.06%. Through a parametric study, the present integrated system in various conditions is assessed. One of the results of main outcomes is the increase of overall efficiency up to 83.39% due to the reduction of inlet biogas methane mole content up to 50%. Rising the methane in inlet biogas, although leading to more production of system products, reduces the efficiencies of various parts of the system, including the MCFC unit and GSP cycle, as well as integrated system total efficiency.

Keywords

absorption refrigeration cycle, biogas upgrading cycle, combined power plant, exergy analysis, molten carbonate fuel cell
1 INTRODUCTION

Nowadays, global energy demand is constantly increasing due to population growth, industrialization, and economic growth. On the other hand, the use of fossil fuels has increased global warming due to greenhouse gas (GHG) emissions. Environmental concerns as well as the non-renewability of fossil fuels have led scientists to use renewable fuels. Biomass is one of the most important renewable energy sources. At present, there has been considerable emphasis on the concept of growth development and maximizing the utilization of biomass in added value products. Biomass fuels can be defined as produced minerals in a renewable process. Almost all available biomass fuels are divided into two groups: wood fuels and animal waste. Municipal solid waste (MSW) is another source of biomass fuels. The combustion of wood fuels to produce steam or electricity power is a well-known technology. Forest and agricultural residues are an example of wood fuels. The most important application of biomass is energy production. Biomass can be converted to many biofuels, such as methane, ethanol, and biodiesel. Different industry methods are common for applying the biomass, one of which involves processes that use the whole biomass as a raw material in thermal conversion processes in which the basic structure and composition of the biomass have little effect on the obtained fuel. The use of heat in the presence or absence of oxygen to convert biomass into various forms of energy is called a thermal conversion. Degassing and pyrolysis are the two main options for this type of process. High temperature and the great variety of products are the characteristics of this type of process. Zhang et al. reviewed the principles of reactions and applications of the four basic thermal processes called combustion, pyrolysis, degassing, and liquefaction for biological production. Some advanced thermal processes, including simultaneous combustion, biomass combustion with coal or natural gas (NG), rapid gas decomposition, plasma degassing, and supercritical degassing of water are introduced, then in terms of pros and cons, their potential for plans and challenges of these processes are discussed. Plasma techniques have great potential for the purification of hazardous wastes due to the destruction of any type of waste. As mentioned, the gasification process is one of the thermal processes in which raw materials are converted into combustible gases at high temperatures and pressures. One of the products of this process is synthesis gas. Synthesis gas is not the end product of the process. Of course, this gas can be used to generate heat or steam, but in most processes, it is necessary to convert the synthesis gas to methane, methanol, ethanol, or the necessary chemicals. Biogas is produced from organic raw materials by anaerobic digestion. This four-step process includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The composition of produced biogas depends on the type of technology and the type of input feed. Biogas mainly consists of methane (CH₄) (50%–75%), carbon dioxide (CO₂) (25%–50%) hydrogen sulfides (H₂S), hydrogen (H₂), ammonia (NH₃) (1%–2%), and traces of other gases such as oxygen (O₂) and nitrogen (N₂). The presence of impurities such as CO₂ and H₂S negatively affects its performance. Biomethane with approximately 98% methane is obtained from biogas. Biomethane is a promising renewable energy option and a viable alternative to NG in grid and vehicle applications. The use of upgraded biogas is very beneficial in reducing GHG emissions. Several different methods are known for upgrading biogas. Hosseinipour et al. simulated and compared four upgrading methods, including cryogenic separation (CS), water wash, amine scrubbing, and caustic wash with NaOH. The results showed that in the amine scrubbing method, the use of amines for CO₂ uptake is very effective but H₂S uptake is not acceptable compared to other processes. Although they consume less energy but require a lot of heat. However, recycling NaOH was very expensive and consumes a lot of energy. The cryogenic separation method was recommended to upgrade a large amount of biogas. Ansarinasab and Mehrpooya used the concept of advanced exergy and exergoeconomic analyses to evaluate biogas upgrading, that is, high-pressure water scrubbing (HPWS) and cryogenic separation. Water scrubbing is the most widespread technology in the world. However, during the biogas upgrading process, some CH₄ molecules are released through the water leaving the wash column. Kapoor et al. investigated different effective parameters of impurity removal from biogas with the water scrubbing method. Starr et al. evaluated life cycle assessment (LCA) for three biogas upgrading methods (HPWS), alkaline with regeneration (AWR) and bottom ash upgrading (BABIU). It was determined that the AWR process had an 84% higher impact in all LCA categories largely due to the energy-intensive production of the alkaline reactants. AWR and BABIU also have little effect on global warming due to their immediate CO₂ storage. For AWR, using NaOH instead of KOH improves environmental performance by up to 34%. In general, the type of technique that has been used usually depends on economic or possibly ecological issues. Also, achieving the highest amount of methane is an important factor in choosing the type of process. Biomethane can be used as a fuel in all types of cycles and power plants. Mehrpooya et al. presented an hybrid system consisting of the water scrubbing biogas upgrading (WSBU) process with water regeneration, flat plate collectors, and Kalina
cycle. The WSBU process was capable of removing H₂S and CO₂ and produces upgraded biogas with a mass flow rate of 2293 kg/h. The exergy efficiency of the proposed integrated system was 92.36%.

One of the superior technologies in the field of exploitation of renewable sources is the use of fuel cells. The fuel cell is a relatively novel technology for energy production that generates high-efficiency electrical energy from a direct combination of fuel and oxidizer without causing environmental or noise pollution. The fuel cell removes the pollution caused by the burning of fossil fuels and water is its only byproduct. A new integrated locomotive system including an internal combustion engine, molten carbonate fuel cell (MCFC), gas turbine, and absorption refrigeration (AR) system was developed by Seyam et al. Exergy, economic and environmental analyzes were used to evaluate the integrated structure. The entire levelized capital cost and exergetic yield in the Integrated locomotive scheme have 32.15 $/h and more than 83%, respectively. Carrette et al. studied the principles and applications of fuel cells by emphasizing the benefits of fuel cells compared to conventional techniques. Then, various kinds of fuel cells and the comparison of theoretical and actual efficiency of fuel cells with combustion engines were discussed. The use of high-temperature fuel cell systems such as solid oxide and molten carbonate fuel cells (MCFCs) increases the electrical efficiency of hybrid power plants. The MCFC unit produces power through hydrogen and oxygen as input feed. Akrami et al. designed a hybrid system consisting of a downdraft gasifier, a gas turbine, MCFC, an organic Rankine plant, and a CO₂ separation unit based on refrigeration with MSW inlet fuel. This hybrid configuration was evaluated from a thermodynamic, economic and environmental perspective. Multi-objective optimization was employed to increase exergy efficiency and decrease CO₂ emissions and electricity costs. Polymer electrolyte membrane fuel cells (PEMFCs), which utilize hydrogen as their fuel, are fuel cell pioneers that perform well in many applications, such as the automotive industry. However, hydrogen fuel is usually stored at high pressures. Failure to use hydrogen properly can lead to accidents such as explosions. Direct liquid fuel cells can be one of the most promising types of fuel cells due to their high energy density, simple system, and small fuel cartridge. Seyam et al. designed an integrated system consisting of a gas turbine and the MCFC with an internal combustion engine with environmentally friendly fuels in the ASPEN PLUS environment. The fuels used in the integrated structure include hydrogen, ethanol, methanol, and dimethyl ether. The thermal and exergy yields were calculated at 43% and 55%, respectively. Koroglu et al. proposed a PEM fuel cell/biogas purification cycle that utilized dairy wastewater with subsequent biogas purification to produce Biohydrogen. Biohydrogen has been employed as a fuel in the PEM fuel cell. Rashidi et al. reviewed the performance of a hybrid system including the turboexpander and MCFC installed in Toronto, Canada. The thermodynamic analysis of the system demonstrated that the energy efficiency of the whole structure was obtained by 60%. Jienkulsawad and Arpornwichanop designed hybrid solid oxide fuel cell (SOFC) and MCFC systems to produce power using CO₂ and fuel. In the hybrid system, SOFC acted as a primary power generator and MCFC was used from the exhaust gas of SOFC and afterburner. Kang et al. modeled a hybrid configuration including the MCFC unit and examined the effect of key parameters on system efficiency. The results showed that for high efficiency, the MCFC unit should be utilized as a combined power plant, also operating conditions, fuel, oxidant utilization, and cathode recycle ratio influence the cycle performance.

So far, numerous hybrid systems have been evaluated for the production of power and refrigeration employing gas/steam combined power plants and AR units. According to research in the literature, most research has been done on the usage of refined biogas in the trigeneration systems of power, refrigeration, and heat, which leads to the increase of CO₂ production. As a proposed solution to increase efficiency and reduce CO₂, refined biogas can be used in fuel cell units to generate power and heat. Also, wasted heat from fuel cell units can be utilized in the CCHP systems. In this study, a CCHP structure based on the MCFC unit for the trigeneration of power, refrigeration, and hot water with WSBU process, gas/steam combined power plant, and the AR plant is introduced. The water scrubbing method is used for the biogas purification and the resulting biomethane with a purity of 96 mol% is used as fuel in the MCFC to produce power and heat. Wasted energy is utilized for heat supply in the gas/steam combined power plant and cooling system. Energy, exergy, and sensitivity investigations are employed to study the proposed hybrid structure.

2 | PROCESS DESCRIPTION

The development of hybrid systems for tri-generation of power, heat, and refrigeration decreases the number of components and increases efficiency. Figure 1 illustrates
the hybrid system for the generation of power, cooling, and hot water by biogas. The system consists of four main parts:

1. Biogas upgrading cycle
2. MCFC cycle
3. Combined cycle power plant
4. AR cycle

According to the presented block flow diagram, after upgrading of biogas with a purity of 96% methane, it enters the MCFC cycle as feed. Biomethane is known as one of the renewable energies that is a suitable alternative to natural gas. The use of biogas upgraded also plays an important role in reducing the emission of environmental pollutants. As shown in the figure, a suitable approach to utilize biogas for the generation of power, hot water, and cooling is depicted. Table 1 contains the molar composition of some essential streams nominated in the proposed configuration in this investigation. Table 2 shows the operating conditions of each system flows, according to the process flow diagram of the system (Figure 2). Basic information for modeling any stream in software including temperature, pressure, molar flow, and composition is extracted from the structures developed in articles and industrial patents, which are mentioned in the process description and validation section.

2.1 Biogas upgrading cycle

As mentioned, the fermentation of wood, animal, and municipal waste can be used as feed for the biogas system. The composition of produced biogas depends on the type of feed and usually includes CH₄, CO₂, N₂, O₂, H₂S. To use biogas in heat and power production cycles, methane with a purity of more than 90% needs to be upgraded under the name of biomethane. Impurities such as CO₂ and H₂S must also be separated, in which various technologies such as HPWS, cryogenic separation, membrane separation, organic physical scrubbing, chemical scrubbing, and pressure swing adsorption can be used. In this study, the biogas upgrading method was used to produce biomethane by water scrubbing. The WSBU process is based on Henry’s law, which refers to more solubility of H₂S and CO₂ in water than methane. Figure 2 depicts the process flow diagram of a hybrid process. As can be seen, the feed stream (B1) enters the biogas upgrading cycle with a purity of approximately 60%. First, the C₂ compressor increases the stream B1 pressure to 800 kPa and increases the temperature to 466.4 K, which can be used as a heat source in the reboiler to launch the AR cycle. Since the operating temperature of the water scrubbing process is lower than 313 K based on literature, the stream loses its excess heat after passing through HE1. It is also observed that the solubility of CO₂ increments at low temperatures. The cooled and compressed biogas at 209 K, enters the absorption column (T100) from below, while water is sprayed from above (stream B10). Upgraded biogas with 96% purity and flow rate of 4.191 kg/s come out from the T100 column (stream B11). To remove water impurities, stream B5 enters the flash drum and stream B7 enters the T200 column, while high-pressure air (stream F18) enters the T200 column. After the dissolved gases in the water are separated, the dissolved gases with air are released from the top of the regeneration column. Then the pure water (stream B9) is compressed through pump P5 and returned to the T100 column. Information about the initial simulation of the WSBU process is extracted from Reference [31].

2.2 MCFC cycle

Biogas enters the MCFC power generation cycle after being converted to biomethane. In the MCFC, the
chemical energy of biomethane is converted to power. At the cathode, $\text{CO}_3^{2-}$ ions are produced and then at the anode, $\text{CO}_3^{2-}$ ions, after reacting with $\text{H}_2$, produce electrons. Biomethane (stream B12) and water steam (N3) are mixed at 14.87 kg/s. Then the mixture stream (N4) enters exchanger HE20 to preheat. Afterward, stream M1 enters the reformer at 571 K to generate the required $\text{H}_2$. The $\text{H}_2$ production reaction is as follows:\cite{12, 33}:

\begin{equation}
\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2, \tag{1}
\end{equation}

\begin{equation}
\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2. \tag{2}
\end{equation}

Eventually:

\begin{equation}
\text{CH}_4 + 2\text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 4\text{H}_2. \tag{3}
\end{equation}

| Stream | $\text{N}_2$ | $\text{H}_2\text{O}$ | $\text{NH}_3$ | $\text{CH}_4$ | $\text{H}_2\text{S}$ | $\text{CO}_2$ | $\text{O}_2$ | $\text{CO}$ | $\text{H}_2$ | $\text{C}_2\text{H}_4$ | Carbonate ion |
|--------|--------------|------------------------|---------------|----------------|----------------|----------------|----------------|----------------|---------------|----------------|----------------|
| N1     | 1            | 0                      | 0             | 0             | 0             | 0              | 0              | 0              | 0             | 0              | 0              |
| N4     | 0.0047       | 0.7649                 | 0             | 0.2268        | 0             | 0              | 0.0037         | 0              | 0             | 0              | 0              |
| N5     | 0.7900       | 0.0000                 | 0             | 0             | 0             | 0              | 0.2100         | 0              | 0             | 0              | 0              |
| N7     | 0.6737       | 0.2748                 | 0             | 0             | 0             | 0.0002         | 0.0509         | 0.0001         | 0.0003        | 0.0001         | 0              |
| N8     | 0.6737       | 0.2748                 | 0             | 0             | 0             | 0.0002         | 0.0508         | 0.0001         | 0.0003        | 0.0001         | 0              |
| N10    | 0.6737       | 0.2748                 | 0             | 0             | 0             | 0.0002         | 0.0508         | 0.0001         | 0.0003        | 0.0001         | 0              |
| M1     | 0.0047       | 0.7649                 | 0             | 0.2268        | 0             | 0              | 0.0037         | 0              | 0             | 0              | 0              |
| M2     | 0.0039       | 0.4730                 | 0             | 0.1066        | 0             | 0.0827         | 0.0031         | 0.3307         | 0              | 0              | 0              |
| M4     | 0.0008       | 0.1456                 | 0             | 0.0023        | 0             | 0.0821         | 0.0007         | 0.0207         | 0.0693        | 0              | 0.6785         |
| M6     | 0.6625       | 0.2726                 | 0             | 0             | 0             | 0.0016         | 0.0500         | 0.0004         | 0.0014        | 0              | 0.0114         |
| M12    | 0            | 0                      | 0             | 0             | 0             | 0              | 0              | 0              | 0             | 0              | 0              |
| B1     | 0.0097       | 0                      | 0.0003        | 0.6073        | 0.0082        | 0.3649         | 0.0097         | 0              | 0              | 0              | 0              |
| B5     | 0            | 0.9976                 | 0.0017        | 0             | 0.0000        | 0.0007         | 0              | 0              | 0              | 0              | 0              |
| B6     | 0.0120       | 0.0021                 | 0.0001        | 0.7471        | 0.0015        | 0.2253         | 0.0119         | 0              | 0              | 0              | 0              |
| B7     | 0            | 0.9976                 | 0.0017        | 0             | 0             | 0.0007         | 0              | 0              | 0              | 0              | 0              |
| B8     | 0.7270       | 0.0103                 | 0.0006        | 0             | 0.0015        | 0.0672         | 0.1934         | 0              | 0              | 0              | 0              |
| B10    | 0            | 0.9983                 | 0.0017        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| B11    | 0.0198       | 0.0021                 | 0.0001        | 0.9624        | 0             | 0              | 0.0156         | 0              | 0              | 0              | 0              |
| F11    | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| F10    | 0.6737       | 0.2748                 | 0             | 0             | 0             | 0.0002         | 0.0508         | 0.0001         | 0.0003        | 0.0001         | 0              |
| F17    | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| F18    | 0.7900       | 0                      | 0             | 0             | 0             | 0.2100         | 0              | 0              | 0              | 0              | 0              |
| A1     | 0            | 0.7393                 | 0.2607        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A3     | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A5     | 0            | 0.7500                 | 0.2500        | 0             | 0             | 0              | 0.0009         | 0.9991         | 0              | 0              | 0              |
| A7     | 0            | 0.0603                 | 0.9397        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A10    | 0            | 0.2334                 | 0.7666        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A11    | 0            | 0.0009                 | 0.9991        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A12    | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| A22    | 0            | 0.9339                 | 0.0661        | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| W1     | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| W3     | 0            | 1                      | 0             | 0             | 0             | 0              | 0              | 0              | 0              | 0              | 0              |
| Stream | Temperature (K) | Pressure (kPa) | Molar enthalpy (kJ/kmol) | Molar entropy (kJ/kmol·K) | Molar flow (kmol/h) | Mass flow (kg/s) | Exergy (kW) |
|--------|----------------|---------------|--------------------------|---------------------------|---------------------|----------------|-------------|
| B1     | 323.2          | 200.0         | −188,476.0               | 182.7                     | 1445.9              | 10.71          | 209,587.6   |
| B2     | 466.4          | 800.0         | −182,713.1               | 185.9                     | 1445.9              | 10.71          | 211,518.5   |
| B3     | 429.2          | 800.0         | −184,319.7               | 182.3                     | 1445.9              | 10.71          | 211,303.0   |
| B4     | 299.2          | 800.0         | −189,510.1               | 168.0                     | 1445.9              | 10.71          | 210,937.7   |
| B5     | 283.6          | 600.0         | −287,243.7               | 49.5                      | 723,488.5           | 3624.01        | 2,482,365.4 |
| B7     | 283.6          | 600.0         | −287,243.7               | 49.5                      | 723,488.5           | 3624.01        | 2,482,362.8 |
| B8     | 283.6          | 120.0         | −29,468.9                | 153.1                     | 7850.5              | 64.89          | 6068.0      |
| B9     | 283.6          | 120.0         | −287,170.7               | 150.7                     | 14,670.6            | 117.57         | 684.1       |
| N1     | 298.2          | 101.0         | −286,355.9               | 53.3                      | 2960.0              | 14.81          | 9628.2      |
| N2     | 298.2          | 250.0         | −236,409.7               | 180.8                     | 2960.0              | 14.81          | 19,439.4    |
| N3     | 460.0          | 250.0         | −197,960.4               | 184.4                     | 3872.4              | 19.00          | 222,314.7   |
| N4     | 414.8          | 250.0         | −287,960.4               | 184.4                     | 3872.4              | 19.00          | 222,314.7   |
| N5     | 288.2          | 101.4         | −298.5                   | 150.7                     | 14,670.6            | 117.57         | 684.1       |
| N6     | 399.8          | 250.0         | −298.5                   | 150.7                     | 14,670.6            | 117.57         | 11,490.6    |
| N7     | 1047.6         | 250.0         | −41,897.8                | 194.6                     | 1,282,236.4         | 9069.72        | 6,880,682.9 |
| F1     | 854.7          | 87.0          | −48,617.5                | 196.3                     | 17,236.4            | 121.92         | 39,251.0    |
| F2     | 785.5          | 87.0          | −50,965.4                | 193.4                     | 17,236.4            | 121.92         | 32,098.3    |
| F3     | 628.2          | 87.0          | −56,181.2                | 186.0                     | 17,236.4            | 121.92         | 17,696.9    |
| F4     | 553.0          | 87.0          | −58,611.4                | 181.9                     | 17,236.4            | 121.92         | 11,943.0    |
| F5     | 544.4          | 87.0          | −58,884.4                | 181.4                     | 17,236.4            | 121.92         | 11,346.1    |
| F6     | 419.4          | 87.0          | −62,831.7                | 173.2                     | 17,236.4            | 121.92         | 4199.6      |
| F7     | 417.7          | 87.0          | −62,828.4                | 173.1                     | 17,236.4            | 121.92         | 4129.7      |
| F8     | 416.6          | 87.0          | −62,919.0                | 173.0                     | 17,236.4            | 121.92         | 4080.0      |
| F9     | 405.3          | 87.0          | −63,269.5                | 172.1                     | 17,236.4            | 121.92         | 3619.6      |
| F10    | 348.8          | 87.0          | −65,014.9                | 167.5                     | 17,236.4            | 121.92         | 1882.9      |
| F11    | 840.0          | 8686.0        | −223,693.1               | 124.7                     | 3408.5              | 17.06          | 36,582.1    |
| F12    | 322.8          | 12.0          | −245,428.0               | 132.2                     | 3408.5              | 17.06          | 13,888.9    |
| F13    | 508.2          | 750.0         | −235,119.7               | 126.3                     | 1748.0              | 8.75           | 12,981.5    |
| F14    | 322.8          | 12.0          | −246,108.8               | 130.1                     | 1748.0              | 8.75           | 7097.6      |
| F15    | 322.8          | 12.0          | −245,658.7               | 131.5                     | 5156.5              | 25.80          | 20,986.5    |
| F16    | 315.4          | 326.0         | −284,543.8               | 10.8                      | 976,960.4           | 4888.90        | 3,185,220.2 |
| F17    | 318.1          | 252.0         | −284,339.9               | 11.5                      | 976,960.4           | 4888.90        | 3,187,578.9 |
| F18    | 298.2          | 120.0         | −8.1                     | 150.3                     | 7229.6              | 57.94          | 1165.3      |
| F19    | 318.8          | 9.8           | −284,291.8               | 11.6                      | 5156.5              | 25.80          | 16,822.2    |
| F20    | 318.9          | 1853.0        | −284,254.6               | 11.7                      | 5156.5              | 25.80          | 16,870.3    |
| F21    | 396.2          | 600.0         | −278,420.4               | 28.1                      | 5156.5              | 25.80          | 18,204.6    |
| F22    | 411.4          | 350.0         | −277,248.9               | 31.0                      | 5156.5              | 25.80          | 18,643.5    |
| F23    | 411.4          | 350.0         | −277,248.9               | 31.0                      | 5156.5              | 25.80          | 6319.8      |

(Continues)
The released heat by the reformer is sent to the catalytic burner (R100). Stream M3 enters the anode along with stream M12. The reactions that occur in the MCFC are as follows:

Cathode side reaction:

$$\text{CO}_2 + 0.5 \text{O}_2 + 2\overline{e} \rightarrow \text{CO}_3^{2-}. \quad (4)$$

Anode side reaction:

$$\text{CO}_3^{(-2)} + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{CO}_2 + 2\overline{e}. \quad (5)$$

The overall reaction:

$$\text{H}_2 + 0.5 \text{O}_2 \rightarrow \text{H}_2\text{O}. \quad (6)$$

Unreacted fuel exits the anode (stream M4) and enters the catalytic burner after mixing with stream N8. The output stream (M7) is mixed with the compressed air (stream N6) and fed to the cathode. The output stream from the cathode (M11) enters the splitter and is divided into two parts. The stream M12 is fed to the anode and the stream N9 enters the Tur1 turbine at a pressure of 250 kPa and a temperature of 1048 K.

| Stream | Temperature (K) | Pressure (kPa) | Molar enthalpy (kJ/kmol) | Molar entropy (kJ/kmol·K) | Molar flow (kmol/h) | Mass flow (kg/s) | Exergy (kW) |
|--------|----------------|----------------|--------------------------|---------------------------|---------------------|------------------|-------------|
| F24    | 411.4          | 350.0          | −277,248.9               | 31.0                      | 3408.5              | 17.06            | 12,323.7    |
| F25    | 412.6          | 9006.5         | −277,059.5               | 31.1                      | 3408.5              | 17.06            | 12,488.9    |
| F26    | 445.0          | 810.0          | −237,812.0               | 120.0                     | 1748.0              | 8.75             | 12,579.3    |
| F27    | 411.5          | 860.0          | −277,235.5               | 31.0                      | 1748.0              | 8.75             | 6325.1      |
| F28    | 418.0          | 835.0          | −276,736.0               | 32.2                      | 1748.0              | 8.75             | 6393.6      |
| A1     | 327.3          | 120.0          | −225,211.1               | 80.6                      | 260.0               | 1.28             | 10,876.7    |
| A2     | 305.1          | 120.0          | −230,824.9               | 62.9                      | 260.0               | 1.28             | 10,854.0    |
| A3     | 298.2          | 200.0          | −285,010.0               | 6.6                       | 3878.6              | 19.41            | 12,618.1    |
| A4     | 303.2          | 190.0          | −284,634.6               | 7.9                       | 3878.6              | 19.41            | 12,621.2    |
| A5     | 305.2          | 1300.0         | −230,794.3               | 62.9                      | 260.0               | 1.28             | 10,856.0    |
| A6     | 399.9          | 1300.0         | −222,020.4               | 87.5                      | 260.0               | 1.28             | 10,958.7    |
| A7     | 377.4          | 1300.0         | −55,228.9                | 159.0                     | 72.8                | 0.35             | 10,537.7    |
| A8     | 318.6          | 1300.0         | −64,434.9                | 132.3                     | 72.8                | 0.35             | 10,512.4    |
| A9     | 243.9          | 120.0          | −49,462.0                | 155.6                     | 54.2                | 0.26             | 8243.4      |
| A10    | 318.6          | 1300.0         | −118,519.5               | 79.9                      | 18.6                | 0.09             | 2191.6      |
| A11    | 318.6          | 1300.0         | −45,883.0                | 150.3                     | 54.2                | 0.26             | 8320.8      |
| A12    | 298.2          | 200.0          | −285,010.9               | 6.6                       | 1781.3              | 8.91             | 5795.2      |
| A13    | 303.2          | 190.0          | −284,634.6               | 7.9                       | 1781.3              | 8.91             | 5796.6      |
| A14    | 307.1          | 1300.0         | −66,320.8                | 83.9                      | 54.2                | 0.26             | 8311.6      |
| A15    | 248.7          | 1300.0         | −71,072.0                | 66.7                      | 54.2                | 0.26             | 8316.9      |
| A16    | 243.6          | 120.0          | −71,072.0                | 66.9                      | 54.2                | 0.26             | 8316.2      |
| A17    | 243.7          | 120.0          | −54,213.2                | 136.1                     | 54.2                | 0.26             | 8259.4      |
| A18    | 310.2          | 1300.0         | −271,519.3               | 59.2                      | 205.8               | 1.03             | 2662.6      |
| A19    | 310.4          | 120.0          | −271,519.3               | 59.2                      | 205.8               | 10.71            | 2661.2      |
| A20    | 298.2          | 200.0          | −285,010.9               | 6.6                       | 2944.6              | 10.71            | 9579.7      |
| A21    | 303.2          | 190.0          | −284,634.6               | 7.9                       | 2944.6              | 10.71            | 9582.1      |
2.3 Combined cycle power plant

The combined cycle power plant has received a lot of attention due to its high efficiency compared to the Rankine and Brayton cycles.35,36 This section includes a gas turbine, three pumps, two heat recovery steam generators (HRSG), two steam turbines, a feedwater heater, and a deaerator. The plant is capable of generating 58,340 kW of electricity, which is 25,914 kW of power generated by steam turbines. In fact, in the power plant, the waste heat in the exhaust gases from the gas turbine is used by using the HRSG to produce the required superheated steam in steam turbines. The HRSG is important and critical equipment of a combined cycle power plant that connects the gas turbine system to the steam cycle. The output stream from the gas turbine (N10) enters the HRSG at 870 K. The HRSG has three components: superheater, evaporator, and economizer. Each of these components has a high pressure (HP) and low pressure (LP) component. The stream N10 passes through the HE4 superheater and then enters the HP evaporator and the temperature decreases. At the same time, the saturated liquid (stream F30), in this part, becomes saturated vapor. The exhaust gas of the HE5 heat exchanger enters the HP economizer (HE6). In this section, the lost heat of stream F3 is used to heat the water (F29) to saturation temperature. The gas leaving the HE6 heat exchanger enters the LP superheater and this time all the above steps are performed at a pressure of 800 kPa. High-pressure HRSG steam enters the Tur2 turbine at 840 K and 8686 kPa, and HRSG low-pressure steam enters the Tur3 turbine at 508 K and 750 kPa, producing 20,578 and 5336 kW of power, respectively. The streams coming out of the steam turbines are pumped by the P2 pump while liquefying in the condenser (HE13). The stream F20 is first preheated by the feedwater heater and then enters the deaerator. Each of the streams F23 and F24 is compressed by separating the P3 and P1 pumps up to 860 and 9007 kPa, respectively, and enters the high-pressure and low-pressure sections of the HRSG, completing the cycle. Information on the design of the gas/steam power (GSP) cycle is supplied in Reference [36].

2.4 AR system

The purpose of this section is to produce cold energy. The ammonia-water solution is the most widely used working fluid for refrigeration production. The mixture of water
and ammonia enters the P4 pump after passing the HE14 exchanger, the pressure of which increases the operating pressure of the generator. A column and a reboiler are utilized to model the generator and a cooler and flash drum (column condenser) as the rectifier. The heat required to separate the refrigerant (ammonia) and absorbent (water) in the generator is provided by stream B2, which exits the C2 compressor. Before entering the generator, the high-pressure mixture (A5), which contains 25% ammonia and 75% water, passes through the HE13 heat exchanger. The HE13 retrieves the heat energy of the generator output stream to increase the mixing temperature, which enhances the coefficient of performance (COP). Ammonia evaporates at a concentration of more than 99.9 mol% in the generator and then enters the rectifier and then the condenser (HE18) to decrease the problems that may occur in the evaporator to reduce its water content. The ammonia in the condenser is completely liquefied and enters the HE17 exchanger. Water is used as a coolant in the rectifier and condenser. The stream A15 enters the V1 expansion valve and as a result, the temperature and pressure are reduced to the required amount of cooling (120 kPa, 243.6 K). Then, under the name stream A16, it enters the evaporator and supplies the required cooling. Information about the structure and stream characteristics for the initial simulation of the GSP cycle is provided in Reference [37].

3 | PROCESS SIMULATION

The presented integrated structure in this study has been modeled using the HYSYS package and m-file code (MATLAB programming). The first step in thermodynamic simulation is to define the state equation based on the compositions of each stream in each section. The state equations of Soave–Redlich–Kwong (SRK) and Peng–Robinson are employed to simulate WSBU structure and GSP unit, respectively. Based on studies, the Peng–Robinson and SRK thermodynamic equations are the best choices for simulating the AR cycle and the MCFC cycle, respectively. MATLAB software has also been applied for parametric studies and exergy analysis. The used hypotheses in the simulation are presented in the following:

- Environmental conditions are considered at 298 K temperature and 101.3 kPa pressure.
- The proposed structure in HYSYS software works in a steady state. All process components are assessed insulated, tube connections are supposed to be ideal and tubes pressure decreases are ignored.

- Heat dissipation is ignored in the equipment utilized for pressure change and heat transfer.
- The package of distillation tower and reboiler (generator) is employed in HYSYS software to separate water from ammonia.

Also, Table 3 illustrates the characteristics of the equipment used in the integrated system for the cogeneration of power and cooling. Preliminary information to determine the specifications of the equipment used in the hybrid structure developed has been extracted from References [31,36,37], which are presented in detail in the subsections.

3.1 | MCFC

In the MCFC unit, chemical energy is converted to power. As described in the previous section, the cathode produces carbonate ions through a chemical reaction between oxygen, CO2, and electrons. The carbonate ion reaches the anode through the electrolyte and eventually reacts with hydrogen to generate water vapor, carbon dioxide, and electrons. The parameter values used in the MCFC simulation are presented in Table 4 that the initial input data for the MCFC simulation in HYSYS software and m-file code are extracted from References [32,34].

The hypotheses employed to model the MCFC are as follows:

- The MCFC unit is developed based on a one-dimensional sample in HYSYS software and m-file code. The developed MCFC unit is employed in the combined structure based on steady states. In the MCFC, the anode, reforming reactions, and cathode are modeled utilizing reactors of the conversion, plug, and conversion.
- The MCFC performance was calculated based on nominal temperature.
- The temperature distribution along the MCFC unit is also neglected.
- The composition of the inlet air in the MCFC cathode is considered to be 21 mol% oxygen and 79 mol% nitrogen.

The thermodynamic relationships of fuel cell electrodes and their simulation have already been discussed in HYSYS software, but their power output must be calculated with the relationships that model cell electrochemically. If V is the actual voltage and \( E_{\text{Nerst}} \) is the ideal reversible voltage, then the actual output voltage of the MCFC can be obtained by subtracting the polarization losses from the ideal voltage.34,38
| Pump | Isentropic efficiency (%) | Power (kW) | ΔP (kPa) | Pressure ratio |
|------|--------------------------|------------|----------|---------------|
| P1   | 90.00                    | 179.4      | 8657     | 25.73         |
| P2   | 90.00                    | 53.29      | 1843     | 189.1         |
| P3   | 75.00                    | 6.504      | 510.0    | 2.457         |
| P4   | 85.00                    | 2.114      | 1180     | 10.83         |
| P5   | 72.00                    | 1877       | 380.0    | 4.167         |
| P6   | 60.00                    | 3.652      | 149.0    | 2.475         |
| Compressor | Isentropic efficiency (%) | Power (kW) | ΔP (kPa) | Pressure ratio |
| C1   | 75.00                    | 13,394     | 148.6    | 2.465         |
| C2   | 75.00                    | 2315       | 600      | 4.000         |
| Turbine | Isentropic efficiency (%) | Power (kW) | ΔP (kPa) | Pressure ratio |
| Tur1  | 77                       | 32,667     | 172      | 0.3120        |
| Tur2  | 90                       | 20,579     | 8674     | 0.0014        |
| Tur3  | 90                       | 5336       | 738      | 0.0160        |
| Heat exchanger | Minimum approach(K) | LMTD (K) | Duty (kW) | Cold Pinch temp (K) |
| HX1   | 1.000                    | 17.63      | 2085     | 25.00         |
| HX2   | 8.150                    | 37.99      | 41,063   | 186.9         |
| HX3   | 30.00                    | 49.01      | 2503     | 566.9         |
| HX4   | 74.72                    | 131.2      | 11,242   | 506.9         |
| HX5   | 65.80                    | 121.6      | 24,973   | 289.2         |
| HX6   | 65.80                    | 97.46      | 11,636   | 289.2         |
| HX7   | 44.80                    | 67.15      | 1307     | 235.0         |
| HX8   | 1.359                    | 23.24      | 18,899   | 144.9         |
| HX9   | 1.359                    | 3.192      | 242.6    | 144.9         |
| HX10  | 2.732                    | 3.321      | 175.4    | 141.9         |
| HX11  | 5.122                    | 6.936      | 1678     | 138.3         |
| HX12  | 9.135                    | 17.52      | 8357     | 123.0         |
| HX13  | 3.413                    | 4.011      | 55,337   | 42.20         |
| HX14  | 5.000                    | 15.86      | 633.7    | 32.03         |
| HX15  | 6.910                    | 13.54      | 405.4    | 25.00         |
| HX16  | 20.49                    | 40.45      | 186.2    | 25.00         |
| HX17  | 5.141                    | 7.232      | 307.8    | 29.00         |
| HX18  | 5.000                    | 23.53      | 71.56    | −29.50        |
| HX19  | 312.0                    | 317.7      | 6371     | 298.0         |
| Column | Number of stages | Tray/packed space (m) | Tray/packed volume (m³) |
| T100  | 10                       | 0.5000     | 0.8836   |
| T200  | 10                       | 0.5000     | 0.8836   |
| T300  | 6                        | 0.5500     | 0.9719   |
The Gibbs free energy difference depends on the temperature of the fuel cell. \( T \) is the average temperature of the fuel cell. Finally, the ideal reversible voltage is calculated as follows:

\[
E_{\text{Nernst}} = \frac{\Delta G}{n_e F} + R T \ln \left( \frac{P_{\text{H}_2,\text{an}} \times (P_{\text{O}_2,\text{ca}})^{1/2} \times P_{\text{CO}_2,\text{ca}}}{P_{\text{H}_2,\text{O}_2,\text{an}} \times P_{\text{CO}_2,\text{O}_2,\text{an}}} \right)
\]  

(13)

where the constant \( R \) of the gases is equal to 8.314 J/mol·K. The MCFC output power is also evaluated as follows \(^{34} \):

\[
\text{Power} = n_{\text{cells}} \times A_{\text{cell}} \times j \times V,
\]

(14)

where \( n \) is the number of cells and \( A \) is the cell active area.

3.2 Distillation column

Column design and performance calculations are done under constant conditions for each column. Based on the principle of conservation of mass in the steady-state, the amount of mass entering the column is equal to the mass leaving the column. A schematic of a general distillation column tray is shown in Figure 3. All of the used equations to show the constant performance of the distillation are named the

**TABLE 4** MCFC model input data and results\(^{32,34} \)

| Parameter                 | Value     |
|---------------------------|-----------|
| Current density (mA/cm\(^2\)) | 60.10     |
| Fuel utilization          | 0.680     |
| Cell voltage (V)          | 0.910     |
| Net power output (kW)     | 117,570   |
| Effective area per cell (m\(^2\)) | 0.697 |
| Environment temperature (°C) | 25.00    |
| Environment pressure (bar) | 1.000    |
| Fuel flow rate (kmol/h)   | 912.4     |
| Operating temperature (°C) | 666.7    |
| Operating pressure (kPa)  | 250.0     |
| LHV of fuel (MJ/kg)       | 46.72     |
| Inverter efficiency       | 0.9645    |

Abbreviations: LHV, lower heating value; MCFC, molten carbonate fuel cell.
MESH equations, and then by solving these equations, the operating conditions of the distillation are computed simultaneously, these equations are as follows:

Mass balance equations in each tray:

\[ L_{j-1}x_{i,j-1} + V_{j+1}y_{i,j+1} + F_jZ_{i,j} - (L_j + U_j)x_{i,j} - (V_j + W_j)y_{i,j} = 0. \]  

Equilibrium equations in each tray:

\[ E_{ij} = y_{i,j} - k_{ij}x_{i,j} = 0. \]

Summation equations in each tray:

\[ \sum_{i=1}^{c} x_{i,j} - 1 = 0, \]  
\[ \sum_{i=1}^{c} y_{i,j} - 1 = 0. \]

Heat balance equations in each tray:

\[ L_{j-1}H_{L_{j-1}} + V_{j+1}H_{V_{j+1}} + F_jH_F - (L_j + U_j)H_{L_j} - (V_j + W_j)H_{V_j} - Q_j = 0. \]

The inlet of each tray contains one or two phases current with stream \( F_j \), concentration \( z_{i,j} \), temperature \( T_{ij} \), pressure \( P_{ij} \), and enthalpy \( H_{ij} \), respectively. The above equations are solved using the simultaneous correction (SC) method based on the Newton–Raphson method. At first, must arrange the variables and the equations (MESH equations) containing these variables. From the MESH equations, Equation (17) must be multiplied by \( V_j \) and Equation (18) must be multiplied by \( L_j \), which results as follows:

\[ V_j = \sum_{i=1}^{c} v_{i,j}, \]  
\[ L_j = \sum_{i=1}^{c} l_{i,j}. \]

The Mole fraction in the liquid and vapor phase is defined as follows:

\[ y_{i,j} = \frac{y_{i,j}}{V_j}, \]
\[ x_{i,j} = \frac{l_{i,j}}{L_j}. \]

3.3 | Energy analysis

According to the first law of thermodynamic, also known as the law of work and energy survival, for a system going through a cycle, the contour integral of heat is equal to the contour integral of work:

\[ \oint \delta Q = \oint \delta W. \]

This equation represents the first law of thermodynamics for a control mass during a cycle. If the system is allowed to interact with the environment or there is a state change, the system is transferred from its original macroscopic state to another macroscopic state. The energy change for this process, from state \( i \) to \( j \), can be shown as follows:

\[ E_j - E_i = Q_j - W_j, \]
\[ \left( \frac{1}{2}mv_j^2 + m_ju_j + m_jgz_j \right) - \left( \frac{1}{2}mv_i^2 + m_iu_i + m_igz_i \right) = Q_j - W_j. \]

According to the law of conservation of mass and the relation \( h = u + pv \), the first law of thermodynamics is written as follows:

\[ q + \frac{1}{2}v_j^2 + h_j + g\varepsilon_j = w + \frac{1}{2}v_i^2 + h_i + g\varepsilon_i. \]

The thermal efficiency of a cycle is also defined as follows:

\[ \eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{\sum W_T - (\sum W_P + \sum W_C)}{\sum Q_{in}}. \]

If the kinetic energy and potential changes in turbines and pumps or compressors are ignored and also considered adiabatic, according to the first law of thermodynamics and isentropic efficiency, the work of each of these components is defined as follows:

\[ W_T = m_T\eta_T (h_{in,T} - h_{out,T}), \]
\[ W_{P-C} = \frac{m_{P-C}(h_{out,P-C} - h_{in,P-C})}{\eta_{P-C}}. \]
The energy equilibrium equations of the heat exchangers are calculated as follows:

\[ Q_{\text{hot}} = \sum m_{\text{hot}} (h_{\text{out,hot}} - h_{\text{in,hot}}), \]
\[ Q_{\text{cold}} = \sum m_{\text{cold}} (h_{\text{in,cold}} - h_{\text{out,cold}}) = Q_{\text{hot}}. \]  

(31)

Regarding the energy equilibrium and mass conservation in separators and valves, the equilibrium equations are given as follows:

\[ m_{\text{in},S} = m_{\text{out},1S} + m_{\text{out},2S}, \]
\[ m_{\text{in},S} h_{\text{in},S} = m_{\text{out},1S} h_{\text{out},1S} + m_{\text{out},2S} h_{\text{out},2S}, \]
\[ h_{\text{in},V} = h_{\text{out},V}. \]

(32-34)

The equilibrium equations of energy and mass conservation of the reactors are computed as follows:

\[ \sum m_{\text{in},R} = \sum m_{\text{out},R}, \]
\[ \sum m_{\text{in},R} h_{\text{in},R} = \sum m_{\text{out},R} h_{\text{out},R} + Q_{\text{out,R}}. \]  

(35-36)

The electrical and overall efficiencies of the entire proposed system are computed from the following equations:

Total electrical efficiency

\[ \text{Total electrical efficiency} = \frac{\text{Net generated power}}{m \text{ LHV}_{\text{Biogas}}} = \frac{Q_{\text{in}}}{m \text{ LHV}_{\text{Biogas}}}. \]

(37)

Total thermal efficiency

\[ \text{Total thermal efficiency} = \frac{\text{Net generated power} + \text{Hot water duty} + \text{Produced cooling duty}}{m \text{ LHV}_{\text{Biogas}}}. \]

(38)

AR cycle performance is also determined by the amount of refrigeration that can be produced based on a specific amount of energy consumption. For this purpose, the parameter (COP) is defined as follows:

\[ \text{COP} = \frac{Q_{\text{evaporator}}}{Q_{\text{generator}} + W_{P4}}. \]

(39)

### 3.4 Exergy analysis

Exergy examination is performed to improve the energy utilization and irreversibility of the structure according to the second law of thermodynamic. Exergy is the maximum useful work that a device can produce. In any process, irreversibility can be defined as follows:

\[ I = |(W_{\text{rev}} - W_{\text{real}})|. \]

(40)

Exergy destruction is also obtained from the following relation:

\[ E_{\text{des}} = T_{0} S_{\text{gen}}. \]

(41)

Exergy flow can be divided into four sections: chemical, physical, kinetic, and potential exergies. Excluding a small amount of kinetic and potential exergy, specific exergy can be described as follows:

\[ e_{x} = e_{x}^{\text{PH}} + e_{x}^{\text{CH}}, \]
\[ e_{x}^{\text{PH}} = (h - h_{0}) - T_{0} (s - s_{0}), \]
\[ e_{x}^{\text{CH}} = \sum x_{i} e_{x_{i}}^{0}, \]

(42-44)

which \( e_{x}^{\text{PH}} \) and \( e_{x}^{\text{CH}} \) are specific physical exergy and specific standard chemical exergy, respectively. In these relations, index 0 corresponds to the standard conditions, \( T \), temperature, \( s \), entropy, and \( e_{x_{i}}^{0} \), the chemical exergy of the components of the ideal mixture, then:

\[ e_{x}^{\text{CH}} = \sum x_{i} e_{x_{i}}^{0} + \Delta G_{\text{mix}}. \]

(45)

\[ \Delta G_{\text{mix}} \] is the free energy of Gibbs.

\[ \Delta G_{\text{mix}} = G - \sum x_{i} G_{i}, \]

(46)

where \( G \) refers to the Gibbs free energy and \( G_{i} \) defines the Gibbs free energy of equipment at temperature and pressure of the stream. Table 5 shows the equations employed for the exergy investigation of the components.

### 3.5 Integrated structure validation

To validate the integrated structure, the partial validation method is used for the subsystems. The three main subsections of the proposed structure include the WSBU process, MCFC unit, and AR system with different structures in the industry and other articles are
compared, and the accuracy of their simulation are confirmed. The mole fraction of the refined biogas and acid gas combinations in the WSBU process developed in the proposed system with References [13,14,18,31] are compared (see Table 6). The characteristics of raw biogas to the biogas treatment system in the present paper and the references are considered constant. The simulation results indicate that the mole fraction of the

| TABLE 5 | Equations used for exergy analysis of the equipment in the integrated structure |
|---------|---------------------------------------------------------------------------------|
| Equipment | Exergy destruction | Exergy efficiency |
| Heat exchangers | $\dot{X}_{\text{des}} = \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = 1 - \frac{\sum (\dot{m} \Delta ex)_{\text{bot}}}{\sum (\dot{m} \Delta ex)_{\text{cold}}}$ |
| Pumps | $\dot{X}_{\text{des}} = \dot{V} + \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\dot{V} (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}}{\dot{V} (\dot{m} \Delta ex)_{\text{in}}}$ |
| Turbine | $\dot{X}_{\text{des}} = -\dot{V} - \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\dot{V} (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}}{\dot{V} (\dot{m} \Delta ex)_{\text{in}}}$ |
| MCFC | $\dot{X}_{\text{des}} = \dot{V} - \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\dot{V} (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}}{\dot{V} (\dot{m} \Delta ex)_{\text{in}}}$ |
| Flash drums and Tank | $\dot{X}_{\text{des}} = \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\sum (\dot{m} \Delta ex)_{\text{out}}}{\sum (\dot{m} \Delta ex)_{\text{in}}}$ |
| Compressors | $\dot{X}_{\text{des}} = -\dot{V} + \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\dot{V} (\dot{m} \Delta ex)_{\text{in}}}{\dot{V} (\dot{m} \Delta ex)_{\text{in}}}$ |
| Reformer | $\dot{X}_{\text{des}} = \dot{Q}_{\text{reformer}} - \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\dot{Q}_{\text{reformer}} (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}}{\dot{Q}_{\text{reformer}} (\dot{m} \Delta ex)_{\text{in}}}$ |
| Expansion valve | $\dot{X}_{\text{des}} = \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}}{\sum (\dot{m} \Delta ex)_{\text{in}}}$ |
| Cycle | $\dot{X}_{\text{des}} = \sum (\dot{m} \Delta ex)_{\text{in}} - \sum (\dot{m} \Delta ex)_{\text{out}}$ | $\eta_{\text{ex}} = \frac{\sum (\dot{m} \Delta ex)_{\text{out}}}{\sum (\dot{m} \Delta ex)_{\text{in}}}$ |

| TABLE 6 | Comparison of methane purity in treated biogas in the present study and recent articles |
| Stream | CH$_4$ | NH$_3$ | H$_2$S | H$_2$O | O$_2$ | N$_2$ | CO$_2$ |
|---------|-------|-------|-------|-------|-------|-------|-------|
| Mehrpooya et al.$^{48}$ | | | | | | | |
| Unrefined biogas | 0.6073 | 0.0003 | 0.0082 | 0 | 0.0097 | 0.0097 | 0.3649 |
| Upgraded biogas | 0.9114 | 0 | 0 | 0.0021 | 0.0129 | 0.0143 | 0.0593 |
| Acid gas | 0 | 0 | 0.0015 | 0.0105 | 0.1981 | 0.7452 | 0.0447 |
| Ansarinasaab et al.$^{14}$ | | | | | | | |
| Unrefined biogas | 0.6076 | 0 | 0.0082 | 0 | 0.0097 | 0.0097 | 0.3649 |
| Upgraded biogas | 0.9187 | 0 | 0 | 0.0027 | 0.0169 | 0.019 | 0.0428 |
| Acid gas | 0.0041 | 0 | 0.0015 | 0.0127 | 0.193 | 0.7265 | 0.0621 |
| Ghorbani et al.$^{31}$ | | | | | | | |
| Unrefined biogas | 0.6073 | 0.0003 | 0.0082 | 0 | 0.0097 | 0.0097 | 0.3649 |
| Upgraded biogas | 0.9624 | 0.0001 | 0 | 0.0021 | 0.0156 | 0.0198 | 0 |
| Acid gas | 0 | 0.0006 | 0.0015 | 0.0103 | 0.1934 | 0.727 | 0.0672 |
| Hosseinipour et al.$^{13}$ | | | | | | | |
| Unrefined biogas | 0.611 | 3 (ppm) | 124 (ppm) | 0 | 0.0098 | 0.0098 | 0.3693 |
| Upgraded biogas | - | - | - | - | - | - | - |
| Acid gas | 0.0044 | 0 | 110 (ppm) | 0 | 0.1927 | 0.7253 | 0.0771 |
| In this paper | | | | | | | |
| Unrefined biogas | 0.6073 | 0.0003 | 0.0082 | 0 | 0.0097 | 0.0097 | 0.3649 |
| Upgraded biogas | 0.9624 | 0.0001 | 0 | 0.0021 | 0.0156 | 0.0198 | 0 |
| Acid gas | 0 | 0.0006 | 0.0015 | 0.0103 | 0.1934 | 0.727 | 0.0672 |
main output stream from the biogas upgrading system with other references is very close. Table 7 presents the validation of the initial MCFC simulation in HYSYS software and MATLAB software compared with References [22,32,49]. The results show that the power production and the number of cells used in the MCFC simulated in this paper are slightly different from the references. This slight difference is related to the composition of inlet natural gas. The accuracy of the AR system has been investigated by comparing the Reference [37] in Table 8. The results demonstrate that the difference in specifications of some simulated streams in HYSYS software with streams of Reference [37] are very little, but its performance coefficient is lower than the reference due to its use in different operating conditions. Figure 4 indicates the comparison of the hybrid system developed in this paper with similar cogeneration structures based on the MCFC.25,27,34,44,50–54 The results demonstrate that the hybrid system developed has higher electrical and overall efficiencies than the investigated structures. One of the main reasons for the high electrical efficiency, thermal efficiency, and exergy efficiency in the integrated structure developed is the use of dissipative heat properly in the power generation cycle.

4 | RESULTS OF INTEGRATED STRUCTURE SIMULATION

The outcomes of the simulation as well as the investigation of the exergy and parametric analyses of the combined system are described in this part. The principal input of the structure is biogas with a mass flow rate of 10.71 kg/s, from which impurities are separated by the WSBU process and enter the MCFC cycle with a purity of 96.20 mol%. 4.193 kg/s methane enters the MCFC cycle and during the electrochemical process, produces 117,600 kW of power. The output stream from this section (stream N9) with a temperature of 1048 K enters the GSP cycle to produce more power, in this way, 55,340 kW of net power will be generated. The excess heat of the water scrubbing cycle was initially used to generate cooling at 243.6 K, so that by supplying the required heat of the AR system, 253.9 kW of cooling is produced at this temperature. Then the remaining heat of the cycle is
used to generate 8.391 kg/s hot water. The efficiency of the MCFC, gas/steam combined power cycles, and the coefficient of performance of the AR cycle, are 60.06%, 49.98%, and 0.3922, respectively.

Based on the presented relationships, the electrical and overall efficiencies of the present proposed system are 78.68% and 79.86%, respectively. Figure 5 shows the power density and voltage of fuel cell changes with respect to current density.

The outcomes of exergy investigation, as well as parametric study, are given as follows.

4.1 | Results of exergy analysis

Table 2 demonstrates the exergy of some streams used in the proposed structure. Utilizing these values as well as the exergy efficiency and irreversibility relationships governing the system components according to Table 5, the exergy efficiency and irreversibility of each piece of equipment are computed and shown in Table 9. Figures 6 and 7 illustrate exergy efficiency and irreversibility in equipment, respectively. Based on these figures, the most exergy destruction belongs to turbines/compressors/pumps and MCFC/reformer sections with values of 24,700 kW (with a share of 34.37% of the total) 22,285 kW (with a share of 31.01% of the total) have the most irreversibility, respectively. The results display that pumps, compressors, and reformers have the lowest share of exergy destruction, respectively. The investigation of exergy analysis of heat exchangers displays that the largest share of exergy degradation in these components is allocated to HX2 (22.59%), HE5 (16.29%), and HE13 (12.48%), respectively. Also, to evaluate the exergy of the proposed system, the exergy efficiency and exergy destruction of components must be calculated separately. The results of exergy efficiency in Figure 7 demonstrates that the throttle valve has the lowest exergy efficiency, while the effect of exergy degradation of these components on the hybrid structure is very low. Also, the exergy efficiency of heat exchangers and power generation and consumption devices is higher than other components, while the share of exergy degradation of these components is more in the proposed structure. Figure 8 shows the exergy flow diagram of the system. The results exhibit that most of the exergy is wasted in the gas/steam combined power plant and only 176,400 kW is produced as a product. Based on the obtained results, the exergy efficiency of the whole proposed system is 71.06%. 

FIGURE 4 Comparison of the hybrid system developed with similar cogeneration structures based on the MCFC.25,27,34,44,50-54

FIGURE 5 Molten carbonate fuel cell polarization curve in the integrated structure
| Component | Fuel exergy (kW) | Product exergy (kW) | Exergy destruction (kW) | Exergy efficiency (%) |
|-----------|-----------------|---------------------|------------------------|-----------------------|
| HE1       | 216,757         | 216,563             | 193.7                  | 90.71                 |
| HE2       | 35,501          | 32,235              | 3266                   | 92.05                 |
| HE3       | 75,833          | 74,582              | 1251                   | 50.03                 |
| HE4       | 68,351          | 67,088              | 1264                   | 88.76                 |
| HE5       | 49,154          | 46,797              | 2356                   | 90.56                 |
| HE6       | 30,233          | 28,998              | 1235                   | 89.39                 |
| HE7       | 24,522          | 24,328              | 194.8                  | 85.10                 |
| HE8       | 17,740          | 16,779              | 960.7                  | 94.92                 |
| HE9       | 10,525          | 10,523              | 1.459                  | 100                   |
| HE10      | 16,619          | 16,616              | 2.356                  | 98.66                 |
| HE11      | 22,285          | 22,263              | 21.49                  | 98.72                 |
| HE12      | 20,490          | 20,088              | 402.4                  | 95.19                 |
| HE13      | 3,206,207       | 3,204,401           | 1806                   | 96.74                 |
| HE14      | 13,649          | 13,621              | 27.83                  | 84.85                 |
| HE15      | 23,495          | 23,475              | 19.54                  | 95.18                 |
| HE16      | 16,333          | 16,309              | 23.88                  | 87.17                 |
| HE17      | 17,901          | 17,894              | 6.840                  | 97.78                 |
| HE18      | 16,571          | 16,560              | 10.67                  | 85.10                 |
| HE19      | 464,936         | 463,536             | 1400                   | 78.02                 |
| Tur1      | 91,230          | 72,260              | 18970                  | 63.26                 |
| Tur2      | 36,582          | 34,468              | 2114                   | 90.68                 |
| Tur3      | 12,981          | 12,433              | 548.2                  | 90.68                 |
| C1        | 14,078          | 11,491              | 2587                   | 80.68                 |
| C2        | 211,902         | 211,518             | 383.7                  | 83.42                 |
| P1        | 12,503          | 12,489              | 14.15                  | 92.11                 |
| P2        | 16,875          | 16,870              | 5.176                  | 90.29                 |
| P3        | 6326            | 6325                | 1.223                  | 81.20                 |
| P4        | 10,856          | 10,856              | 0.1321                 | 93.75                 |
| P5        | 2,475,848       | 2,475,773           | 74.41                  | 96.03                 |
| P6        | 9632            | 9631                | 0.7210                 | 80.26                 |
| Reformer  | 270,111         | 242,621             | 9677                   | 64.80                 |
| MCFC      | 250,218         | 237,609             | 12,608                 | 83.97                 |
| T100      | 2,686,711       | 2,685,404           | 1307                   | 99.95                 |
| T200      | 2,483,528       | 2,480,039           | 3489                   | 99.86                 |
| T300      | 16,732          | 11,114              | 5618                   | 66.42                 |
| Evaporator| 56.85           | 50.78               | 6.068                  | 89.33                 |
| D1        | 2,482,365       | 2,482,363           | 2.607                  | 100                   |
4.2 Results of the parametric study

In this study, power production as the principal product and hot water and refrigeration as byproducts have been designed via the proposed structure and biogas as the major feed of the process. Also, changing any parameter of each unit in the combined cycle can influence the performance of all other subsections. One of the essential parameters of the proposed system is the composition of inlet biogas. Inlet biogas composition is entirely conditional on the biomass different sources from that it is generated. As result, the value of inlet CH$_4$ and other compositions can over a wide range. In this part, the influence of CH$_4$ content in inlet biogas on the performance of the combined structure is examined and reported. In the primary cycle, the value of CH$_4$ in the inlet biogas (stream B1) is considered to be 60.72 mol%. This amount has been varied from 50 to 70 mol% in the performed parametric investigation. It is essential to note that in composition biogas only the value of CH$_4$ and

### Table

| Component | Fuel exergy (kW) | Product exergy (kW) | Exergy destruction (kW) | Exergy efficiency (%) |
|-----------|------------------|---------------------|------------------------|-----------------------|
| D2        | 10,512           | 10,512              | 0                      | 99.99                 |
| V1        | 8316             | 8316                | 0.6903                 | 78.34                 |
| V2        | 2662             | 2661                | 1.4110                 | 63.24                 |
| Cycle     | 248,276          | 176,417             | 71,859                 | 71.06                 |

**FIGURE 6** Exergy destruction of each component in the proposed cycle. (A) Exergy destruction shares of the heat exchangers section and (B) exergy destruction shares of the integrated structure component. MCFC, molten carbonate fuel cell.
CO₂ change, so that the higher the CH₄ composition, the lower the value of CO₂, and vice versa.

Biogas composition influences its lower heating value. In Figure 9, in addition to showing the amount of lower heating value (LHV) of biogas entering the system according to its composition change, its CO₂ and CH₄ values are also shown. As the molar percentage of CH₄ in biogas increases, so its LHV is increased. On the other hand, with the increase of CH₄ in biogas according to Figure 9, the quality of produced treated biogas (entering MCFC cycle) increments, so that by increasing inlet biogas methane content from 50 mole% to 70 mole%, treated biogas CH₄ content will rise from 95.43 mole% to 96.63 mole%, and of course its LHV will also enhance.

Figure 10 depicts the effect of biogas composition on the temperature of streams N9 and N10, MCFC power production, gas, and steam power production, and the Tur1 turbine power production. According to this figure, with increasing inlet biogas methane content, N9 and N10 flow temperatures decrease slightly. But power production is incrementing in all three sections. The main reason is the increase in the quality of the fuel entering them due to the increase in methane.
The effect of biogas composition on the values of the proposed structure products is depicted in Figure 11. First, changes in system total power production and consumption are examined. As is demonstrated in Figure 11, by raising methane composition in inlet biogas, both total power consumption and total power production will increment. The system’s net power production can be obtained by combining these two graphs so that with the increase of methane content, the trend of this graph is also enhanced. This increase shows that the effect of incrementing total power production is greater than incrementing total power consumption. Increasing the inlet biogas methane content enhances the amount of produced hot water, but the absorption cycle is ineffective on the produced refrigeration and its amount remains constant. The main reason is the lack of change in the quantity and quality of absorption cycle heat source during changes applied to the biogas composition. By growing CH4 content from 50 mol% to 70 mol%, total power consumption, total power production, total net power production, and hot water production rate increments from 14,137 kW, 134,225 kW, 120,088 kW, and 7.301 kg/s to 21,793 kW, 209,019 kW, 187,226 kW, and 9.555 kg/s, respectively.

The changes in the efficiency of different units of the integrated cycle, as well as total thermal and electrical efficiencies with changes in biogas composition, are shown in Figure 12. According to this figure, the efficiency of different parts, as well as the efficiency of the whole system, will decrease with the increase of methane.

**FIGURE 9** Inlet biogas composition effects on system parameters (biogas and stream B12 LHV, Stream B1 methane and CO2 rate, and Stream B12 methane content). LHV, lower heating value

**FIGURE 10** Inlet biogas composition effects on system parameters (different system sections power production and streams N9 and N10 temperature)
in biogas despite the increase of products including power and hot water. The main reason is the more enhancements in the heating value of the system input as rising the methane content of biogas rather than an increase in the system products. By increasing methane content from 50 mol% to 70 mol%, MCFC cycle, gas and steam cycle, electrical efficiency, and overall efficiency decreases from 64.35%, 49.83%, 81.93%, and 83.39% to 55.30%, 49.76%, 74.31%, and 75.35%, respectively.

5 | CONCLUSION

In this study, a combined cycle for the tri-production of power, cooling, and hot water is proposed. This proposed configuration consists of the biogas upgrading unit, MCFC cycle, GSP cycle, and absorption cooling process. 10.71 kg/s biogas enters the system as feed and exits 1583.51 kW net produced power, 8.391 kg/s hot water, and 253.9 kW cooling as products. The thermodynamic analysis, as well as exergy and sensitivity outcomes of the hybrid system, are as follows:

- In the present work, the efficiency of the MCFC cycle, GSP cycle, as well as electrical and overall efficiencies, are 60.06%, 49.98%, 78.68%, and 79.86%, respectively. The coefficient of performance of the AR system is calculated to be 0.3922.
- The outcomes of the exergy investigation indicate that the most exergy destruction of the entire structure is related to the turbines/compressors/pumps and MCFC/reformer sections, which accounts for 65.38%
of the total exergy destruction. Also, the exergy efficiency of the present combined system is 71.06%.

- Using a parametric study, conclude that the electrical and overall efficiencies of the entire structure can be improved up to 81.98% and 83.39%, respectively. This happens if the amount of methane in biogas is reduced to 50 mol%. By this reduction, the efficiency of MCFC and gas and steam cycle sections will also be improved.

- For future work in this field, the economic study along with the environmental evaluation of the current system can be referred. Examining the integration of the current system with the process of producing biogas from different types of biomass will also be valuable. It is also desirable to consider replacing MCFCs with other fuel cells, including SOFCs, in the current integrated system.

NOMENCLATURE

EQUIPMENT NAMES

C compressor
D flash drum
HE heat exchanger
P pump
Tur turbine
V expansion valve

VARIABLES/PARAMETERS

\( E_{\text{Nerst}} \) ideal reversible voltage
\( R \) resistance
\( I \) irreversibility (kW)
\( P \) partial pressure
\( E \) energy
act activation
\( F \) Faraday constant
\( n \) number
\( z \) molar flow rate of the reacted electrons
\( G \) Gibbs free energy (kW)
\( T \) temperature
\( R \) universal gas constant (8.314 J/mol·K)
\( A \) area
\( Q \) heat duty (kW)
\( W \) work transfer rate (kW)
\( m \) mass
\( v \) velocity
\( u \) internal energy
\( h \) enthalpy (kJ/kg mol)
\( g \) gravitational acceleration (9.806 m/s\(^2\))
\( z \) height
\( p \) pressure
\( S \) entropy
\( L \) liquid flow rate
\( V \) vapor flow rate
\( x \) liquid mole fraction
\( y \) vapor mole fraction
\( \text{ex} \) exergy

GREEK LETTERS/SYMBOLS

\( D \) difference operator
\( \oint \) contour integration
\( \eta \) efficiency
\( \Sigma \) summation sign
\( \delta \) declination

SUPERSCRIPTS AND SUBSCRIPTS

an anode
cathode ca cathode
act activation
\( i \) \( \text{ith} \) stream
\( j \) \( \text{jth} \) stream
in intel
out outlet
\( \text{th} \) thermal
rev reversible
des destroyed amount
0 standard condition
gen generation
CH chemical
mix mixture
PH physical

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