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By Ozgur Balli

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*Keywords: trigeneration, micro gas turbine engine, exergy analysis, energetic performance paramaters, exergetic performance indicators.*

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Based on the exergy, the electrical to heating ratio, electrical to cooling ratio, cooling factor, and heating factor are found to be 38.42%, 13.231, 53.328, 0.199 and 0.801, respectively. Performance indicators show that system owners and researchers focus on the combustion chamber, heat exchanger, water pump, and absorption chiller to improve the exergetic efficiency values of these components. Additionally, these parameters help us to measure environmental/ ecological impacts and sustainability of system.

*Keywords: trigeneration, micro gas turbine engine, exergy analysis, energetic performance paramaters, exergetic performance indicators.*

*Nomenclature*

| | |
|---|---|
| *AC* | air compressor |
| *ACh* | absorption chiller |
| $c$ | specific heat capacity (kJ/kg.K) |
| *CC* | combustion chamber |
| *CF* | cooling factor |
| *e* | specific energy (kJ/kg) |
| $\dot{E}$ | energy rate(kW) |
| *Eco EFF* | ecological effect factor ( -) |
| *ECR* | electrical to cooling ratio |
| *EEF* | environmental effect factor (-) |
| *EHR* | electrical to heating ratio |
| $\dot{E}x$ | exergy rate (kW) |
| $\dot{E}xIP$ | exergetic improvement potential (kW) |
| $ExSI$ | exergetic sustainability index (-) |
| *FRI* | fuel ratio indicator (%) |
| *FExDR* | fuel exergy depletion ratio (%) |
| *FExIPR* | fuel exergy improvement potential ratio (%) |
| *h* | specific entalphy (kJ/kg) |
| *HE* | heat exchanger |
| *HF* | heating factor |
| *G* | generator |
| *GT* | gas turbine |
| *GTMS* | gas turbine mechanical shaft |
| $LHV$ | lower heating value of fuel (kJ/kg) |
| $\dot{m}$ | mass flow rate (kg/s) |
| *MICTRIGEN* | trigeneration system with micro gas turbine engine |
| $P$ | pressure (kPa) |
| *PLR* | productivity lack ratio (%) |
| *PRI* | product ratio indicator (%) |
| *R* | universal gas constant (kJ/kg-K) |
| *REC* | recuperator |
| *RExIPR* | relative exergetic improvement potential ratio (%) |
| *RWExCR* | relative waste exergy cost rate (%) |
| *RWExR* | relative waste exergy rate (%) |
| *RWExIPR* | relative waste exergy improvement potential ratio (%) |
| *s* | specific entrophy (kJ/kg-K) |
| *SEF* | sustainable efficiency factor (-) |
| *SP* | selling price (\$) |
| $\dot{Q}$ | heat rate (kW) |
| $T$ | temperature (K) |
| $\dot{W}$ | work rate or power rate(kW) |
| *WExCR* | waste exergy cost rate (kW/\$) |
| *WP* | water pump |

*Greek Letters*

| | |
|---|---|
| $\varepsilon$ | specific exergy (kJ/kg) |
| $\gamma$ | fuel exery grade function |
| $\eta$ | energy efficiency (%) |
| $\psi$ | exergy efficiency (%) |
| $\Psi$ | improved exergy efficiency (%) |

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*Subscripts*

| | |
|---|---|
| *a* | air |
| *AC* | air compressor |
| *ACh* | absorption chiller |
| *CC* | combustion chamber |
| *ch* | chemical |
| *cool* | cooling energy/exergy |
| *D* | destruction |
| *elect* | electrical energy/exergy |
| *en* | energy |
| *ex* | exergy |
| *F* | fuel |
| *heat* | cooling energy/exergy |
| *g* | combustion gas |
| *G* | generator |
| *GT* | gas turbine |
| *GTMS* | gas turbine mechanical shaft |
| *HE* | heat exchanger |
| *in* | input |
| *j* | location |
| *k* | the *k*'th component |
| *kn* | kinetic |
| *L* | losses |
| MICTRIGEN | trigeneration system with micro gas turbine engine |
| *out* | output |
| *P* | pressure |
| *ph* | physical |
| *Pr* | product |
| *pt* | potential |
| *REC* | recuperator |
| *T* | temperature |
| *WEx* | waste exergy |
| *WP* | water pump |
| 0 | dead (environment or reference) state |

## I. Introduction

The world energy utilization is quickly increasing at a worrying rate. This has already upraised concerns over potential supply problems, lessening of energy resources and expediting environmental impacts (ozone layer depletion, global warming, climate change, etc.). The global expending pattern in buildings energy using, both residential and commercial, has rised steadily; coming to figures between 20% and 40% in developed countries. In fact, it has gone beyond the other major sectors, namely, industrial and transportation. Key reasons associating to this increasing figure include: (i) growth in population; (ii) greater requirement for building services; (iii) the necessity for better comfort levels; and (iv) longer duration of residers consumed time inside buildings. Without a doubt, the upraising trend in energy demand will continue into the future [1]. For this reason, enhancing energy efficiency in energy conversion systems is today a main aim for global energy policy makers. Suitable way is to optimize the use of energy delivered from the fossil fuels by designing more energy-efficient power systems [2]. In this respect, high-efficiency trigeneration systems are gaining more attention. [3]

There are many advantages of trigeneration systems, involving higher system efficiency, lessened greenhouse gas emissions, short transmission lines, decreased thermal losses and waste heat, discounted operating cost, miniaturized distribution units, multiple generation options, raised reliability, and fewer grid failure [4]. The primary mover is a important part of a trigeneration plant and the making its selection is very important. The dominant primary movers are internal combustion engines, external combustion engines (e.g. Stirling engines), gas turbines, steam turbines, micro-turbines, and fuel cells. [4-5]

In the open literature, some studies have examined to evaluate the energy and exergy performance of the trigeneration systems, to assess the economical and exergoeconomic performance of the trigeneration systems, and to determine the optimal operating strategies of trigeneration systems based on different prime movers. Balli et al. [6, 7] evaluated the thermodynamic and thermo economic performance of a trigeneration system with a rated output power of 6.5 MW gas-diesel engine integrated with an absorption chiller. The results of this study can be beneficial to change the components that have low thermodynamic efficiencies and large exergy consumptions, allowing to regulate the sale price of the products and to review the plant's economic policy. Additionally, Acıkkalp et al. [8, 9] investigated the advanced exergy and advanced exergoeconomic performance of the same trigeneration system. The exergy destruction rate and investment cost rate were divided into four components: endogenous, exogenous, avoidable and unavoidable. The results indicated that the components of trigeneration system had strong relationships with each other since the endogenous exergy destruction of the components was smaller than exegenous exergy destruction. Wang et al. [10] examined a trigeneration system with an 6.5 kWe-hydrogen fueled engine whose losses heats, discarded from exhausts and engine cooling system, are used for household purpose (hot and cooling water). Their study indicated that the hydrogen is a very interesting fuel that gives permission performing equal or better performance to the conventional diesel fuel in terms of energetic performance and near zero carbon emissions. Thus, the authors highlighted the tremendous potential fuel savings and large reductions in greenhouse gas emissions per. Lin et al. [11] studied and realized a trigeneration system based on 9.5 kW-a small-scale diesel engine coupled with both a heat recovery system and absorption cooler. The experimental results pointed that if the engine load was over 50%, the exhaust gases were hot enough to run the absorption refrigerator allowing very low temperature. Smilarly, Jannnelli et al. [12] analyzed a small-size trigeneration system with a 20 kW Lombardini diesel engine and a double effect water-LiBr absorption chiller by applying the available operating data. This combined system has been configured to produce both hot water and cooled water, by recuperating heat from the engine exhaust gasses. Rey et al. [13] examined the performance of micro-trigeneration system with a Honda Internal Combustion Engine (ICE) and validated the model with test data. They pointed out that this system is a well-chosen one for using a stand-alone system in buildings to produce electricity, heating and cooling. For an office building in Hong Kong, the performance of three types of trigeneration systems, driven by ICEs, are investigated and compared with a conventional chiller powered by the grid electricity [14]. The results indicated that the total yearly electricity demand from the building is decreased by 10.4% for the natural gas-fueled engine. For an ICE-based trigeneration system, two different operational strategies are researched and compared by Santo [15]. The energy utilization factor (energy efficiency) was estimated to be between 65% and 81% while the exergy efficiency was obtained to be between 35% and 38.4%. In an experimental investigation, Angrisani et al. [16] suggested a micro trigeneration system with a natural gas–fueled ICE coupled with an absorption cooling unit. They reported that, the system produced 5.4 kW-electrical power besides providing a considerable reduction of greenhouse gas emissions.,-Another experimental investigation of a micro-trigeneration system with a diesel engine coupled to an absorption chiller is examined by Khatri et al. [17]. The thermal efficiency of the system was calculated to be 86.2% and the reduction on the CO2 emissions was found to be 60.71%.

Micro gas turbines in available and in development are described as gas turbines with electrical power capacity ranges between 30 and 350 kW. Micro gas turbines alike large gas turbines can be used in power generation, cogeneration and trigeneration applications. Micro gas turbines are able to operate on variety of fuels, including natural gas, sour gases and liquid fuels such as gasoline, kerosene and diesel fuel/distillate heating oil [18, 19]. Bruno et al. [20] conducted the integration of four micro turbines (in the range 30-100 kW-electrical power) with a double effect direct-fired absorption chiller. The authors examined the effect of the post-combustion level on the trigeneration performance and defined the working conditions that permitted getting the maximum efficiency. The results showed that a directly driven absorption chiller with a post-combustion system can familiarise advantages with respect to the more conventional single effect hot water system in terms of higher coefficient of performance (COP) and flexibility. This is due to the decoupling between the electricity and the chilled water production. Ho et al. [21] studied a cogeneration system with a Capstone microturbine (30 kW) integrated with - a single effect - absorption chiller. The results of this study presented that the electric efficiency was obtained to be 21% and the overall system efficiency was determined to be 46%. Huicochea et al. [22] evaulated the performance of a tigeneration system based on a double effect absorption chiller driven by the exhaust gas of a 30 kW-microturbine. The reducing tendency of all performance parameters (i.e. COP and electric efficiency) with the increase of ambient temperature was shown. The results indicated that the suggested system for the co-production of electric, cooling and heating powers based on the micro turbine technology represents an attractive solution in the fields of the distributed generation. However, Thu et al. [23] investigated the energy and exergy performance of a 65 kWe-CNG fueled micro turbine enegine coupled with 112 kW-waste heat recovery system. The results showed that the combustor was responsible for approximately 70% of the total exergy destruction. The energy efficiency of the system varied from 15.7% at 25% load to 28.95% at full load operation while the exergy efficiency was found to be around 30.4% at full load operation. On the other hand, Ming et al. [24] analyzed a natural gas-fired micro turbine trigeneration system with absorption chiller at Tongji University, China. The maximum energy efficiency of system was estimated to be 80% in the winter, depending on power output, and 65% in the summer. Finally, Chen et al. [25] examined the behavior and performance of a small-scale gas turbine (1747 kW-electrical power) with a double effect chiller and a heat exchanger during the off-design operation. The estimated efficiency of the gas turbine ranged from 27 at full load to 11% at partial load, while the COP increased slightly with the decreasing of the load level of the trigeneration system. Thus, the performance breakdown of the system was due to the bad performance of the gas turbine under the off-design conditions.

Some researchers also investigated the performance of the biomass-fueled trigeneration systems. Wang et al. [26] analyzed a biomass trigeneration system that involves a biomass gasifier, a heat pipe heat exchanger for recovering waste heat from product gas, an internal combustion engine to produce electricity, an absorption chiller/heater for cooling and heating, and a heat exchanger to produce domestic hot water. Operational flows were represented in three work conditions: summer, winter, and the transitional seasons. Energy and exergy analyses were evaluated for different operational flows. The energy efficiencies were obtained to be 50.00% for summer season, 37.77% for winter season, and 36.95% for transitional season while the exergy efficiencies were calculated to be 6.23% for summer season, 12.51% for winter season, and 13.79% for transitional season, respectively. Waste

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analyses of energy and exergy indicated that the largest exergy destruction occured in the gasification system, which accounts for more than 70% of the total waste exergy rate. Annual performance indicated that the suggested biomass-fueled trigeneration system lessened biomass consumption by 4% compared with the non-use of a heat recovery system for high-temperature product gases. Huang et al. [27] carried out the technical and economic modelling and performance analysis of biofuel fired trigeneration systems equipped with energy storage for remote households. To adapt the dynamic energy demand for electricity, heating and cooling, both electrical and thermal energy storage devices were integrated to balance larger load changes. Technical performance, the emissions from the system, and the impacts of electrical and thermal energy storages had been examined. Finally, an economic evaluation of the systems was analyzed It was obtained that the internal combustion engine (ICE) based trigeneration and/or combined heat and power (CHP) system was more suitable for heat to electricity ratio value below 1.5 for a household. The biomass boiler and Stirling engine based system was also beneficial for heat to electricity energy demand ratio lying between 3 and 3.4. Parise et al. [28] analyzed the performance of a trigeneration system with a biofuel-driven compression ignition engine as the prime mover. They reported a reduction of around 50% and 95% in primary energy consumption and CO2 emissions, respectively. Furthermore Wang et al. [29] examined the energy, environmental and economic evaluation of four different trigeneration systems driven by ICE applied for a remote island. All energy demands for the investigated island were covered by the trigeneration system without the assistance of electric grid. These systems were assesmend in terms of primary energy saving ratio, carbon dioxide emission saving ratio and annualized life cycle cost. The results indicated that all trigeneration system was superior to the conventional system. It was observed that the trigeneration system with a double-effect absorption chiller offered a better option compored with a single-effect absorbtion chiller.

Recently, some research works have been devoted to analyze trigeneration systems with fuel cell prime movers. Al-Sulaiman et al. [30] suggested a trigeneration system based on a solid oxide fuel cell (SOFC) and Organic Rankine Cycle (ORC) coupled with an absorption chiller and conducted the energy analysis of the system. The results indicated a trigeneration efficiency of 74%, cooling cogeneration efficiency of 57% and heating cogeneration efficiency of 71%. Energy, exergy and exergoeconomic assessments for a novel trigeneration system based on a SOFC coupled to an absorption refrigeration system were examined by Chitsaz et al. [31] and Ranjbar et al. [32]. They reported the maximum energy and exergy efficiency values of the system were obatained to be 79% and 47% for, respectively. However, Ma et al. [33] suggested a SOFC trigeneration system with ammonia-water waste heat recovery cycle. The possible energy efficiency was obtained to be 80% and more under the specified conditions. On the other hand, Tippawan et al. [34] researched the energy and exergy performances of a trigeneration system with an ethanol-fueled SOFC integrated with an absorption chiller. They concluded that the trigeneration plant gained 32% gain in efficiency compared to the conventional power cycle. Another SOFC-trigeneration system with LiBr/H2O absorption refrigeration cycle and fueled by coke oven gas was analyzed by Zhao et al. [35]. They reported that overall trigeneration efficiency was estimated to be approximately 90%. On the other hand, Wang et al. [36] investigated a novel micro trigeneration system combined a direct flame fuel cell, a boiler and an absorption chiller for residential applications. The electricity efficiency of the system was lower than 20% while cogeneration efficiency reached above 90%. It was noted that the electric efficiency of the microtobuler SOFC stack-trigeneration was estimated to be around 30% that this better value was acquired by improving the SOFC materials.

In addition to the above mentioned trigeneration systems, other technologies are introduced in the literature to serve as prime movers for trigeneration applications. These technologies consist of: steam turbine and Organic Rankine Cycle (ORC)-based trigeneration systems, solar energy driven technologies, biomass-driven trigeneration systems, Stirling engine-based trigeneration systems and systems with multiple prime movers. For a novel ORC-based trigeneration system producing power, pure water, cooling and heating, Mehr et al. [37] reported that the maximum thermal and exergy efficiencies of 89.2% and 43.05%, respectively. Boyaghchi and Heidarnejad [38] examined a micro solar-energy based trigeneration system integrated with an ORC for summer and winter seasons. They concluded that the thermal and exergy efficiencies and the product cost rate are 23.66%, 9.51% and 5114.5 $/year, respectively. Al-Sulaiman et al. [39] assessed a trigeneration system with parabolic trough solar collectors combined with ORC. The maximum energy efficiency of the system was calculated to be 94% in the trinegeneration mode operation. Design, simulation and optimization of a small trigeneration plant supplied by geothermal and solar energies, with a 6 kW micro-ORC and a 30 kW-single effect LiBr/H2O chiller is presented by Buonomano et al. [40]. For a solar energy based trigeneration system with flat-plate solar collectors, a multiobjective optimization is conducted by Wang et al. [41] using genetic algorithm for power mode, combined heat and power mode and combined cooling and power mode. Zare [42] studied a comparative thermodynamic analysis and optimization for two different designs of geothermal energy-based trigeneration systems. The two considered systems were an organic Rankine cycle and a Kalina cycle for power generation units. Additionally, A LiBr/water absorption chiller and a water heater coupled to the Organic Rankine and Kalina cycles were used for cooling and heating loads. The maximum exergy efficiency values of the Kalina cycle-based system and the ORC-based system were accounted to be 50.36% and 46.51%. These results indicated that Kalina cycle-based system was more efficient. On the other hand, Fontalvo et al [43] proposed and modeled a trigeneration system powered by Rankine cycle using an ammonia-water mixture with an absorption refrigeration cycle. It was found that the absorber, the boiler and the turbine were the sources of greatest exergy destruction. Furhermore, Chua et al. [44] examined different trigeneration systems integrated with renewable to serve an electrically isolated island in Singapore. A wide variety prime mover was analyzed at altering levels of renewable energy insertion: micro turbines, solar photovoltaics, solar Stirling dish, fuell cells, and biomass power generation with absorption cooling. Primary energy was reduced for each case, and high renewable penetration (40%) corresponded to the potential reduction in CO2 emissions, but the increased capital costs in this case resulted in a net projected economic loss.

The main goal and orginality of this study is to evaulate the exergetic performance of a micro gas turbine engine trigeneration system (*MICTRIGEN*) installed in Turkey with the exergy analysis methodology for the first time according to the best of the author's knowledge.

## II. System Description

### a) General description of the MICTRIGEN

A schematic of the investigated micro gas turbine trigeneration (*MICTRIGEN*) system is given in Figure 1. This system consists of an air compressor (*AC*), a combustion chamber (*CC*), a gas turbine (*GT*), a gas turbine mechanical shaft (*GTMS*), a recuperator (*REC*), an electrical generator (*G*), a heat exchanger (*HE*), a water pump (*WP*) and an absorption chiller (ACh). The *MICTRIGEN* system produces 225 kW-net electrical power rates, 109.1 kW-net heating energy rates and 78.76 kW-net cooling energy rates. The *MICTRIGEN* consumes 0.01258 kg/s-natural gas while the mass flow of air is 1.4544 kg/s. The mass flow rates of the hot and chilled water are measured to be 1.3 kg/s and 3.75 kg/s. The pressure and temperature values of hot water inletting at the *HE* are 323.15 K and 1025kPa while the pressure and temperature values of hot water outleting the *HE* are 363.15 K and 1000kPa, respectively. On the other hand, the pressure and temperature values of hot water at hot section outlet of the *Ach* are measured to be 343.15 K and 950 kPa. However, the cold water flows in the *ACh* with 285.15 K and 300 kPa when it discarges from the *ACh* with 280.15 K and 275 kPa, respectively. The selling price (*SP*) of the system is estimated to be 345000 $ (USA).

### b) Assumptions made

In this study, the assumptions made are listed below:

- The MICTRIGEN system operates in a steady-state and steady flow.
- The principle of ideal-gas mixture is applied for the air and combustion gaseous.
- The combustion reaction is complete.
- The fuel injected to combustion chamber is the natural gas. The low heating value (LHV) of natural gas is assumed to be 49234.5kJ/kg.
- The compressor and the gas turbine considered are reckoned as adiabatic.
- The changes in the kinetic energy, the kinetic exergy, the potential energy and the potential exergy within the engine are assumed to be negligible.
- The temperature and the pressure of the dead (environmental) state are measured to be 298.15 K and 101.33 kPa, respectively.
- The air-to-fuel mass ratio is equal to 105.61.

### c) Combustion balance, specific heat capacity of emissions and air

The air is composed of nitrogen 77.48%, oxygen 20.59%, carbon dioxide 0.03% and water vapour 1.90%. There are very small amount of argon, carbon monoxide, etc., in the air, which are neglected in this study. The pressured air mixed with fuel and burned in the combustion chamber to enable stable burning and the air-to-fuel ratio is to be at appropriate level. To have completed burning of fuel and to decrease the temperature, the air-to-fuel ratio in the combustion chamber is always higher than stoichiometric ratio. Because of this, there is a significant amount of oxygen within the combustion gases. When Air-Fuel Ratio is 105.61, the general combustion reaction equation is found to be:

$$\left(0.9334CH_4 + 0.00211C_2H_6 + 0.00029C_3H_8 + 0.00012C_4H_{10} + 0.06408N_2\right) +$$
$$62.1733\begin{pmatrix} 0.7448N_2 + \\ 0.2059O_2 + \\ 0.0003CO_2 + \\ 0.019H_2O \end{pmatrix} \rightarrow 0.9576CO_2 + 3.0574H_2O + 10.9244O_2 + 48.4922N_2 \quad (1)$$

After combustion reaction, the mass compositions of combustion gases are obtained to be 2.38% $CO_2$, 2.99% $H_2O$, 19.50% $O_2$ and 75.13% $N_2$. The specific heat capacity of the combustion gaseous can be written in the following form:

$$c_{P,g}\left(T\right)=0.995904+\frac{0.008608}{10^{2}}T+\frac{0.017167}{10^{5}}T^{2}-\frac{0.070978}{10^{9}}T^{3} \quad (2)$$

The ideal gas constant value of combustion gases was estimated to be 0.291942 $kJ(kg-K)^{-1}$. The specific heat capacity of air is a function of temperature is given as follows [45]:

$$c_{P,a}\left(T\right)=1.04841-\left(\frac{3.83719T}{10^{4}}\right)+\left(\frac{9.45378T^{2}}{10^{7}}\right)-\left(\frac{5.49031T^{3}}{10^{10}}\right)+\left(\frac{7.92981T^{4}}{10^{14}}\right) \quad (3)$$

where the temperature is evaluated in *K*.

## III. Methodology

*a) Mass, energy and exergy balance equations*

Mass, energy and exergy balances for each component of a system under steady state conditions can be written as follows [46]:

$$\sum \dot{m}_{in}=\sum \dot{m}_{out} \quad (4)$$

$$\dot{Q}-\dot{W}=\sum \dot{m}_{out}e_{out}-\sum \dot{m}_{in}e_{in} \quad (5)$$

$$\sum\left(1-\frac{T_o}{T_j}\right)\dot{Q}_j-\dot{W}=\sum \dot{m}_{out}\varepsilon_{out}-\sum \dot{m}_{in}\varepsilon_{in}+\dot{E}x_D \quad (6)$$

where $\dot{m}$ is the mass flow rate, $e$ is the specific energy, $\dot{Q}_j$ is the heat transfer rate through the boundary at temperature $T_j$ at location *j*, $\dot{W}$ is the work rate, $\varepsilon$ is the specific exergy, and $\dot{E}x_D$ is the exergy destruction rate. In the absence of nuclear, magnetism, electricity and surface tension effects in the thermal systems, the total specific energy and exergy can be determined from [6, 18, 26]:

$$\sum e=e_{kn}+e_{pt}+e_{ph}+e_{ch} \quad (7)$$

$$\sum \varepsilon=\varepsilon_{kn}+\varepsilon_{pt}+\varepsilon_{ph}+\varepsilon_{ch} \quad (8)$$

Where subscripts of $kn$, $pt$, $ph$ and $ch$ denote the kinetic, potential, physical and chemical, respectively. In this study, the changes in the kinetic energy/exergy and potential energy/exergy within the *MIGTRIGEN* were assumed to be negligible.

The specific physical energy for air, combustion gases and water may be written as [6, 18]:

$$e_{ph}=c_PT-c_{P,o}T_o \quad (9)$$

$$e_{ph}=h-h_o \quad (10)$$

The specific physical exergy is claculatde from th following equations [18, 26, 47]:

$$\varepsilon_{ph}=c_{P(T)}\left[T-T_o-T_o\ln\left(\frac{T}{T_o}\right)\right]+RT_o\ln\left(\frac{P}{P_o}\right) \quad (11)$$

$$\varepsilon_{ph}=h-h_o-T_o\left(s-s_o\right) \quad (12)$$

The specific chemical energy and exergy of gaseous hydrocarbon fuels $(C_aH_b)$ on a unit mass can be determined as follows [18, 47, 48]:

$$e_{ch}=LHV \quad (13)$$

$$\varepsilon_{ch}=\gamma_F.LHV \quad (14)$$

$$\gamma_F\cong 1.033+0.0169\frac{b}{a}-\frac{0.0698}{a} \quad (15)$$

where $\gamma_F$ denotes the fuel exergy grade function that is estimated to be 1.0308 fornatural gas. However, energy rate and exergy rate is calculated by [18]:

$$\dot{E}=\dot{m}e \quad (16)$$

$$\dot{E}x=\dot{m}\varepsilon \quad (17)$$

*b) Performance evaluation metrics*

i. *Energetic performance parameters*

Evaluating the trigeneration system's efficiency is important and requires the use of suitable indicators. The overall energy efficiency of the MIGTRIGEN is defined as the ratio of total useful energy output (electrical, heating and cooling) to the total fuel energy input and can be expressed as [49-51]:

$$\eta_{MICTRIGEN}=\frac{\dot{E}_{elect}+\dot{E}_{heat}+\dot{E}_{cool}}{\dot{E}_F} \quad (18)$$

Additionally, several performance indicators are were suggested to evaluate the energetic performance of the trigeneration system by Al-Sulaiman et al. [51] and Maraver et al. [52]. These are given as follows:

The electrical to heating ratio based on energy [51]:

$$EHR_{en,MICTRIGEN}=\frac{\dot{E}_{elect}}{\dot{E}_{heat}} \quad (19)$$

The electrical to cooling ratio based on energy [51]:

$$ECR_{en,MICTRIGEN} = \frac{\dot{E}_{elect}}{\dot{E}_{cool}} \quad (20)$$

The cooling factor based on energy [52]:

$$CF_{en,MICTRIGEN} = \frac{\dot{E}_{cool}}{\dot{E}_{cool} + \dot{E}_{heat}} \quad (21)$$

The heating factor based on energy:

$$HF_{en,MICTRIGEN} = \frac{\dot{E}_{heat}}{\dot{E}_{cool} + \dot{E}_{heat}} \quad (22)$$

ii. *Exergetic performance parameters*

Some useful assessment parameters based on the exergy methodology were offered by Balli [53]. These are given as follows:

- *Exergetic efficiency* $(\psi)$*:* The $\psi$ is calculated by the ratio of the sum of the outlet flows as product exergy to the sum of the inlet flows as fuel exergy. It can be estimated as follows:

$$\psi = \frac{\dot{E}x_{\Pr}}{\dot{E}x_F} = 1 - \frac{\dot{E}x_{WEx}}{\dot{E}x_F} \quad (23)$$

For the MICTRIGEN system, the product exergy rate is obtained from:

$$\dot{E}x_{\Pr,MICTRIGEN} = \dot{W}_{elect} + \dot{E}x_{heat} + \dot{E}x_{cool} \quad (24)$$

- *Relative waste exergy ratio (RWExR):* The *RWExR* is determined by the ratio of the waste exergy rate of k'th component to total waste exergy rate of the system. It is accounted by;

$$RWExR = \frac{\dot{E}x_{WEx,k}}{\dot{E}x_{WEx,MICTRIGEN}} \quad (25)$$

For the MICTRIGEN system, the total waste exergy rate is estimated by:

$$\dot{E}x_{WEx,MICRTRIGEN} = \dot{E}x_{F,MICTRIGEN} - \dot{E}x_{\Pr,MICTRIGEN} = \sum \dot{E}x_D + \sum \dot{E}x_L \quad (26)$$

- *Fuel exergy depletion ratio (FExDR):* The *FExDR* can be defined as the ratio of the waste exergy rate of the k'th component to the fuel exergy rate supplied in the system. It is formulated as follows:

$$FExDR = \frac{\dot{E}x_{WEx,k}}{\dot{E}x_{F,MICTRIGEN}} \quad (27)$$

- *Productivity lack ratio (PLR):* The *PLR* can be identified as the ratio of the waste exergy rate of the k'th component to the product exergy rate of the MICTRIGEN. It is formulated as follows:

$$PLR = \frac{\dot{E}x_{WE,k}}{\dot{E}x_{\Pr,MICTRIGEN}} \quad (28)$$

- *Product ratio indicator(PRI):* The *PRI* is calculated by dividing the product exergy rate of the k'th component to the product exergy rate (*Pr*) of the MICTRIGEN as follows;

$$PRI = \frac{\dot{E}x_{\Pr,k}}{\dot{E}x_{\Pr,MICTRIGEN}} \quad (29)$$

- *Fuel ratio indicator(FRI):* The *FRI* is estimated by dividing the fuel exergy rate of the k'th component to the total fuel exergy rate of the MICTRIGEN as follows;

$$FRI = \frac{\dot{E}x_{F,k}}{\dot{E}x_{F,MICTRIGEN}} \quad (30)$$

- *Exergetic improvement potential (ExIP):* The maximum improvement in the exergy efficiency for a process or a system can be achieved when the exergy consumption (losses and destruction) minimized. Consequently, it is useful to employ the concept of an "exergetic improvement potential" when analyzing different processes and systems.

  The *ExIP*is written as follows;

$$\dot{E}xIP = (1-\psi)\dot{E}x_{WEx} \quad (31)$$

- *Relative exergetic improvement potential ratio (RExIPR):* The *RExIPR* is defined as the ratio of the exergetic improvement potential of k'th component to the total exergetic improvement potential of all components. This parameter indicates that which compenent within a system provides the maximum improvement when it is changed or improved. The *RExIPR* is obtained from;

$$RExIPR = \frac{\dot{E}xIP_k}{\dot{E}xIP_{MICTRIGEN}} \text{ (n= number of components)} \quad (32)$$

- *Waste exergy improvement potential ratio (WExIPR)*: The *WExIPR* is obtained from the ratio of the exergetic improvement potential of k'th component to the waste exergy rate of k'th component. High value of exergetic destruction improvement ratio demonstrates that exergetic improvement potential rate for a component occurs in high level. The *WExIPR* is calculated from:

$$WExIPR = \frac{\dot{E}xIP_k}{\dot{E}x_{WEx,k}} \tag{33}$$

- *Fuel exergy improvement potential ratio (FExIPR)*: The *FExIPR* is presented as the ratio of the exergetic improvement potential rate of k'th component to the total fuel exergy of the system. It is found from:

$$FExIPR = \frac{\dot{E}xIP_k}{\dot{E}x_{F,MICTRIGEN}} \tag{34}$$

- *Improved exergetic efficiency* $(\Psi)$: If an exergetic improvement is realized in a component, the fuel exergy rate required for a component decreases for constant production and the exergy efficiency of the component increases. This new value of exergetic efficiency can be named as the improved exergetic efficiency. The $\Psi$ is calculated as flows:

For the components:

$$\Psi_k = \frac{\dot{E}x_{\Pr,k}}{\dot{E}x_{F,k} - \dot{E}xIP_k} \tag{35}$$

Fort the MICTRIGEN system:

$$\Psi_{MICTRIGEN} = \frac{\dot{E}x_{\Pr,MICTRIGEN}}{\dot{E}x_{F,MICTRIGEN} - \dot{E}xIP_{MICTRIGEN}} \tag{36}$$

- *Waste exergy cost rate (WExCR):* Exergy consumption (losses and destruction) creates an extra monetary lost during a production. A system with lower exergy consumption has more useful product exergy and subsequently more potential to do work. A less efficient system has low useful product exergy and less potential to do work. The loss in production potential can be represented as a cost rate. The *WExCR*is the ratio of the waste exergy rate of k'th component to the selling price of the system. It can be taken from;

$$WExCR_k = \frac{\dot{E}x_{WEx,k}}{SP_{MICTRIGEN}} \tag{37}$$

- *Relative waste exergy cost rate (RWExCR):* The *RWExCR* is the ratio of the waste exergy cost rate of k'th component to the total waste exergy cost rate within the system. This paremeter indicates that which component of the system is more effective in the waste exergy cost rate. The *RWExCR* is estimated by:

$$RWExCR_k = \frac{WExCR_k}{WExCR_{MICTRIGEN}} \tag{38}$$

- *Environmental effect factor (EEF):* One of the sustainability indicators is the environmental effect factor which is calculated the ratio of fuel waste exergy ratio to the exergy efficiency. Environmental impact factor indicates whether or not it damages the environment because of its unusable waste exergy output, losses and exergy destruction. The *EEF* can be counted by;

$$EEF = \frac{FWExR}{\psi} \tag{39}$$

- *Exergetic sustainability index (ExSI)*: Exergetic sustainability index is vital parameter among exergetic sustainability indicators to assess the system's sustainability level. Its function of environmental effect factor can be found out by ratio of 1 to the environmental effect factor. The range of this index is between 0 and $\infty$. The higher efficiency means low exergy destruction ratio and low environmental effect factor as a result higher exergetic sustainability index. Exergy clearly helps determine efficiency improvements and reductions in thermodynamic losses attributable to a process. Measures to increase exergy efficiency can reduce environmental impact by reducing exergy losses. Within the scope of exergy methods, such activities lead to increased exergy efficiency and reduced exergy consumption (both waste exergy emissions and internal exergy destructions). The *ExSI* is figured out from;

$$ExSI = \frac{1}{EEF} \tag{40}$$

- *Sustainable efficiency factor (SEF):* If a process or system uses low amount fuel or energy for the desired production, it is said that this process or system has high exergetic efficiency value as well as high sustainability level because low emissions are emitted to the environment. An increasing in the exergetic efficiency results a rising in the sustainability level of the system. Consuquently, the sustainable efficiency factor can be used as a sustaianability assessment parameter and the *SEF* is picked up as follows;

$$SEF = \frac{1}{1-\psi} \tag{41}$$

- *Ecological effect factor (EcoEF):* The $EcoEF$ of the k'th component is estimated from following equation;

$$EcoEF = \frac{\dot{E}x_F}{\dot{E}x_{\Pr}} = \frac{1}{\psi} \tag{42}$$

Above-mentioned assessment parameters, the relations between eqn. (19) and eqn. (22) can be written with the exergy terms as the following:

The electrical to heating ratio based on exergy:

$$EHR_{ex,MICTRIGEN} = \frac{\dot{E}x_{elect}}{\dot{E}x_{heat}} \tag{43}$$

The electrical to cooling ratio based on exergy:

$$ECR_{ex,MICTRIGEN} = \frac{\dot{E}x_{elect}}{\dot{E}x_{cool}} \tag{44}$$

The cooling factor based on exergy:

$$CF_{ex,MICTRIGEN} = \frac{\dot{E}x_{cool}}{\dot{E}x_{cool} + \dot{E}x_{heat}} \tag{45}$$

The heating factor based on exergy:

$$HF_{ex,MICTRIGEN} = \frac{\dot{E}x_{heat}}{\dot{E}x_{cool} + \dot{E}x_{heat}} \tag{46}$$

## IV. Results and Discussion

In this study, the performance assesments of a trigeneration system with micro gas turbine engine (MICTRIGEN) is evaluated by the energy and exergy analyses methodology.

*a) Energetic performance evaluation of the MICTRIGEN*

The MICTRIGEN system produces 225 kW-net electrical power rates $(\dot{W}_{14})$, 109.1 kW-net heating energy rates $(\dot{E}_{19})$ and 78.76 kW-net cooling energy rates $(\dot{E}_{22})$ at maximum operation mode while the system consumes 619.374 kW-fuel energy rates $(\dot{E}_4)$. According to these data, the energy efficiency $(\eta)$, the electrical to heating ratio $(EHR_{en})$, the electrical to cooling ratio $(ECR_{en})$, the cooling factor $(CF_{en})$ and the heating factor $(HF_{en})$ are determined to be 66.67%, 2.062, 2.857, 0.419 and 0.581, respectively. If the MICTRIGEN system is only operated to produce the electrical power, the prime mover energy efficiency of the system is calculated to be 36.33%. This value indicates that the energy efficiency of the trigeneration system is approximately double (1.845) of the energy efficiency of the simple cycle. The typical prime mover and overall energy efficiency performances of a micro turbine cogeneration system were given as 18-27% and 65-75%, repectively [54]. According to this data, the prime mover and overall energy efficiency values of the investigated trigeneration system is superior to reference values.

*b) Exergetic performance evaluation of the MICTRIGEN*

The *MICTRIGEN* system consumes 640.87 kW-fuel exergy rates $(\dot{E}x_4)$ in order to produce 246.23 kW-product exergy rates that are 225 kW-net electrical power rates $(\dot{W}_{14})$, 17.01 kW-net heating exergy rates $(\dot{E}x_{19})$ and 4.22 kW-net cooling exergy rates $(\dot{E}x_{22})$ at maximum operation mode. According to these data, the exergy efficiency $(\psi)$, the electrical to heating ratio $(EHR_{ex})$, the electrical to cooling ratio $(ECR_{ex})$, the cooling factor $(CF_{ex})$ and the heating factor $(HF_{ex})$ are found to be 38.42%, 13.231, 53.328, 0.199 and 0.801, respectively. The 640.87 kW- fuel exergy rates can be divided into 246.23 kW-product exergy rates and 394.64 kW-waste exergy rates. In other words, the 38.42% of fuel exergy rate can be converted to useable product exergy rate while the 61.58% of fuel exergy creates the waste exergy rate. However, the net electrical power is the 91.38% of product exergy rate when the net heating exergy rate is the 6.91% of product exergy rate and the cooling exergy rate is the 1.71% product exergy rate. The percent combinations of fuel exergy, waste exergy and product exergy are illustrated in Fig.2.

The exergetic balance equations (eqn. no: 47-62) of the *MICTRIGEN* system and its main components *(AC, CC, GT, GTMS, REC, G, HE, WP* and*ACh)* are listed in Table 1. On the other hand, thermodynamic cycle data of the MICTRIGEN system under actual operating conditions are given in Table 2 for maximum operation mode. Using the data in Table 2, exergy analysis is conducted to assess the exergetic performance of the *MICTRIGEN* and its main components. The obtained values of the performance indicators are listed in Table 3. The main findings of the exergetic analysis are summarized as follows:

- The exergy efficiency values of the *AC, CC, GT, GTMS, G, REC, HE, WP* and*ACh* are obtained to be 89.09%, 60.66%, 98.39%, 97.50%, 97.71%, 94.11%, 40.96%, 25.51%, and 36.77%, respectively. The maximum exergy destruction rate is calculated to be 252.15 kW in the combustion chamber *(CC)* with 60.66% exergetic efficiency hence the combustion processes exhibit very high thermodynamic inefficiencies caused by chemical reaction, heat transfer, friction, and mixing. On the other hand, the maxiumum exergetic improvement potential (99.21 kW) will be realized by improving energy efficiency of component and/or using new design combustion chamber (high temperature resistance material, laminar and uniform flow, etc.) The waste exergy rate and the exergetic improvement potential rate of the system components are shown in the Fig.3.

- The exergy efficiency of all componetscan be increased if some technological improvements are developed and applied. The real and improved exergy efficiency values of engine componets are illustrated in Fig.4. Fig.4 indicates that effects of improvement scan be seen as an exergy efficiency increasing with 11.10% in the *CC*, 21.92% in the *HE*, 24.49% in the *ACh*, 31.80% in the *WP* and 19.13% in the *MICTRIGEN* system.
- The *WP* has the best value of relative waste exergy ratio with 0.15% while the *CC* has the worst value with 63.89%. These values show that the maximum exergy destruction rate occurs in the *CC* between the engine components.
- The maximum fuel exergy depletion take place in the *CC* with 39.34 % even as the minimum fuel exergy depletion occurs within the *WP* with 0.09%. Total fuel exergy depletion ratio of the system is calculated to be 61.58%. However, the productivity lack ratio is obtained to be the maximum value with 102.49% within the *CC* since the ***CC*** has the maxiumum product exergy rate between the components. On the other hand, Total productivity lack ratio of the *MICTRIGEN* is obtained to be 160.28%. Fuel exergy depletion ratio (*FExDR*) and productivity lack ratio (*PLR*) of the *MICTRIGEN* and its components are exhibited in Fig.5.
- The product ratio (*PRI*) and fuel ratio indicators (*FRI*) are illustrated in Fig.6. Between the comoponents, the *GT* has the maximum *PRI* with 205.32% while the *CC* has the maximum *FRI* with 100.0%.
- Between the components, the waste exergy improvement potential ratio (*WExIPR*) is estimated to be 74.49% for the *WP* that is a maximum value while the fuel exergy improvement potential ratio (*FExIPR*) is accaunted to be 15.89% for the *CC* that is a maximum value. For the *MICTRIGEN* system, the *WExIPR* and *FExIPR* are found to be 33.88% and 20.86%, respectively. The values of the *WExIPR* and *FExIPR* are indicated in Fig.7.
- The waste exergy cost rate (*WExCR*) values of components are given in Fig.8. The maximum *WExCR* is calculated to be $0.731\text{x}10^{-3}$ kW/$ for the *CC*. On the other hand, the maximum relative waste exergy cost ratio (*RWExCR*) is estimated to be 63.89% for the *CC* between the components.
- The enviromental effect factor (*EEF*) and ecological effect factor(*EcoEF*) values of the components are illustrated in Fig.9. Fig.9 points that the *CC* has the maximum *EEF* value with 0.649while the *WP* has the highest *EcoEF*value with 3.920. On the other words, the *EEF* values indicate that the *CC* has the highest exergy destruction rate when the *EcoEF* values show that the *WP* has the lowest exergy efficiency.
- The highest value of *ESI* instructs that the component has the lowest environmental effect factor. Between the components, the *WP* has the highest value of the exergetic sustainability index (*ESI*) with 274.36 because the *WP* has the lowest *EEF* value with 0.004. The *ESI* values of the *MICTRIGEN* and its components are demonstrated in the Fig. 10.
- The sustainable efficiency factors (*SEF*) of the *MICTRIGEN* and its components are given in Fig.11. The maximum *SEF*value is calculated to be 62.18 for the *GT* in good agreement with the exergy efficiency value of the *GT.*

Addition to above mentioned results, the exergetic performance indicator values of the whole *MICTRIGEN* are indicated in Fig.12. The $\psi$, $\Psi$, *FExDR, PLR, WExIPR, FEXIPR, WExC, EEF, ExSI, SEF,* and *EcoEF* values of the whole *MIGTRIGEN* are determined to be 38.42%, 48.55%, 61.58%, 160.28%, 33.38%, 20.86%, $1.144\text{x}10^{-3}$ kW/$, 1.603, 0.624, 1,624, and 2.603, respectively. The exergetic improvement potential (*ExIP*) of the *MICTRIGEN* are estimated by two methods. Possible *ExIP* value is obtained from the sum of all components' *ExIP* values. Possible *ExIP* value of the system is accounted to be 133.69 kW. The other method is theoretical and it is estimated from eqn.(31). The theoretical *ExIP* value is found to be 243.02 kW. It is impossible to get the theoretical *ExIP* value hence the sum of the total *ExIP* value (133.69 kW) of all components and the exergy rate (11.03 kW) of emitted exhaust gases to environment is lower than the theoretical *ExIP* value (243.02 kW).

## V. Conclusions

This study presents some developed energetic and exergetic assessment indicators to analyze the exergetic performance evaluation of a trigeneration system with a micro gas turbine engine (*MICTRIGEN*) fueled by natural gas. These parameters help the system designers, owners and researchers to measure the cost rate, the environmental/ecological impacts and the sustainable development. This work aims to create a layout of the possibilities and advantages that exergetic performance analysis offers to the trigeneration systems.

The energy efficiency, the electrical to heating ratio, the electrical to cooling ratio, the cooling factor and the heating factor are determined to be 66.67%, 2.062, 2.857, 0.419 and 0.581, respectively.

The component level exergy analysis indicates that the components of the *CC, HE, WP* and *ACh* have the unfavourable values of exergetic performance parameters. Because of these, the above-mentioned components are selected to be bad factors for the *MICTRIGEN*. All exergetic performance indicators show that the system designer, owner and researchers focus on the components of the *CC, HE, WP* and *ACh* to improve the exergetic efficiency values of these components.

The exergy efficiency, improved exergy efficiency, fuel exergy depletion ratio, productivity lack ratio, exergetic improvement potential, waste exergy improvement potential ratio, fuel exergy improvement potential ratio, waste exergy cost rate, environmental effect factor, exergetic sustainability index, sustainable efficiency factor and ecological effect factor of the *MICTRIGEN* system are estimated to be 38.42%, 48.55%, 61.58%, 160.28%, 133.69 kW, 33.88%, 20.86%, $1.144 \times 10^{-3}$ kW/$, 1.603, 0.624, 1.624 and 2.603, respectively. Furthermore, the electrical to heating ratio, the electrical to cooling ratio, the cooling factor and the heating factor based on the exergy are found to be 38.42%, 13.231, 53.328, 0.199 and 0.801, respectively.

The recommended exergetic performance parameters in this study can be benefical to analyze the exergetic performance evaluation of the similar systems and to determine the sustainability levels of these systems.

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## Figure Captions

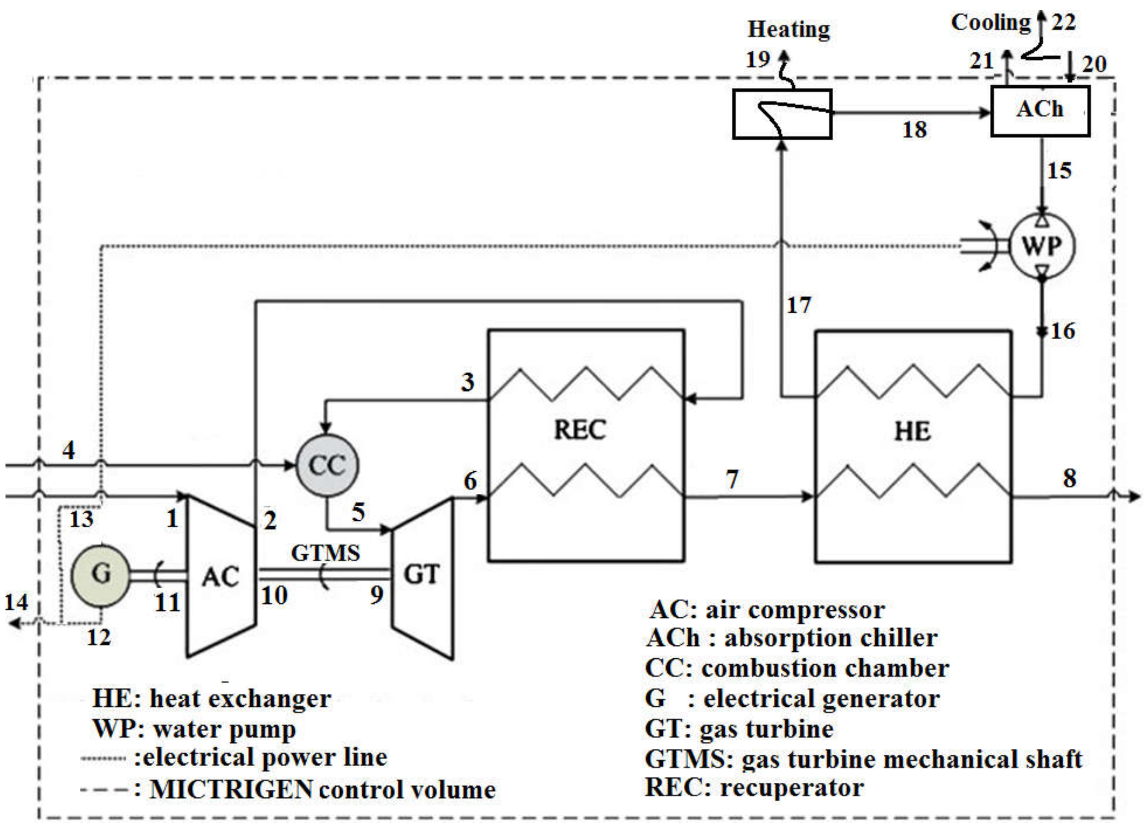


*Fig. 1:* A schematic of the investigated MICTRIGEN.

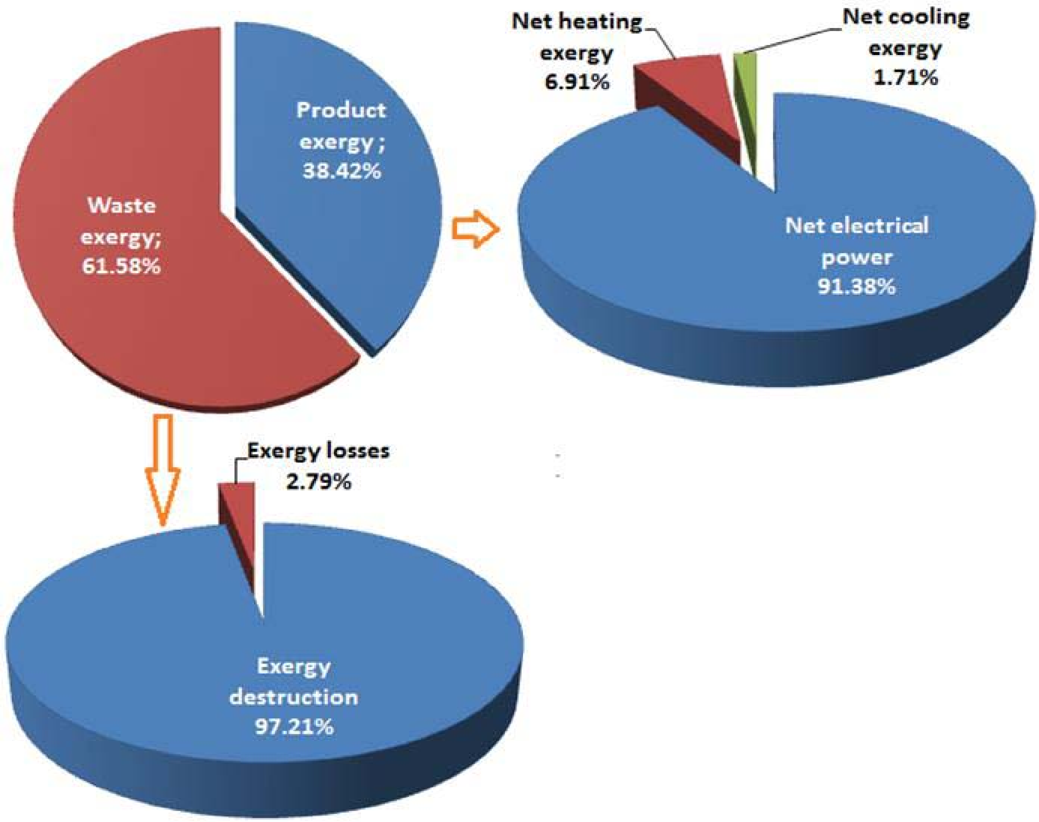


*Fig. 2:* The percent combinations of fuel exergy rate, waste exergy rate and product exergy rate.

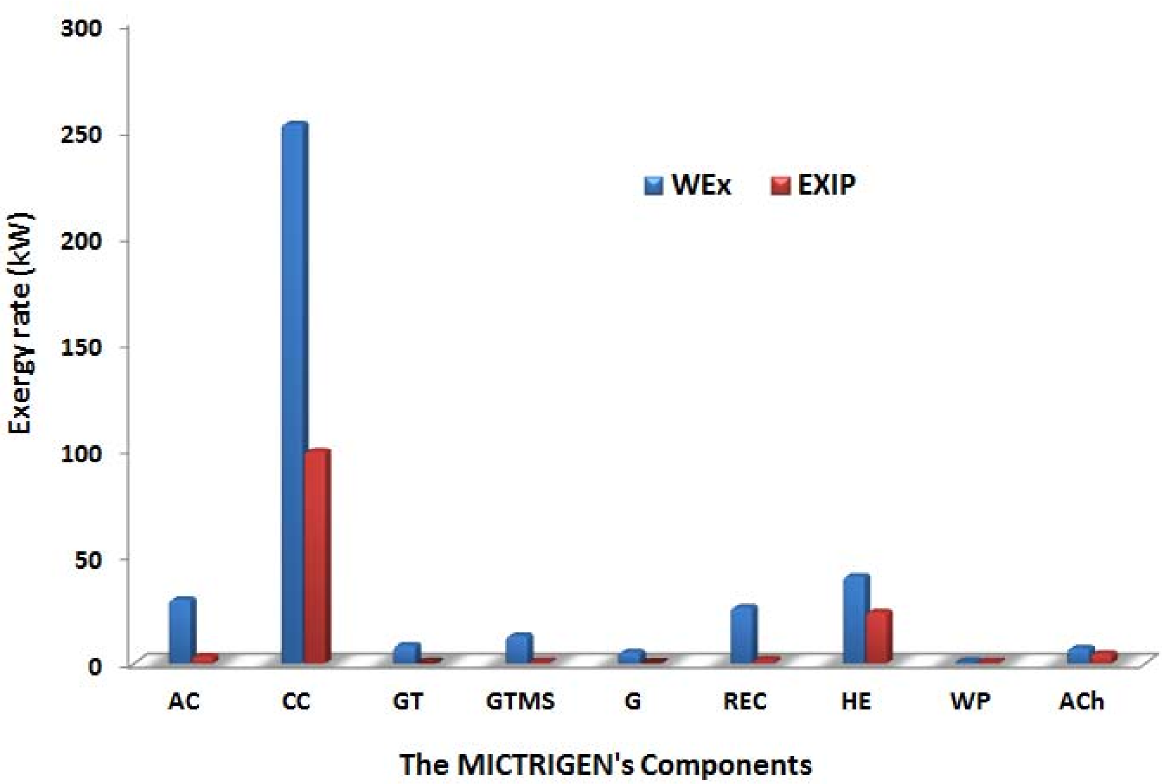


*Fig. 3:* The waste exergy rate and the exergetic improvement potential rate of the system components.

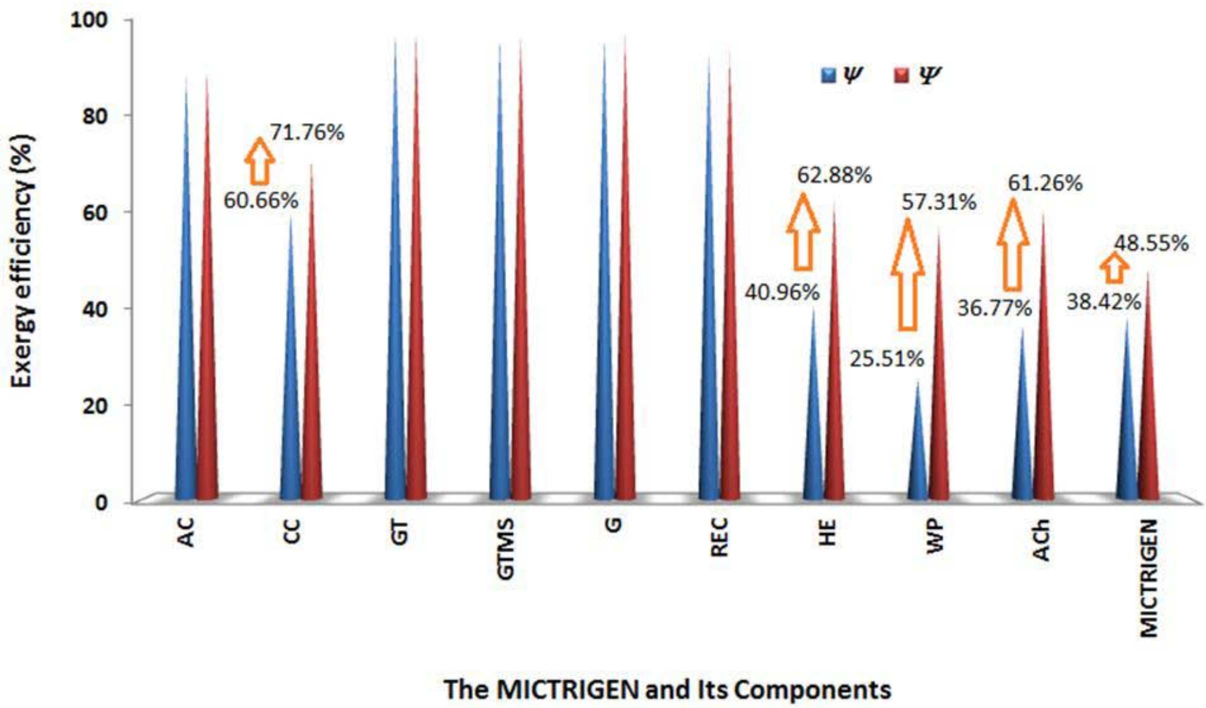


*Fig. 4:* The real and improved exergy efficiency values of the MIGTRIGEN and its componets.

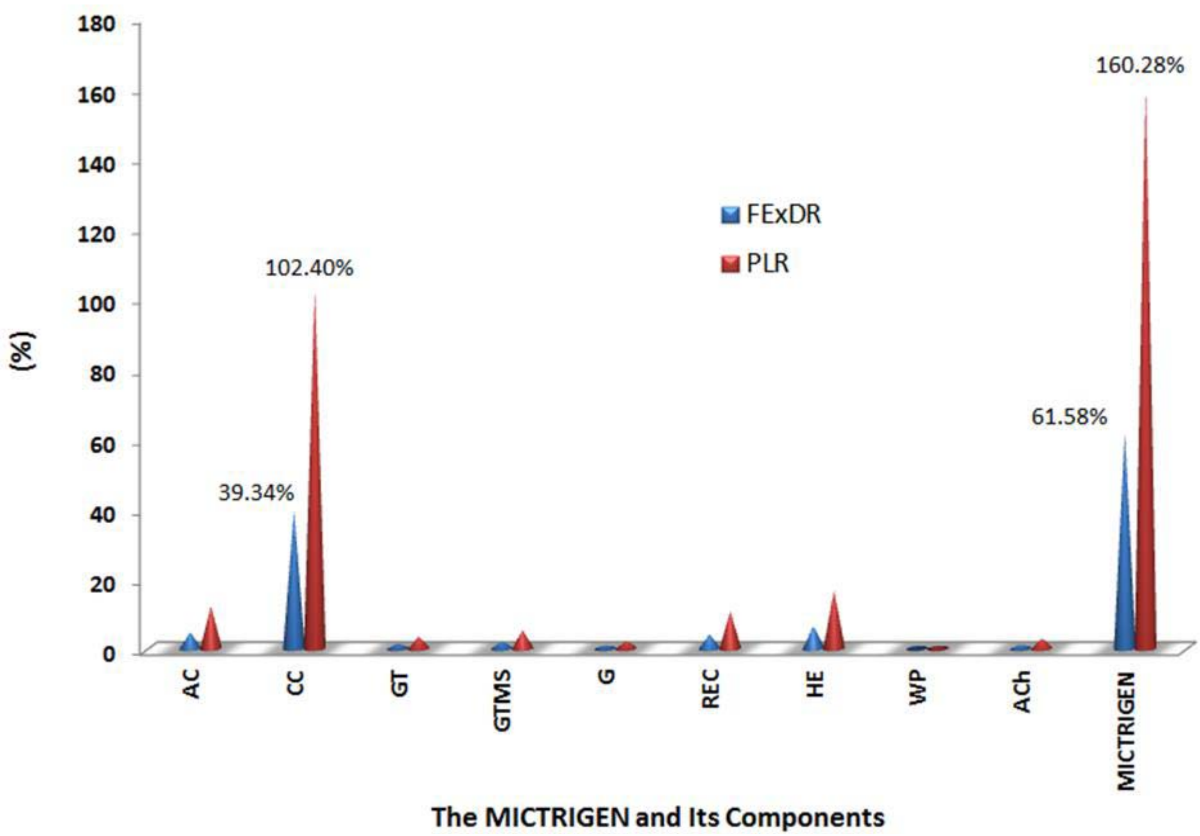


*Fig. 5:* Fuel exergy depletion ratio and productivity lack ratio of the *MICTRIGEN* and its components.

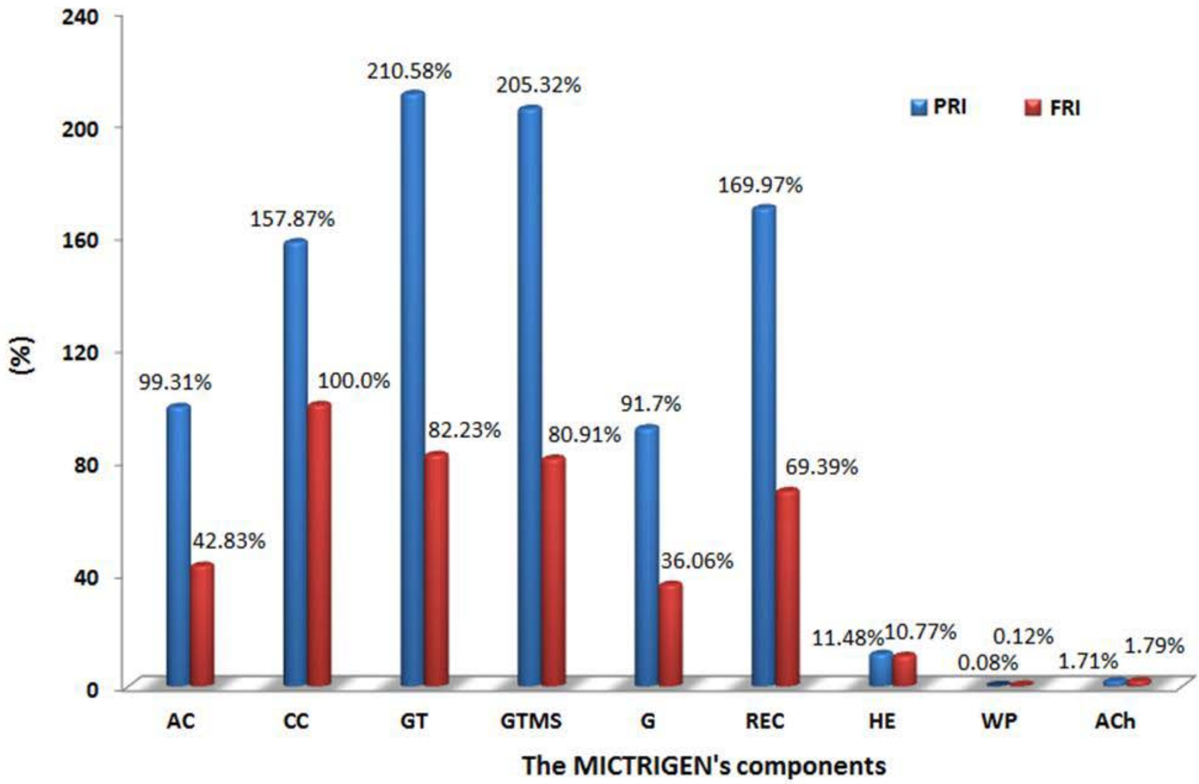


*Fig. 6:* The product ratio and fuel ratio indicators of the system components.

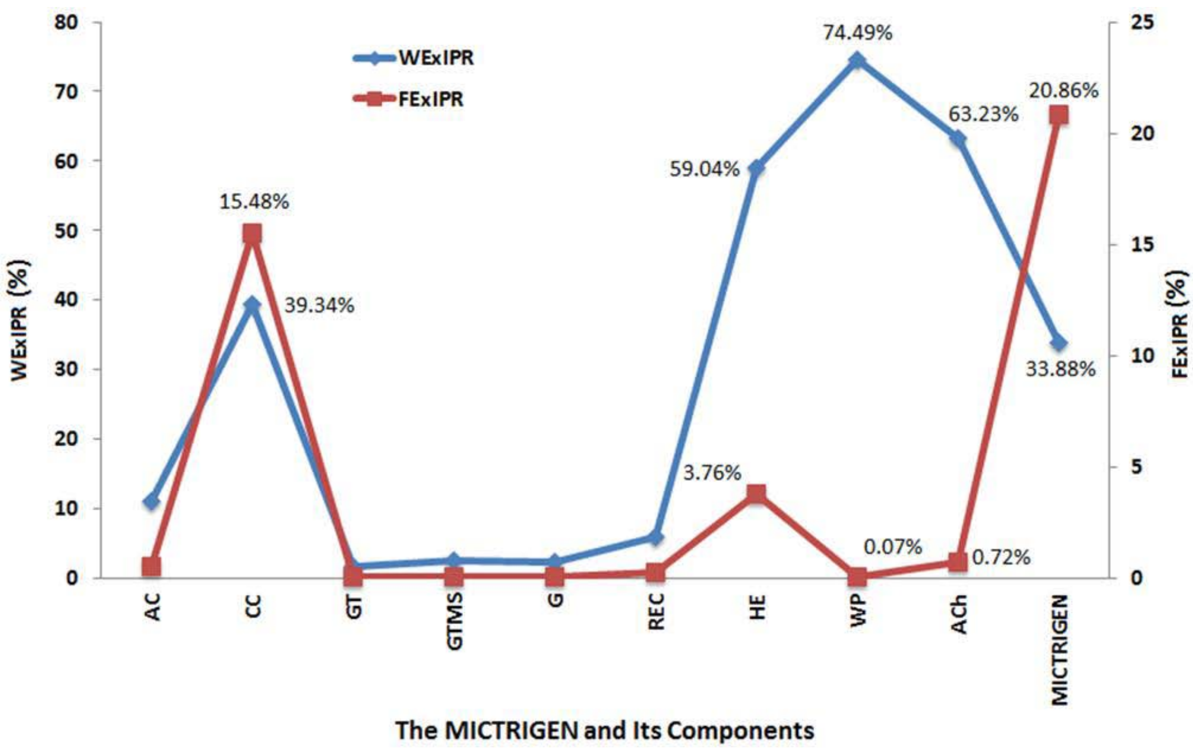


*Fig. 7:* The waste exergy and fuel exergy improvement potential ratios of the MIGTRIGEN and its components.

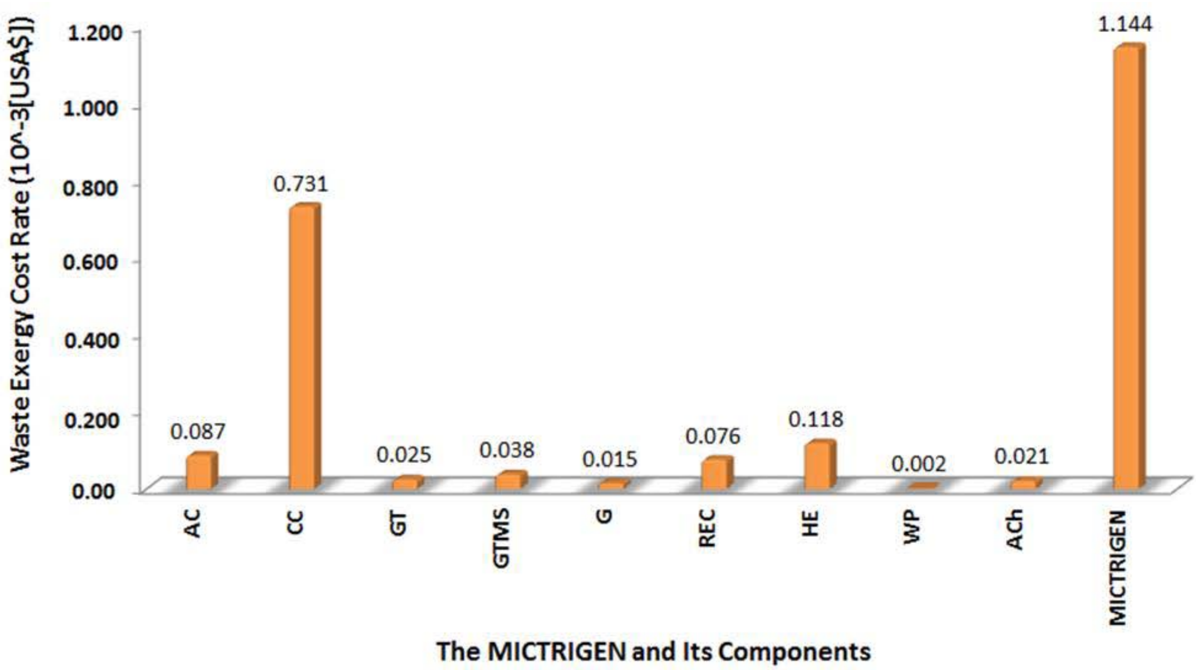


*Fig. 8:* The waste exergy cost rate values of the MIGTRIGEN and its components.

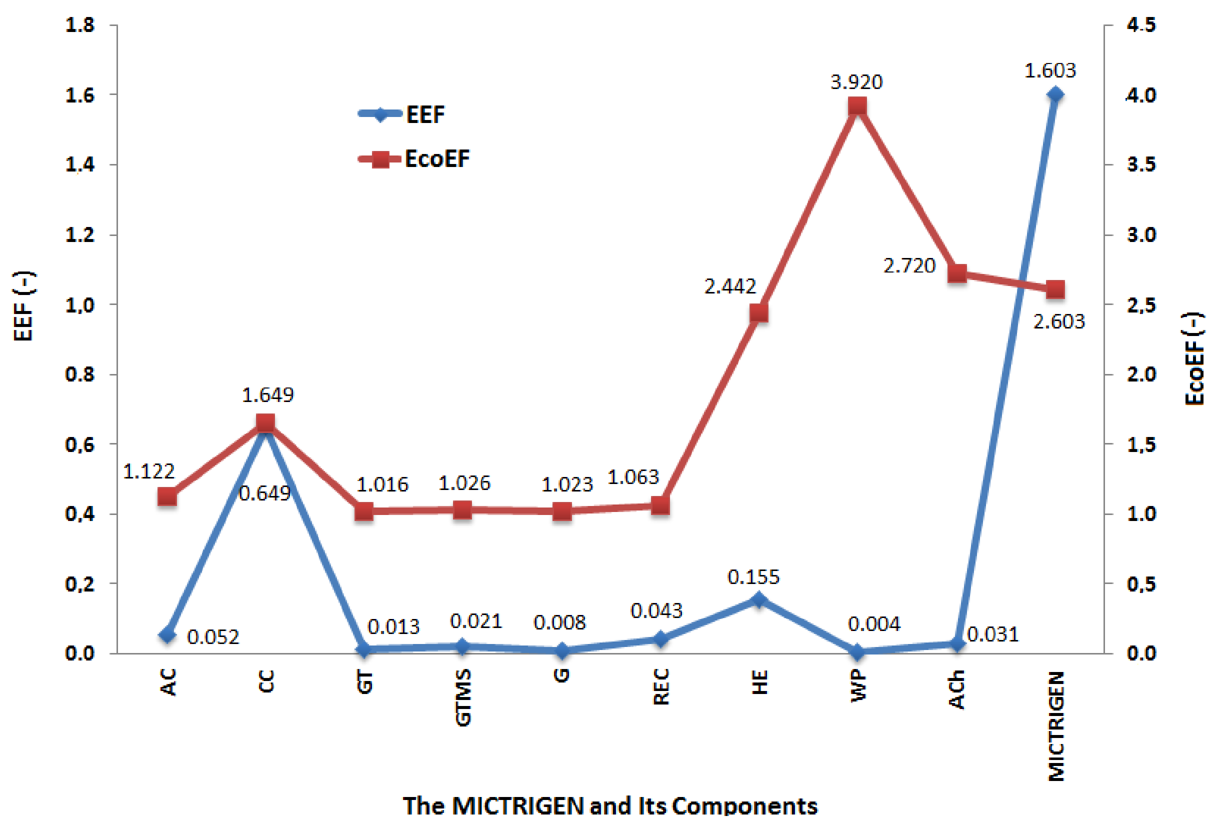


*Fig. 9:* The enviromental effect factor and ecological effect factor values of the MIGTRIGEN and its components.

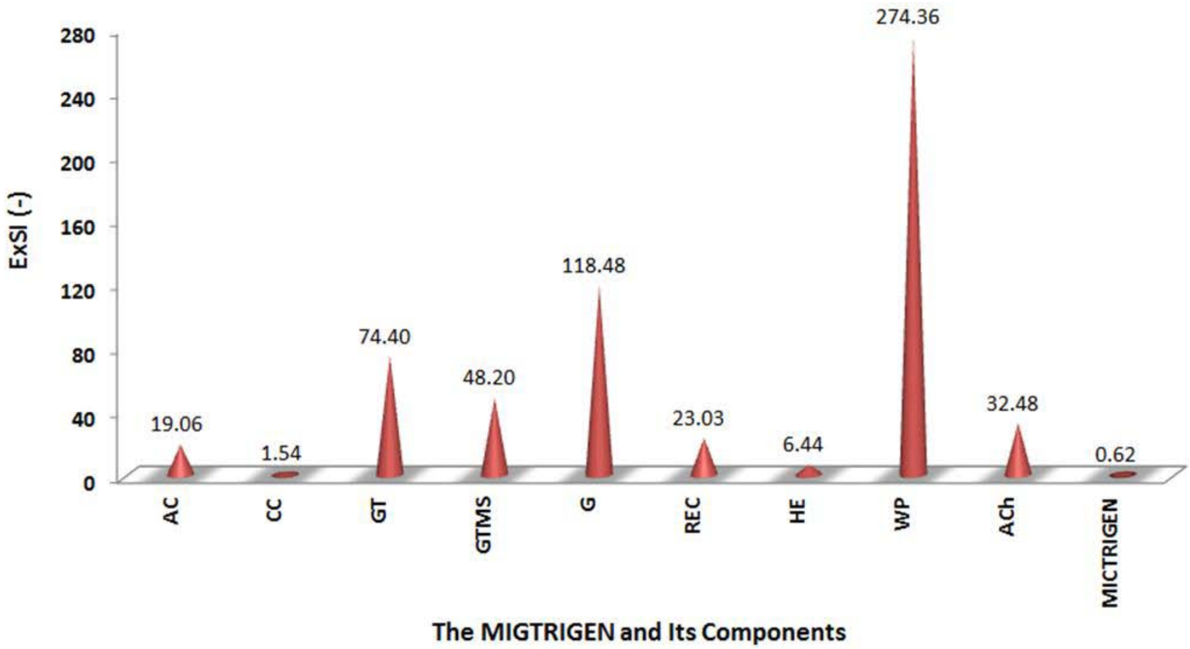


*Fig. 10:* The exergetic sustainability index values of the *MICTRIGEN* and its components.

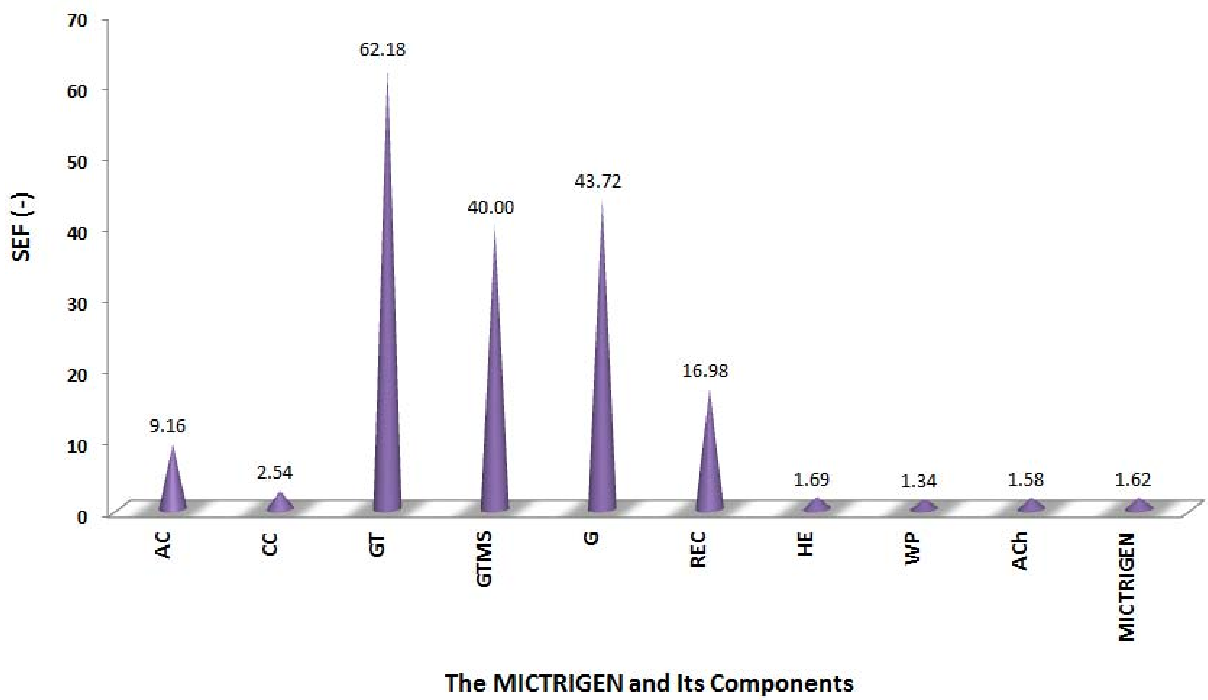


*Fig. 11:* The sustainable efficiency factors of the *MICTRIGEN* and its components.

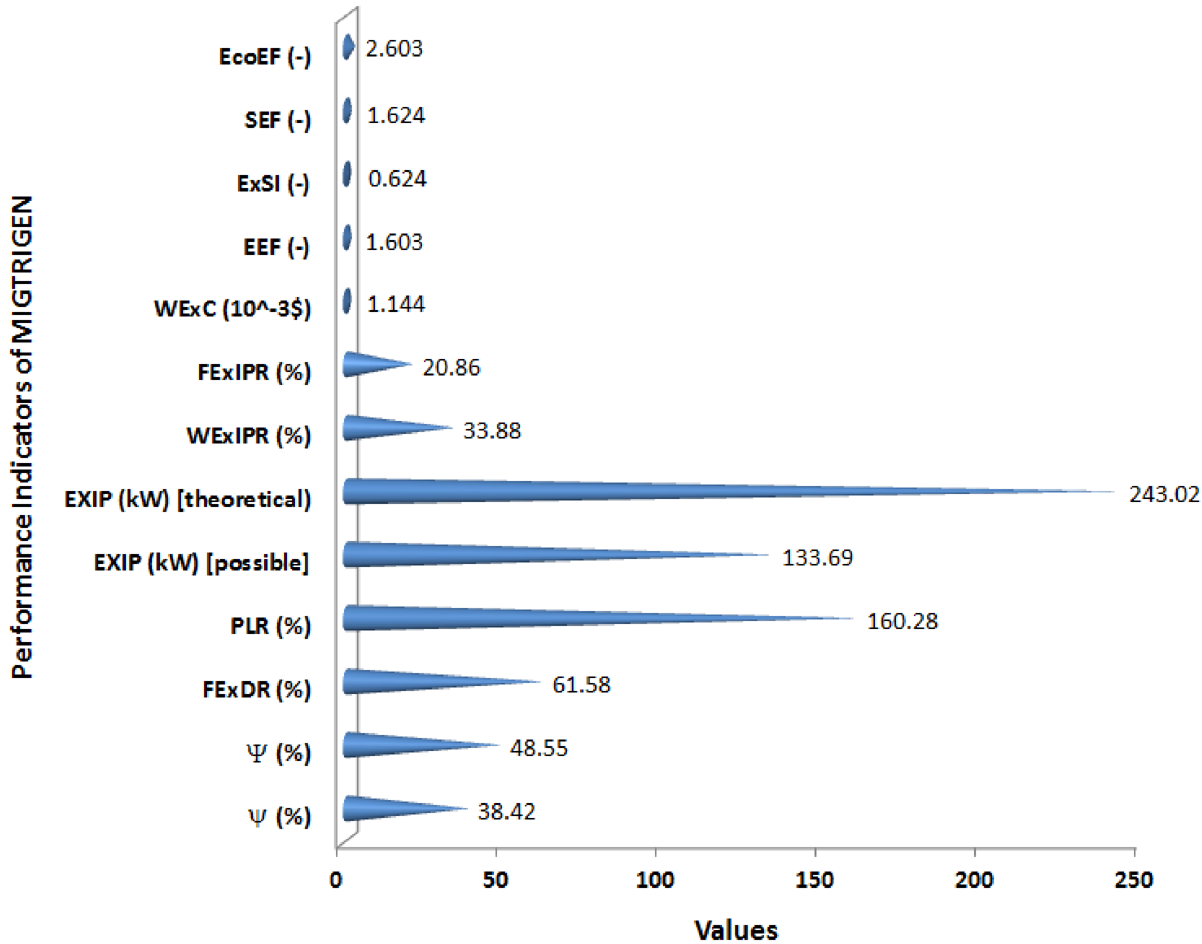


*Fig.12:* The exergetic performance indicator values of the whole *MICTRIGEN*.

## Table Captions

*Table 1:* The exergetic balance equations of the *MICTRIGEN* system and its main components

| Components | Fuel | Product | Waste exergy rate (destruction and losses) | Eqn. No. |
|---|---|---|---|---|
| *AC* | $\dot{W}_{10}-\dot{W}_{13}$ | $\dot{E}x_2-\dot{E}x_1$ | $\dot{E}x_{WEx,AC}=\dot{E}x_{D,AC}=\left(\dot{W}_{10}-\dot{W}_{11}\right)-\left(\dot{E}x_2-\dot{E}x_1\right)$ | (47) |
| *CC* | $\dot{E}x_4$ | $\dot{E}x_5-\dot{E}x_3$ | $\dot{E}x_{WEx,CC}=\dot{E}x_{D,CC}=\dot{E}x_4-\left(\dot{E}x_5-\dot{E}x_3\right)$ | (48) |
| *GT* | $\dot{E}x_6-\dot{E}x_5$ | $\dot{W}_9$ | $\dot{E}x_{WEx,GT}=\dot{E}x_{D,GT}=\left(\dot{E}x_6-\dot{E}x_5\right)-\dot{W}_9$ | (49) |
| *GTMS* | $\dot{W}_9$ | $\dot{W}_{10}$ | $\dot{E}x_{WEx,GTMS}=\dot{E}x_{D,GTMS}=\dot{W}_9-\dot{W}_{10}$ | (50) |
| *G* | $\dot{W}_{11}$ | $\dot{W}_{12}$ | $\dot{E}x_{WEx,G}=\dot{E}x_{D,G}=\dot{W}_{11}-\dot{W}_{12}$ | (51) |
| *REC* | $\dot{E}x_6-\dot{E}x_7$ | $\dot{E}x_3-\dot{E}x_2$ | $\dot{E}x_{WEx,REC}=\dot{E}x_{D,REC}=\left(\dot{E}x_6-\dot{E}x_7\right)-\left(\dot{E}x_3-\dot{E}x_2\right)$ | (52) |
| *HE* | $\dot{E}x_7-\dot{E}x_8$ | $\dot{E}x_{17}-\dot{E}x_{16}$ | $\dot{E}x_{WEx,HE}=\dot{E}x_{D,HE}=\left(\dot{E}x_7-\dot{E}x_8\right)-\left(\dot{E}x_{17}-\dot{E}x_{16}\right)$ | (53) |
| *WP* | $\dot{W}_{13}$ | $\dot{E}x_{16}-\dot{E}x_{15}$ | $\dot{E}x_{WEx,WP}=\dot{E}x_{D,WP}=\dot{W}_{13}-\left(\dot{E}x_{16}-\dot{E}x_{115}\right)$ | (54) |
| *ACh* | $\dot{E}x_{18}-\dot{E}x_{15}$ | $\left\|\dot{E}x_{21}-\dot{E}x_{20}\right\|$ | $\dot{E}x_{WEx,ACh}=\dot{E}x_{D,ACh}=\left(\dot{E}x_{18}-\dot{E}x_{15}\right)-\left(\left\|\dot{E}x_{21}-\dot{E}x_{20}\right\|\right)$ | (55) |
| *MICTRIGEN* | $\dot{E}x_4$ | $\dot{W}_{14}+E\dot{x}_{19}+E\dot{x}_{22}$ | $\dot{E}x_{WEx,MICTRIGEN}=E\dot{x}_4-\left(\dot{W}_{14}+E\dot{x}_{19}+E\dot{x}_{22}\right)$ | (56) |
| | *Auxiliary equations* | | $\dot{E}x_{19,heating}=E\dot{x}_{17}-E\dot{x}_{18}$ | (57) |
| | | | $\dot{E}x_{22,cooling}=\left\|E\dot{x}_{21}-E\dot{x}_{20}\right\|$ | (58) |
| | | | $\dot{E}x_{WEx,MICTRIGEN}=E\dot{x}_L-\sum E\dot{x}_D$ | (59) |
| | | | $E\dot{x}_L=E\dot{x}_8$ | (60) |
| | | | $\sum E\dot{x}_D=E\dot{x}_{D,AC}+E\dot{x}_{D,CC}+E\dot{x}_{D,GT}+E\dot{x}_{D,GTMS}+E\dot{x}_G+E\dot{x}_{D,REC}+E\dot{x}_{D,HE}+E\dot{x}_{D,WP}+E\dot{x}_{D,ACh}$ | (61) |
| | | | $\dot{W}_{12}=\dot{W}_{13}+\dot{W}_{14}$ | (62) |

*Table 2:* Thermodynamic cycle data of the MICTRIGEN system under actual operating conditions

| State no. | Fluid type/work | $\dot{m}$ $(kgs^{-1})$ | $T$ $(K)$ | $P$ $(kPa)$ | $c_P$ $(kJ(kg-K)^{-1})$ | $h / LHV$ $(kJkg^{-1})$ | $s$ $(kJ(kg-K)^{-1})$ | $\dot{E}$ $(kW)$ | $\dot{E}x$ $(kW)$ |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Air | 0 | 298.15 | 101.33 | 1.00412 | | | 0.00 | 0.00 |
| 0' | Water | 0 | 298.15 | 101.33 | | 104.93 | 0.367 | 0.00 | 0.00 |
| 1 | Air | 1.4544 | 298.15 | 101.33 | 1.00412 | | | 0.00 | 0.00 |
| 2 | Air | 1.4544 | 476.25 | 455.96 | 1.02486 | | | 274.46 | 244.52 |
| 3 | Air | 1.4544 | 928.35 | 449.12 | 1.12657 | | | 1085.67 | 663.02 |
| 4 | Fuel | 0.01258 | 298.15 | 202.75 | | | | 619.37 | 640.87 |
| 5 | Combustion gases | 1.46698 | 1193.15 | 442.39 | 1.22244 | | | 1700.49 | 1051.74 |
| 6 | Combustion gases | 1.46698 | 944.15 | 105.90 | 1.17047 | | | 1181.98 | 524.75 |
| 7 | Combustion gases | 1.46698 | 502.15 | 104.20 | 1.07343 | | | 351.56 | 80.06 |
| 8 | Combustion gases | 1.46698 | 363.15 | 102.53 | 1.04640 | | | 118.27 | 11.03 |
| 9 | Mechanical power | | | | | | | 518.51 | 518.51 |
| 10 | Mechanical power | | | | | | | 505.55 | 505.55 |
| 11 | Mechanical power | | | | | | | 231.09 | 231.09 |
| 12 | Electrical power | | | | | | | 225.80 | 225.80 |
| 13 | Electrical power | | | | | | | 0.80 | 0.80 |
| 14 | Net electrical power | | | | | | | 225.00 | 225.00 |
| 15 | Hot water | 1.300 | 323.150 | 900.00 | | 210.102 | 0.703 | 136.72 | 6.42 |
| 16 | Hot water | 1.300 | 323.250 | 1025.00 | | 210.627 | 0.705 | 137.41 | 6.62 |
| 17 | Hot water | 1.300 | 363.150 | 1000.00 | | 377.688 | 1.192 | 354.59 | 34.90 |
| 18 | Hot water | 1.300 | 343.150 | 950.00 | | 293.769 | 0.954 | 245.49 | 17.89 |
| 19 | Net heating energy/ exergy rate | | | | | | | 109.10 | 17.01 |
| 20 | Chilled water | 3.750 | 285.150 | 300.00 | | 50.699 | 0.181 | -203.37 | 5.30 |
| 21 | Chilled water | 3.750 | 280.150 | 275.00 | | 29.696 | 0.106 | -282.13 | 9.52 |
| 22 | Net cooling energy/exergy | | | | | | | 78.76 | 4.22 |

*Table 3:* The exergetic performance indicator values of the MIGTRIGEN's components

| Components | $\dot{E}x_F$ $(kW)$ | $\dot{E}x_{Pr}$ $(kW)$ | $\dot{E}x_{WEx}$ $(kW)$ | $\psi$ $(\%)$ | $RWExR$ $(\%)$ | $FExDR$ $(\%)$ | $PLR$ $(\%)$ | $ExIP$ $(kW)$ | $\Psi$ $(\%)$ | $WExIPR$ $(\%)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *AC* | 274.46 | 244.52 | 29.95 | 89.09 | 7.59 | 4.67 | 12.16 | 3.27 | 90.16 | 10.91 |
| *CC* | 640.87 | 388.72 | 252.15 | 60.66 | 63.89 | 39.34 | 102.40 | 99.21 | 71.76 | 39.34 |
| *GT* | 526.99 | 518.51 | 8.48 | 98.39 | 2.15 | 1.32 | 3.44 | 0.14 | 98.42 | 1.61 |
| *GTMS* | 518.51 | 505.55 | 12.96 | 97.50 | 3.28 | 2.02 | 5.26 | 0.32 | 97.56 | 2.50 |
| *G* | 231.09 | 225.80 | 5.29 | 97.71 | 1.34 | 0.82 | 2.15 | 0.12 | 97.76 | 2.29 |
| *REC* | 444.69 | 418.50 | 26.19 | 94.11 | 6.64 | 4.09 | 10.63 | 1.54 | 94.44 | 5.89 |
| *HE* | 69.04 | 28.28 | 40.76 | 40.96 | 10.33 | 6.36 | 16.55 | 24.07 | 62.88 | 59.04 |
| *WP* | 0.80 | 0.20 | 0.60 | 25.51 | 0.15 | 0.09 | 0.24 | 0.44 | 57.31 | 74.49 |
| *ACh* | 11.47 | 4.22 | 7.26 | 36.77 | 1.84 | 1.13 | 2.95 | 4.59 | 61.26 | 63.23 |

| Components | $RExIPR$ $(\%)$ | $FExIPR$ $(\%)$ | $PRI$ $(\%)$ | $FRI$ $(\%)$ | $WExC$ $(10^{-3}\$)$ | $RWExCR$ $(\%)$ | $EEF$ $(-)$ | $ExSI$ $(-)$ | $SEF$ $(-)$ | $EcoEF$ $(-)$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *AC* | 2.444 | 0.510 | 99.31 | 42.83 | 0.087 | 7.589 | 0.052 | 19.064 | 9.165 | 1.122 |
| *CC* | 74.204 | 15.480 | 157.87 | 100.00 | 0.731 | 63.892 | 0.649 | 1.542 | 2.542 | 1.649 |
| *GT* | 0.102 | 0.021 | 210.58 | 82.23 | 0.025 | 2.148 | 0.013 | 74.402 | 62.181 | 1.016 |
| *GTMS* | 0.242 | 0.051 | 205.32 | 80.91 | 0.038 | 3.285 | 0.021 | 48.203 | 40.000 | 1.026 |
| *G* | 0.090 | 0.019 | 91.70 | 36.06 | 0.015 | 1.339 | 0.008 | 118.484 | 43.723 | 1.023 |
| *REC* | 1.153 | 0.241 | 169.97 | 69.39 | 0.076 | 6.635 | 0.043 | 23.032 | 16.982 | 1.063 |
| *HE* | 18.000 | 3.755 | 11.48 | 10.77 | 0.118 | 10.328 | 0.155 | 6.440 | 1.694 | 2.442 |
| *WP* | 0.332 | 0.069 | 0.08 | 0.12 | 0.002 | 0.151 | 0.004 | 274.359 | 1.342 | 3.920 |
| *ACh* | 3.431 | 0.716 | 1.71 | 1.79 | 0.021 | 1.838 | 0.031 | 32.481 | 1.582 | 2.720 |