Low-carbon fuelled MGT-CHP system coupled with PEM electrolyser and fuel cell units: A Fuel Flexibility and Performance Study

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ABSTRACT:

Recently, micro gas turbine (MGT) systems for combined heat and power (CHP) plants have attracted much attention due to their high energy efficiency and low carbon emissions. Therefore, this work presents a 5.5 kW MGT-CHP system coupled with a proton exchange membrane (PEM) electrolysis cell and a fuel cell unit for domestic applications. The simulation study includes an MGT unit that produces both heat and electricity, a low-temperature PEM electrolysis of H_2O to produce H_2 fuel for the combustor, and a PEM fuel cell to generate electricity during system initialisation. The MGT unit in this study uses H_2, hythane (20% H_2 and 80% CH_4), natural gas (NG) and methane (CH_4) fuels to investigate the thermal and electrical efficiency and CO_2 emission avoidance for each fuel utilisation. The result shows that the combustion of H_2 and hythane in the MGT combustor produces almost the same amount of nitrogen oxides (NOx) due to the lower reaction temperature of the combustor. 7% of CO_2 and CO emissions were avoided by replacing NG with hythane. CO_2 and CO emissions were avoided by burning H_2 instead of other fuels. Higher thermal efficiency was seen on the H_2-fuelled MGT system. However, higher end-use costs were observed for the MGT system running on both H_2 and hythane fuels due to the higher purchase price of both fuels. The addition of a recuperator promoted lean combustion, which improved the overall efficiency of the proposed system. The outcome of the studied work achieved an efficiency of 82% for PEM electrolysis of H_2O and an MGT-CHP efficiency of 96%.

Keywords: Micro-combined heat and power (micro-CHP) system; Micro gas turbine (MGT); Fuel cell (FC); Electrolysis of water (H_2O); Low-carbon fuel.

Nomenclature:

Abbreviations and Symbols:

		O_2	Oxygen
Micro-CHP	Micro-Combined Heat and Power system	MGT	Micro Gas Turbine
FC	Fuel Cell	GHG	Greenhouse Gas
NG	Natural Gas	CO_2	Carbon Dioxide
IEA	International Energy Agency	CO	Carbon monoxide
ICE	Internal combustion engine	kW	Kilowatt
NO_X	Nitrogen Oxides	AWE	Alkaline water electrolyser
MTT	Micro turbine technology	NRTL	Non-Random Two-Liquid
PEME	Proton-exchange membrane electrolysers	CH_4	Methane
SOSE	Solid oxide steam electrolysers	NO	Nitric Oxide
PEMFC	Proton exchange membrane fuel cell	NO_2	Nitrogen Dioxide
C_2H_6	Ethane	N_2O	Nitrous oxide/Oxide of nitrogen
C_3H_8	Propane	N_2O_5	Dinitrogen pentoxide/Nitrogen Pentoxide
C_4H_{10}	Isobutane	CC	Combustion Chamber
C_4H_{10}	n-butane	C_5H_{12}	n-pentane
C_5H_{12}	Isopentane	C_7H_{16}	Heptanes
C_6H_{14}	Hexanes		

1.0 Introduction

The temperature of the earth is constantly rising and projected to reach 2°C - 6°C by the end of the 21st century because of continuous GHG emissions [1]. Climate change, such as sea flooding because of rising sea levels, acid rain, severe cold winters, and heat wave summers are effects of continuous GHG emissions [2]. Not long ago, 195 countries reached an agreement to reduce GHG emissions to avoid impossible reversals of climate change. Such an agreement also includes keeping the temperature rise below 2°C. To prevent such irreversible climate change, transition to low-carbon fuel, and renewable energy systems, improve in end-use efficiency, and carbon capture and storage were proposed to keep the temperature increase below 2 °C by 2030 [3]. Although net targets for carbon dioxide (CO_2) emissions by 2070 are necessary to reduce global warming. Achieving this goal requires a significant reduction in CO_2 emissions as it is the highest among other GHG emissions in all economic sectors [4] [5]. The increase in CO_2 emissions is due to the burning of hydrocarbons and solid fuels to generate heat and electricity in many sectors such as agriculture, utilities, transportation, etc [6].

The CO_2 emission from the utility has increased because of fossil fuels' combustion in an internal combustion engine (ICE) to produce heat and electricity and higher demand. For example, it is predicted that by 2040, the demand for energy will increase to 56%, and approximately 66% of the thermal energy from ICE is unused during combustion. Utility energy use can be classified into residential, commercial, and industrial sectors and accounts for 74% of total energy demand. For example, the share of the residential sector is 21%, the commercial sector is 22% and 31% for the industrial sector. The remaining 26% of the total energy demand goes to the transport sector [7] [8]. The building sector is one of the most important energy-consuming factors [9]. According to the International Energy Agency's 2022 report, buildings used about 34% of the world's total energy and generated about 37% of CO_2 in 2021. Due to population growth, electricity transmission losses and inefficient domestic gas boilers, the demand for energy in buildings is projected to grow to become the largest energy-consuming sector by 2040 [10] [9]. For these reasons, the use of low-carbon fuels and efficient small-scale heat engines and renewable energy are required to reduce CO_2 and other GHG emissions. Micro gas turbines (MGT), which have gained a lot of attention in recent years, can play an important role in improving efficiency and reducing GHG emissions in the building sector [6] [11]. Fig. 1 shows comparisons of building energy consumption and GHG emissions in the USA, Europe, and the UK [12].

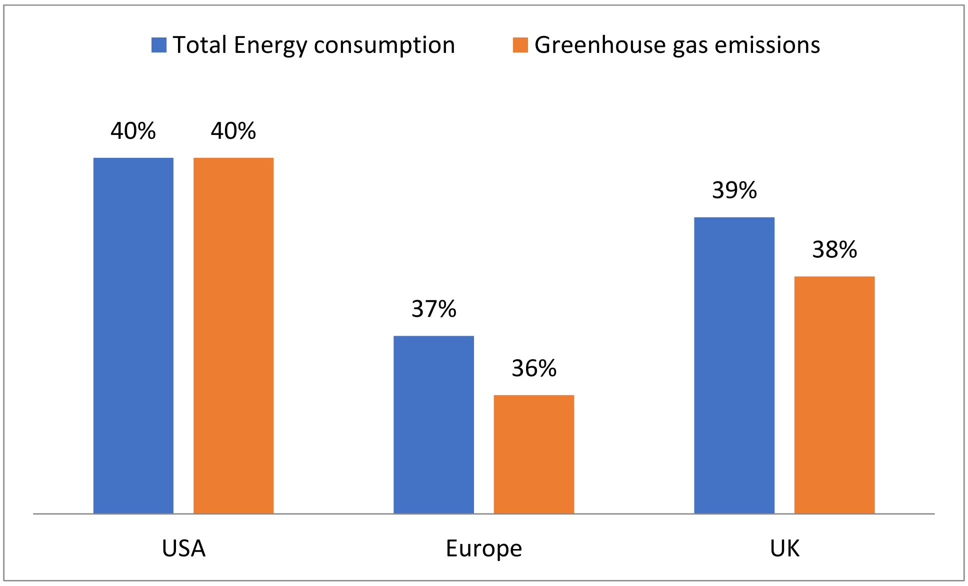

Fig 1: Comparisons of the building energy consumption and GHG emissions in the USA, Europe, and UK.

MGT systems are small types of gas turbines that generate both heat and electricity. Some of the advantages include a small-scale unit, low maintenance costs, weight and emissions, ease of use, and fuel flexibility [6] [11]. The first gas turbine technology with an output of 370 kW was developed by Holz in the 1920s. Although the micro-scale gas turbine system was launched in the 1950s. This system uses a high-speed generator connected to the turbine, a recuperator to recover waste heat, and other components to improve compactness and maximise the overall efficiency by 10%. In addition, the use of high-temperature materials to increase the turbine inlet temperature (TIT) further increased the thermal efficiency by 35% [11]. Initially, gas turbine systems were designed for powertrains and large-scale power distribution sectors. A combined heat and power (CHP) system based on MGT was introduced for a proper distribution of power in microgrid systems [11]. Nowadays, European countries have increased research on the integration of MGT systems into other units to reduce the operational cost of standalone MGT units. For instance, the techno-economic analysis result of hybrid MGT and other renewable energy units such as solar cells, a wind turbine system and a battery revealed that lower operational cost is feasible compared to a hybrid diesel generator or fuel cell coupled with any of these units (solar cells, wind turbine system and battery) [13]. The lower operation cost of MGT CHP systems is related to a feed-in tariff to offset investment costs. Apart from the lower operation cost of integrated MGT systems, *Ismail et al.* concluded that the use of low-carbon CHP systems such as natural gas (NG) based MGT-CHP can significantly reduce CO_2 emission by 40% [14] [15]. Despite carbon reduction by transitioning to the NG-MGT system, 56.4Mt of CO_2 came from UK residential and public sectors that use NG-fuelled gas boilers [16]. Unlike the NG-MGT system for small-scale utility systems, the H_2-fuelled MGT-CHP system has been suggested to achieve a net-zero target by 2050. For instance, replacing NG with grey H_2, $220g\ CO_2eq./kWh$ of heat associated with NG based gas boiler could fall to $64g\ CO_2\ eq./kWh$. This CO_2/kWh value of grey H_2-fuelled gas boiler could be avoided by using biohydrogen or green H_2 fuel from the electrolysis of H_2O [17]. Nonetheless, the thermal stress of combustor or cylinder walls, flame instability and the short reactant residence time which increases NOx formation are drawbacks of H_2-based heat engines [18] [19] [20]. A micro-CHP energy flow diagram for residential applications is displayed in Fig.1. Table 1 shows the properties of the four types of MGT fuel.

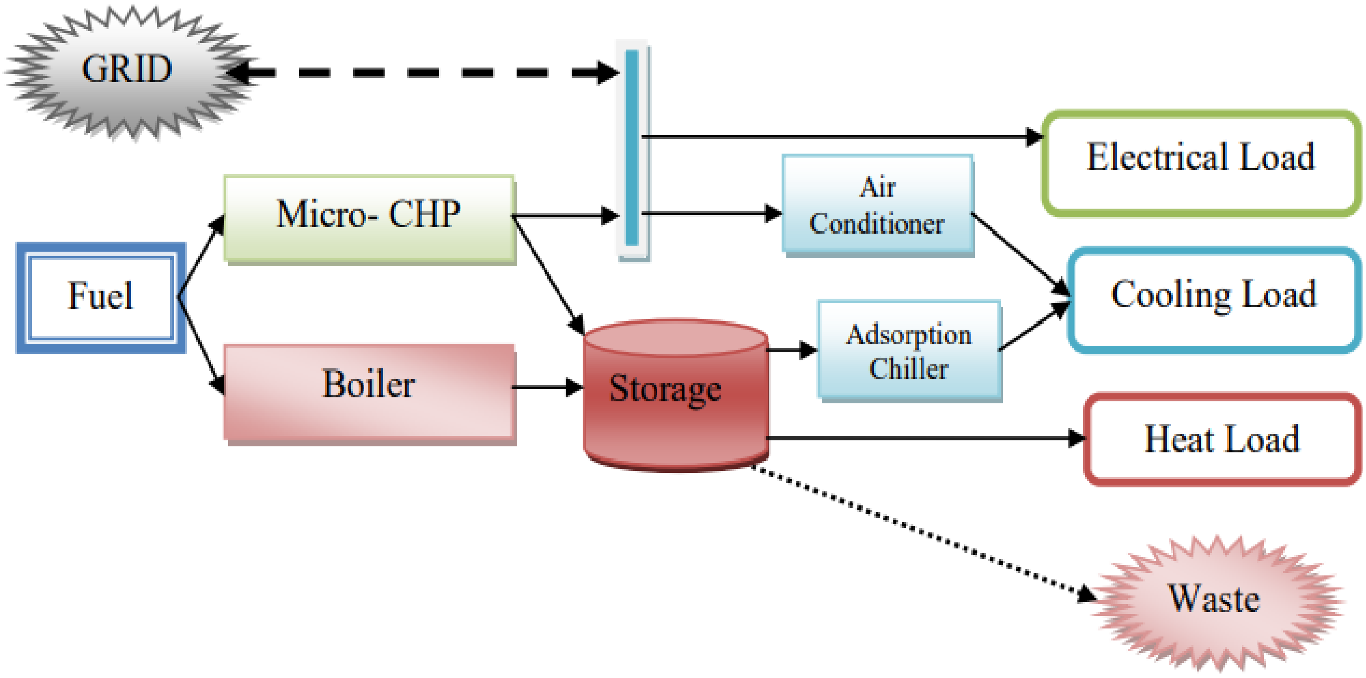

Fig 2: Micro-CHP energy flow diagram for residential applications [21]

Table 1 - The properties of the four types of MGT fuel [22] [23] [24].

Properties	Fuel type				Unit
	Hydrogen (H_2)	Hythane	Natural gas (NG)	Methane (CH_4)	
Lower heating value	120	70-75	42-55	50-55	MJ/kg
Density	0.09	0.4	0.72	0.657	kg/m^3
Boiling point	-253	-198	-161.5	-162	°C
Stoichiometric AFR	34.3	22.58	17.12	17.19	kg(a)/kg(f)
Stoichiometric CO_2 emissions	0	38.2	54.9	55	Mass (%)
Flame speed	1.85	0.68	0.38	0.39	m/s
Minimum ignition energy	0.02	0.19	0.31	0.28	MJ
Latent heat of vaporization	-	-	509	510	kJ/kg

The electrolysis of H_2O is a process where H_2O is split into H_2 and oxygen (O_2) using electricity. There are three main technologies in H_2O electrolysis such as proton exchange membrane electrolyser (PEM), alkaline water electrolyser (AWE) and solid oxide steam electrolyser (SOSE). The first two techniques (AWE and PEME) work at low temperatures, but the third (SOSE) works at high temperatures [25]. The production of H_2 using electrolysis methods is one of the most important advances in reducing carbon emissions [26]. Among the three main types of H_2O electrolysis, some of the advantages of PEMWE are high current density, fast response time, purity, and operating pressure. Integrating PEMWE into a micro-CHP system to produce heat, electricity and H_2 fuel offers more environmental benefits compared to a single NG-based micro-CHP system. In such a hybrid system, the electricity generated by the prime mover of the micro-CHP system which is sold to the grid at a cheaper rate can replace the grid electricity in the electrochemical splitting of H_2O process to produce H_2 [27]. For example, *Nami et al.* [28] reported 56.2 kg/h and 49.2% exergy and energy efficiencies of combined PEMWE and organic Rankine cycle system for H_2 production**.** Additionally, *Ferrero and Santarelli* investigated an integrated PEMWE and high-pressure, low-temperature multi-junction solar system and reported improved performance of the system [29]. Similar to the integrated PEMWE-CHP, the hybrid micro-CHP and proton exchange membrane fuel cell (PEMFC) system is one of the viable options for low-carbon emission and noise reduction [28] [30]. A hybrid PEMFC-based micro-cogeneration system can reduce CO_2 emission and total energy consumption and co-produce heat and electricity using H_2 as fuel [31]. For example, *Lümmen et al.* [27] reported 76.94% and 53.86% energy and exergy efficiencies during a study of micro-combined cooling, heating, and power systems (MCCHPs). The researched work also reported CO_2 emission of 2.8 kg/h. While an integrated micro-CHP plant, PEM electrolysis and fuel cells, and solar or wind renewable energy systems can simultaneously generate electricity at a cheaper rate compared to a single H_2-fuelled MGT system [27].

To promote low-carbon buildings and improve the efficiency of the current micro-CHP system, this study aimed to simulate an integrated MGT-CHP system, coupled with PEM electrolyser and fuel cells units for the first time. The purpose of this proposed system is to investigate the effect of H_2, natural gas (NG), CH_4 and hythane (H_2 and CH_4) combustion and analyses of CO_2 and thermal nitrogen oxide (NOx) emissions of the proposed system. Instead of selling the generated electricity to the grid at a lower price and buying it at a higher price, the generated electricity will be used to operate the downstream units such as PEMWE. Produced H_2 from the combined system will also be utilised to generate electricity via FC during system initialisation and as combustion fuel. Unlike the current micro-CHP unit, this simulated system intends to increase the electrical power output by reducing the heat output for applications that require more electricity.

2.0 Methodology

To achieve the target power of 5.5 kW, Aspen Plus process simulation software was used with H_2, CH_4, NG and hythane as combustion fuels. A rigorous reactor (RGibbs) was considered to simulate the fuel combustion and electrolysis of H_2O using proper electrochemical reactions in the chemistry ID. Other Aspen Plus core components included in this simulation are pumps, compressor, turbine, recuperator (heat exchanger), switch, mixer, splitter, and calculator block. The upstream intake parameters of the proposed system are shown in Table 2**.** The simulation method of this proposed system is categorised in the below scenarios:

- Aspen Plus process simulation of an existing MGT-based micro-CHP system to improve knowledge of the proposed model.
- Aspen Plus process simulation for the proposed model which include a micro-CHP system running on H_2, hythane, NG and CH_4.

Table 2: MGT combustor inlet and outlet parameters.

Property/Parameter	**Value**	**Unit**
MGT combustor intake fuel pressure	2.09	bar
MGT combustor intake fuel temperature	970	K
Air mass flow rate	0.053	kg/s
MGT burner exit temperature	1323.4	K

2.1 Process simulation of existing micro-CHP system and proposed innovative system in Aspen Plus.

The process simulation of the existing micro-CHP system and the proposed model were carried out in Aspen Plus and both the Peng-Robinson and Non-Random Two-Liquid (NRTL) equations of states were employed with mixed as the only substream. The assumptions considered in both process simulations are described below:

- All processes are in steady state condition.
- Intake feed temperature and pressure is ambient and atmospheric conditions.
- The pressure drop at each stage is minimal.
- 78% nitrogen, 21% oxygen, and 1% argon mole flow are the compositions of air fed to the system.
- Dry NG is composed of 96% CH_4 (methane), 2% C_2H_6 (ethane), 0.60% C_3H_8 (propane), 0.18 C_4H_{10} (isobutane), 0.12% C_4H_{10} (n-butane), 0.14% C_5H_{12} (isopentane), 0.06% C_5H_{12} (n-pentane), 0.10% C_6H_{14} (hexanes) and 0.80% C_7H_{16} (heptanes) [32]**.**
- Oxides of nitrogen (NOx) include nitric oxide (NO), nitrogen dioxide (NO_2), nitrous dioxide (N_2O) and nitrogen pentoxide (N_2O_5).
- 80% of CH_4 and 20% of H_2 are composition of hythane.
- Electrolysis of H_2O to generate H_2 for hythane using the electricity generated from the proposed system.
- H_2 fuel cell to generate electricity for the motor during the start-up of the proposed system.
- Air fed to the combustor is preheated by a recuperator (heat exchanger) unit to maximise the overall efficiency.

Fig. 3 shows an NG-operated micro-CHP system for heat and power production. In the process flow diagram, air at 0.053kg/s is compressed to a pressure of 2.9 bar in the compressor and sent to the recuperator system to increase the temperature to 970K. Pressurised hot air from the recuperator is combusted with pressurised NG in a ratio of 106:1 in the combustion chamber (CC). The hot gas leaves the CC at a temperature of 1323.4K to a turbine where electricity is generated. The hot gas in the turbine creates a rotatory motion that turns an electricity generator for the conversion of mechanical energy to electrical energy with 5.5kW power output. The low-pressure hot flue gases exiting the turbine preheat the combustor intake before heating H_2O in another heat exchanger. In a hot H_2O heating system, the cold H_2O from the storage tank is pressurised by a pump before absorbing heat from the flue gases. This is a continuous cycle to provide hot water and heat the environment while the micro-CHP system is in operation. During the system start-up time, electrical energy from the grid is needed to ramp up the compressor for air intake with the use of an electric generator which in turn, works as a motor. In the final stage, the exhaust gas which is a mixture of carbon dioxide (CO_2), nitrogen gas, oxides of nitrogen (NOx) and others from the H_2O heater is discharged into the environment.

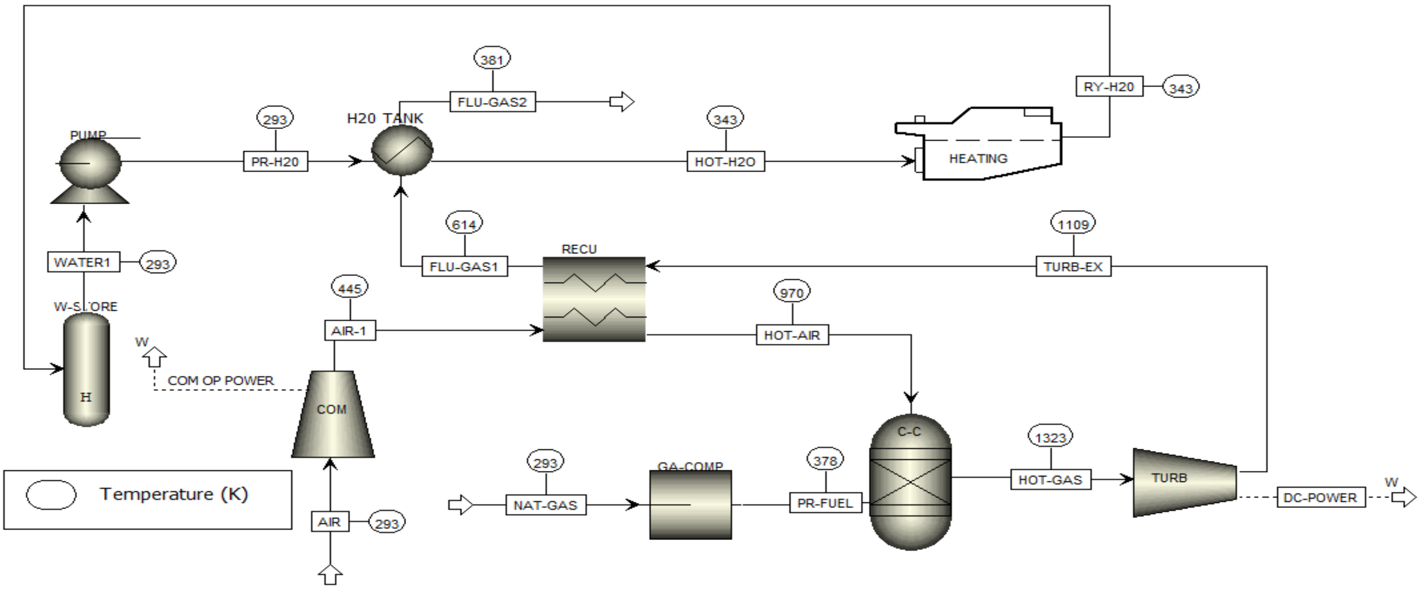

Fig 3: Aspen Plus process diagram of MGT-CHP system operating with NG.

Similar to a conventional micro-CHP system, the proposed model shown in Fig. 4 uses H_2 gas, hythane, NG and CH_4 gas as fuel. Proton exchange membrane (PEM) electrolysis of H_2O and H_2 fuel cells were introduced to generate H_2 feedstock and electricity for the motor during start-up time. The motor which is also an electric generator spins the compressor during the initiation period to suck air in and increases the pressure. Unlike a conventional micro-CHP system, the proposed model has a fuel-switching unit, mixer, splitters and motor-electricity generator. The fuel-switching unit allows one fuel to be used at a time to monitor the heat output of the combustion chamber (CC). The mixer (mix) mixes both the H_2 feed and the H_2 by-product of the PEM electrolyser unit to feed CC. The motor rotates the compressor at a speed of 240000 rpm during the kick-off time. While a controlled amount of O_2 gas into the PEM fuel cell (PEMFC) was possible by using an oxygen (O_2) splitter. Similarly, the H_2 gas splitter controls the flow rate of H_2 gas to the combustor and PEMFC to generate electricity for the motor. The calculator block estimates the power output of the proposed system by subtracting the input powers of the air and gas compressors and a pump from the output power of the turbine. The rest of the unit has the same working principle as the conventional micro-CHP system. This developed system also has the potential to increase the output power by reducing heat production in applications where less thermal energy is needed.

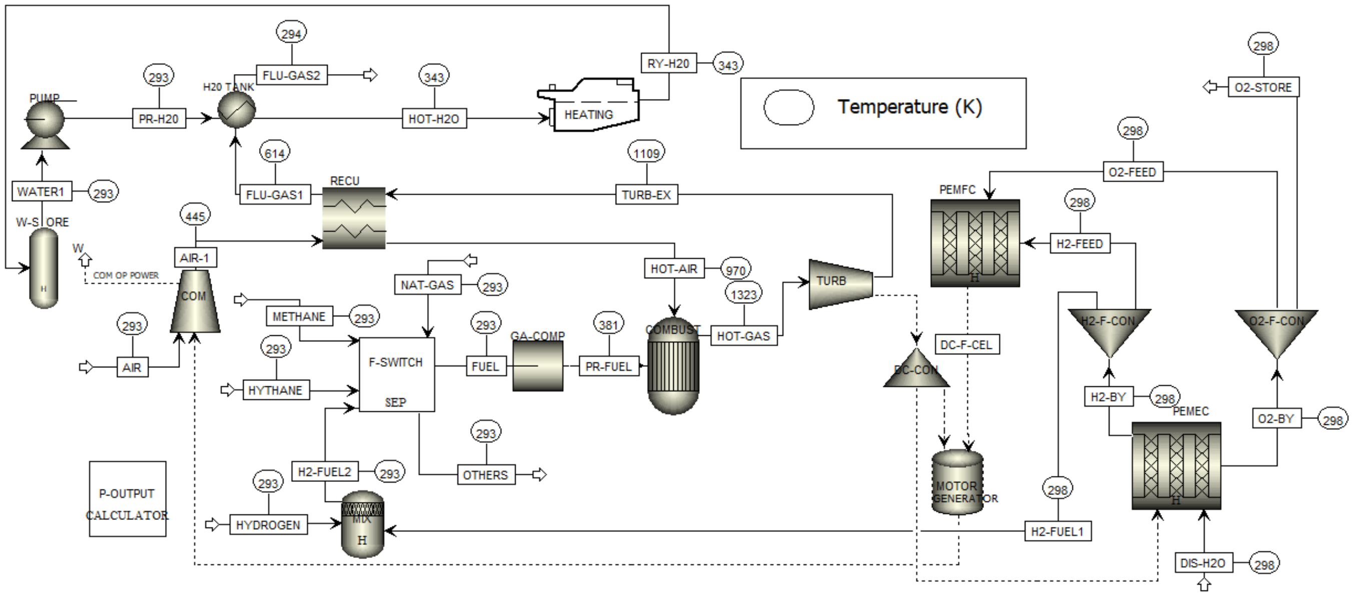

Fig 4: Aspen Plus process diagram of MGT-CHP system coupled with PEM electrolyser and fuel cells.

3.0 Results and Discussions

Table 3 illustrates the process simulation results. To reduce the percentage of CO_2 emissions in a micro-CHP system, a mixture of CH_4 and H_2 (hythane) should be used as the combustion fuel. Whereas the absence of CO_2 emissions from a micro-CHP system requires the burning of pure H_2 fuel in the combustion chamber. Using the same mass flow rate of hythane as NG, the heat output of the combustor was relatively higher, while smaller changes in heat output were observed in the burner operating with CH_4 as the fuel. Combustion of H_2 at the same mass flow rate as NG was extremely higher and increased the amount of NOx emissions and the overall efficiency. Thus, keeping the same fuel mass flow rate means that MGT combustors with larger bore diameters and lengths are needed for both hythane and H_2 to promote longer reactant residence time. To maintain the same combustor heat output for all fuels at a constant oxidant flow rate, the air-to-fuel ratio of 106:1 for NG and CH_4, 135:1 for hythane (80% CH_4 and 20% H_2) and 252:1 for H_2 were utilised. This approach reduced NOx formation and eliminated short reactant residence time which can lead to combustion outside the burner. Considering the mass flow rate of H_2 fuel into the combustor, the introduction of a small-scale renewable energy system such as a solar or wind energy system may be necessary to increase the H_2 by-product of the PEMEC. For example, utilising the power output of the developed model, a maximum of 40% of H_2 can be produced for hythane fuel. The deployment of both PEMEC and PEMFC has shown that it is possible to avoid the need to sell the generated electricity to the grid at a lower price and buy the electricity at a higher price to run the motor at 240,000 rpm during start-up. An increase in the power output of the model was possible by reducing the discharged turbine pressure since the downstream units are not pressure-dependent. For both the combustor and generator units operating at the listed air-to-fuel ratio in Table 3, a thermal energy output of 26.9MJ/h and a net power output of 5.5kW were recorded.

Table 3: Emission result of CC operating at 3 bar pressure and 1323.4K temperature at 26.9MJ/h and 5.5kW energy output.

Fuel % NG	Fuel % CH_4	Fuel % H_2	Prod. CO_2 kg/h	Prod. H_2O kg/h	Prod. O_2 kg/h	Prod. N_2 kg/h	Prod. NOx kg/h	Air-to-fuel ratio
100			5	5.7	31.4	148.8	0.09	106:1
	100		5	5.7	31.3	148.8	0.09	106:1
	80	20	3.1	6.8	31.8	148.8	0.09	135:1
		100		8.5	32.5	148.8	0.095	252:1

3.1 Fuel analysis of the simulated hybrid system.

During the process simulation of the integrated system running on pure H_2, hythane, NG and CH_4, the combustion chamber outlet temperature is maintained at 1323.4 K. At the same mass flow rate of 0.5 g/s, the heat output of the combustion chamber was found to be 39.4 kW for pure H_2, which was much higher than 13.9 kW for hythane, 7.4 kW for NG, and 7.5 kW for CH_4 kW. The adiabatic flame temperature of H_2 is higher than hythane, NG and CH_4 resulting in higher heat production. However, H_2 produced a lower electrical output (5.03 kW) compared to hythane NG and CH_4 because of its low density. As shown in Table 4, the molar and mass enthalpy of the combustion chamber exhaust gas operating with pure H_2 had negative values compared to other fuels because the exothermic reaction releases more energy. By comparing the molar and mass entropy of the combustion chamber exit gases, H_2 has lower values because of its lightweight and movement flexibility [32]. The simulated system shows that the mass flow rate of H_2 and hythane can be reduced to achieve the same heat output of other fuels (NG and CH_4). However, reducing the mass flow rate of both fuels (H_2 and hythane) will further decrease the electrical power output of the MGT-CHP system. Thus, using the same mass flow rate of CH_4 for H_2 fuel to the MGT combustor, and recovering more heat for distilled H_2O production, more H_2 fuel can be produced via the electrolysis of H_2O in an application with less heat requirement. In this approach of substituting NG or CH_4 for pure H_2 fuel for more heat production, a larger micro combustor size with coolant addition such as steam or N_2 may be required to minimise thermal combustor wall stress and prevent exhaust gas exceeding 1323K temperature. The simulated system achieved an efficiency of 96% for CHP and 82% for the electrolysis unit. Fig. 5 shows a thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG and CH_4. From the displayed graph, low-density and higher energy-density fuels produced more heat and less power output.

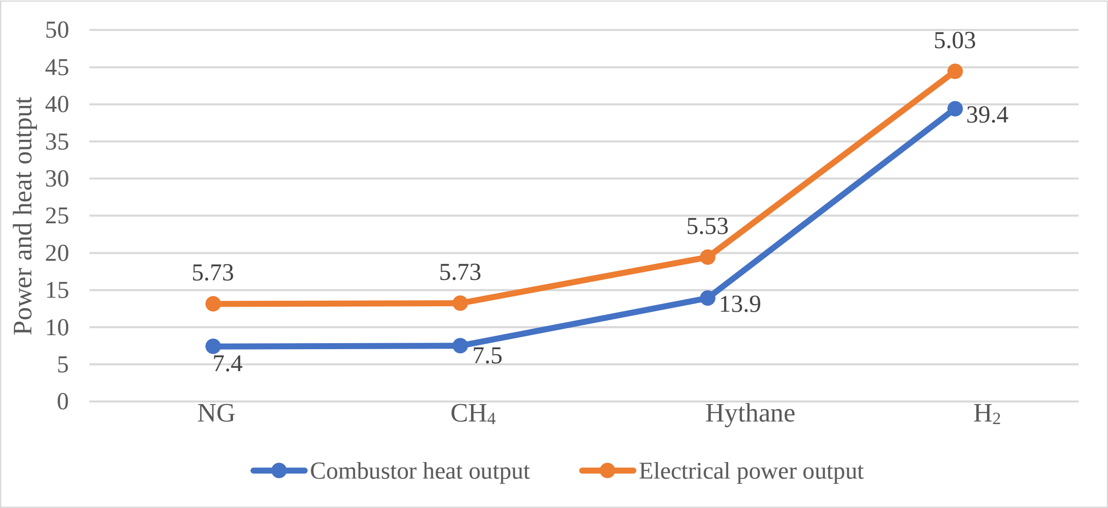

Fig 5: Thermal and electrical power outputs comparison of the simulated system running on H_2, hythane, NG, and CH_4.

Table 4: Comparison of combustor exit gas running on H_2, hythane, NG and CH_4 fuel at 0.5 g/s mass flow rate.

Properties	H_2	Hythane	NG	CH_4	Unit
Combustor heat output	39.4	13.9	7.4	7.5	kJ/s or kW
Electrical power output	5.03	5.53	5.73	5.73	kW
Molar Enthalpy of the combustor exit gas	-84.5	12106.3	15361.1	15304.5	kJ/kmol
Mass Enthalpy of the combustor exit gas	-3.1	429.6	539.6	537.7	kJ/kg
Molar Entropy of the combustor exit gas	38.4	41.1	41.7	41.7	kJ/kmol-K
Mass Entropy of the combustor exit gas	1.4	1459.5	1.5	1.5	kJ/kg-K
Enthalpy Flow of the combustor exit gas	-0.2	23	28.9	28.8	kJ/sec
Average	27.1	28.2	28.5	28.5	MW

3.2 NOx emission analysis and model validation

The simulated hybrid MGT-electrolysers system with an output power of 5.5 kW requires larger H_2 and hythane combustors' size to operate smoothly as NG and CH_4 based MGT systems with low NOx formation. The result shows that NOx production was about 0.09 kg/h for all four fuels at lean combustion. For example, thermal NOx formation occurs at a reaction temperature above 1773.15 K [30]. However, CFD simulation software may be required to properly investigate the NOx amount on each fuel of the simulated system. Nonetheless, the addition of steam or N_2 may be required for H_2 combustion to control the NOx formation rate. The use of these renewable fuels such as H_2 and hythane has been found to provide efficient MGT performance and significantly reduce CO_2 and CO emissions. Designing flameless burners and maintaining H_2-controlled flame temperatures are two key points in the development of H_2 and hythane systems in this field (MGT-based micro-CHP system).

The simulated model is validated part by part with data listed in the literature. Comparing the MGT-CHP unit of this study with another MGT system installed at Staffordshire University, a marginal difference was recorded on combustors operating with H_2 and hythane fuels. The difference was attributed to the higher heat output of combustors operating with both fuels. For instance, NOx emissions <27 ppm (part per million) at 15% O_2, electrical power output of 3kW, electrical efficiency of 16%, and a combined efficiency of >94% were reported for the MTT MGT-CHP system [33]. For this simulated system, higher electrical and lower thermal efficiencies were recorded. Higher electrical power output makes this model more suitable for small-scale units' where higher electrical energy is required. Comparing the efficiency of the PEMEC unit with *Sapountzi, et al.* studied work, both studies achieved nearly the same efficiency. For example, PEMEC efficiency between 65% – 82% was reported by *Sapountzi, et al* [34].

3.3 Environmental assessment and economic analysis

H_2 has many advantages over traditional fuels. The main advantage of H_2 and H_2-rich fuels in MGT is lower GHG emissions [35]. In recent years, H_2 and a mixture of H_2 and CH_4 (hythane) have been used in MGT systems [36]. This section presents the environmental analysis of renewable fuels such as H_2 and hythane with non-renewable fuels like NG or CH_4. The introduction of H_2 and hythane in the MGT-based micro-CHP system was found to reduce GHG emissions. The simulation results show that when producing the same power (i.e. 5.5 kW), H_2 releases zero CO_2 emission. While CO_2 emission of 3.1 kg/h for hythane, 5 kg/h for NG and CH_4 was seen. As current MGT-CHP systems use NG as fuel, GHG emissions and environmental pollution will continue to be on the rise. Although, NG-based MGT systems can still be used as a transitional fuel for coal and oil due to its lower CO_2 emissions, but not the most optimal energy solution [31]. To reduce carbon emissions and increase energy efficiency, H_2 stands out as one of the most potential energy carriers due to its CO_2-free and high energy density. Several countries, such as Germany, Japan, America, China, and others, have proposed strategies to develop H_2-based energy technologies [37]. At the same time, H_2 research increased, including its production, storage and utilisation [38]. Connecting H_2 energy to MGT-CHP systems offers the possibility of even greater efficiency, reliability and lower emissions for residential and commercial applications. Therefore, a H_2-based MGT-CHP system has been considered a promising alternative to fossil fuel-based cogeneration systems in terms of efficiency improvement and reduction of carbon emissions [31].

The price of fuel is one of the most important parameters that has a direct relationship with the economic benefits of the MGT-CHP system operating with low-carbon fuels because it directly affects the operational cost. This section presents the economic analysis of H_2 and hythane with other fuels such as NG and CH_4. H_2 has a lot of potential for sustainable development but also has some disadvantages from an economic point of view because the economics of 100% H_2 dependence is still unknown and the higher cost of H_2 fuel reduces competitiveness [23]. The purchase price of H_2 is much higher compared to other fuels (hythane, NG and CH_4). For instance, green H_2 costs between \$5.10/kg and 10.3/kg in contrast to grey H_2 (obtained from hydrocarbon reforming methods without carbon capture and storage (CCS) units) with a sales price of \$1.89/kg [39]. In addition, H_2 production from NG will increase import by 30% [40]. In this regard, it would be beneficial to build H_2 production plants closer to CHP systems to mitigate storage and transportation costs and challenges [39] [40]. By comparing H_2 and hythane from an economic perspective, it is more cost-beneficial to use hythane instead of 100% H_2 for MGT-CHP systems during the transition period. However, burring H_2 and CH_4 (hythane) at a ratio of 20:80 can reduce carbon emissions only by 7% [41]. In addition, electricity from the grid costs \$0.5/kWh in the UK and \$0.54/kWh in the USA [42]. While the feed-in tariff (FIT) is about \$0.12/kWh or lower. By using produced electricity from the simulated system to produce H_2 rather than selling it at a cheaper rate to the grid, between 6 – 7% of GHG emissions and 43% end-user cost increase can be avoided. To achieve a successful H_2 economy, it is recommended to switch to more efficient and environmentally friendly H_2 production technologies.

4.0 Conclusion

A natural gas (NG), CH_4, hythane and H_2 fuelled MGT coupled with a PEM electrolyser and fuel cell units was simulated as a combined system. The developed system produced H_2 for hythane fuel via the electrolysis of H_2O and electricity using a fuel cell system. By producing H_2 for hythane and electricity for electrical units, selling generated electricity to the grid at a cheaper rate and buying at a higher price were avoided. Low NOx emissions from both hythane and H_2 fuels showed that by burning any of these fuels with the addition of coolants such as H_2O in the combustor, the same NOx levels can be achieved with NG-based MGT. Replacing NG with hythane reduced CO_2 emission by 7%, while the absence of CO_2 emission was observed from H_2 combustion. The findings also suggested the application of renewable solar or wind energy systems to the simulated system operating with H_2 fuel to increase the production rate. CFD simulation of MGT-CHP combustors operating with hythane and H_2 fuel with the addition of coolant was recommended to properly investigate NOx formation and thermal stress of the combustors' walls. An increase in the size of the MGT-CHP combustor operating with H_2 or hythane at the same fuel mass flow rate was also suggested to improve the reactant residence time and prevent combustion outside the combustor. Efficiency of 96% for CHP and 82% for electrolysis were achieved from the developed hybrid system.

CRediT authorship contribution statement

Muhammad Asim Khan: Conceptualization, Methodology, Formal analysis, Investigation, Writing – Original Draft.
Linus Onwuemezie: Conceptualization, Methodology, Software, Validation, Review & Editing, Writing – Original Draft.
Hamidreza Gohari Darabkhani: Methodology, Formal analysis, Investigation, Writing – Original Draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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