



Research article

Thermodynamic analysis of a novel hybrid gas turbine – Solid oxide fuel cell power generation system using ammonia as a zero-carbon fuel

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ARTICLE INFO

Keywords:

Ammonia
Gas turbine
Hybrid energy system
Solid oxide fuel cell
Thermodynamic analysis

ABSTRACT

Ammonia has emerged as a promising hydrogen carrier and carbon-free fuel. This study designs a novel gas turbine-solid oxide fuel cell (GT-SOFC) hybrid energy system, distinct from traditional SOFC-GT configurations, utilising ammonia as the primary fuel. In this hybrid system, ammonia is combusted with oxygen under fuel-rich conditions in the GT, generating both electricity and hydrogen. Hydrogen is then fed into the SOFC for electricity generation. The GT-SOFC hybrid system was designed and modelled using Aspen Plus. The first and second laws of thermodynamics were applied to perform energy and exergy analyses of the proposed system. A parametric study was conducted to study the effect of key parameters on the performance of the hybrid system, including equivalence ratio, combustor pressure, current density in the SOFC, and fuel utilisation ratio. The fuel utilisation ratio in SOFC was found to have a significant impact on the performance of the GT-SOFC hybrid system. The NO_x emissions from this hybrid system were found to be negligible. An energy and exergy efficiencies of 75.5% and 72.1%, respectively, were achieved, which were higher compared with the conventional SOFC-GT system with a similar power output.

1. Introduction

Hydrogen plays an increasingly important role in the decarbonisation of the energy and industrial sectors. However, the hydrogen economy presents many challenges in its storage and transportation due to its low volumetric energy density and the lack of global infrastructure to support cost-effective and efficient distribution. Ammonia has been recognised as an excellent hydrogen carrier, as it offers high flexibility in transportation and storage [1]. Currently, ammonia is mainly produced through the Haber-Bosch process [2] and used as a fertiliser with a global capacity of approximately 200 Mt per annum [3]. Ammonia can be used directly as a fuel, and recent research presented significant progress in ammonia combustion in gas turbines (GTs) [4]. However, the limitations of this technology include high NO_x emissions and low combustion efficiency, mainly due to the slow burning rate of ammonia and nitrogen in the fuel [5]. Ammonia has also been suggested to be used directly in solid oxide fuel cells (SOFCs) [6,7]. However, challenges associated with direct NH₃ SOFC include slow ammonia decomposition kinetics, potential NO_x emissions, and catalyst (e.g., nickel) deactivation due to nitridation [8,9].

The integration of SOFC with GT for power generation offers an option to increase the energy efficiency [10], as shown in previous studies focusing on the use of ammonia in the combined SOFC-GT system [11,12]. In the conventional SOFC-GT system, ammonia is first cracked to produce hydrogen, which is then supplied to the SOFC for power generation. The unreacted H₂ from the SOFC is fed into the combustor of the GT for power generation. This process requires intensive energy for ammonia cracking, leading to high costs and low overall energy efficiency. Also, the unreacted hydrogen from the cracking unit leads to NO_x emissions when combusted in the GT [13,14].

To address the challenges associated with conventional hybrid SOFC-GT systems, a new concept of a GT-SOFC system is proposed. In this process, the ammonia feedstock is fuel-rich combusted and cracked, before the products (H₂, N₂, and H₂O) enter the GT. The fuel-rich ammonia combustion offers 2 functions: producing NO_x-free hot combustion gas for power generation and producing hydrogen for the SOFC for additional power generation [15,16]. Unutilised hydrogen in the SOFC can be burned in the combustor to enhance ammonia fuel-rich combustion. The overall aim of this paper is to understand the

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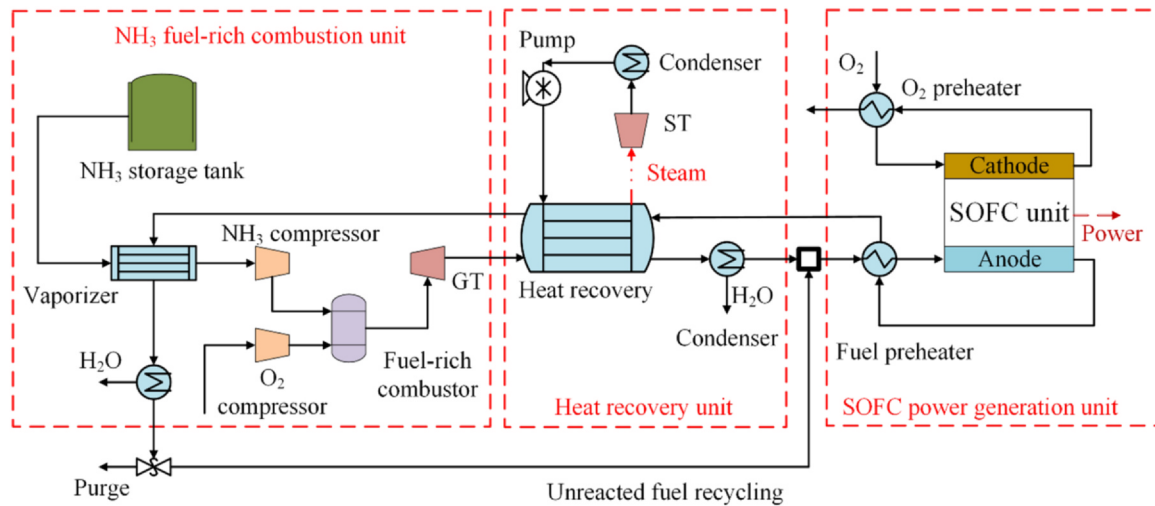


Fig. 1. Schematic diagram of the ammonia-based GT-SOFC power generation system with unreacted fuel recycling. GT = gas turbine; SOFC = solid oxide fuel cell; ST = steam turbine.

thermodynamic performance of the GT-SOFC system. The outcomes will shed some light on the design of effective ammonia energy systems.

2. System description, modelling, and evaluation

2.1. System description

The schematic diagram of the novel GT-SOFC power generation system with unreacted fuel recycling is presented in Fig. 1. In green ammonia production processes, a large amount of oxygen is usually generated as a byproduct from the electrolysis of water to produce green hydrogen – a precursor for green ammonia synthesis [17]. Therefore, in this study, oxygen is adopted for fuel-rich combustion and as the oxidation agent in the cathode of the SOFC unit. Firstly, the liquid ammonia from the storage tank is vaporised and compressed. After compression, ammonia is preheated and mixed with compressed O_2 . The mixture of NH_3 and O_2 is then sent to the combustor, which operates under the fuel-rich condition with an equivalence ratio (ER) of 4.5–6 [18]. Following the fuel-rich combustion process, the high-temperature output stream (mainly including H_2 , H_2O , and N_2) is expanded in the GT for power generation. The sensible heat of the exhaust gas is recovered for steam generation in the heat recovery steam generator (HRSG) and then conveyed to the SOFC unit along with the recycled H_2 . In the SOFC unit, H_2 is oxidised by the oxygen transported from the cathode, where the chemical energy of the inlet fuel is converted to power. Following power generation in the SOFC unit, the unreacted O_2 stream from the cathode of the SOFC unit is sent back to the oxygen preheater to be preheated and recycled back to the SOFC. The sensible heat of the unreacted high-temperature fuel is recovered by preheating the inlet fuel of the SOFC unit, generating steam in the HRSG, and vaporising NH_3 from the storage tank. After heat recovery, 99% of the unreacted fuel stream can be recycled at the anode of the SOFC unit for power generation.

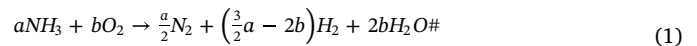
2.2. Process modelling

The GT-SOFC power generation system was modelled with the Aspen Plus V.12.1 software and can be divided into 3 main units (shown in Fig. 1): the NH_3 fuel-rich combustion unit, the heat recovery unit (HRSG), and the SOFC power generation unit.

2.2.1. NH_3 fuel-rich combustion unit

The NH_3 fuel-rich combustion unit (also called the Brayton cycle unit) consists of 2 gas compressors, gas-gas heat exchangers, the fuel-

rich combustor, and the GT. The gas compressors and the GT were modelled using the Compr Block, and the gas-gas exchangers were modelled using the MHEATX Block. The fuel-rich combustor is modelled by the RGibbs block, which is widely used in the simulation of combustion processes [19,20]. The partial oxidation of NH_3 under fuel-rich conditions produces heat and hydrogen, which was represented by Eq. (1). The ER is defined as the ratio between the actual fuel to oxygen ratio and the stoichiometric fuel to oxygen ratio (Eq. (2)).



$$ER = \frac{3a}{4b} \quad (2)$$

2.2.2. Heat recovery unit (HRSG)

In the heat recovery unit, the Rankine cycle is applied for waste heat recovery. The unit converts heat energy into mechanical energy, which is ultimately transformed into electricity. This unit consists of a boiler, a steam turbine (ST), a condenser, and a pump. The boiler was modelled as a heat exchanger to provide heat sources. Water is pressurised through the pump and then delivered to the heat exchanger, where it is heated. The ST allows for the expansion of the high-temperature, high-pressure steam, and the internal energy of the steam is converted into mechanical energy, which is subsequently converted into electricity. After expansion, the steam is condensed into liquid form in the condenser, releasing residual heat. The condensed water is then fed back to the pump to start the next cycle.

2.2.3. SOFC power generation unit

To model the SOFC unit, 3 parts were considered: the anode, the cathode, and the heat exchanger. The SOFC anode was modelled as a Gibbs reactor (RGibbs block), as an electrochemical reaction occurs within unit. The SOFC cathode is modelled using a separator (Sep), as oxygen ions are transferred within the SOFC. Only a portion of the heat generated by the electrochemical reaction is converted to power, and the heat flow function is applied to the heat exchanger. The heat exchanger is used to simulate the temperature of the exhaust gas of the SOFC cathode, and the exit temperature of the heat exchanger is set to 800 °C, which is the same as the temperature of the exhaust gas of the SOFC cathode and the SOFC operating temperature. As shown in Fig. 1, a recirculating stream from the anode chamber is mixed with the fed fuel stream to the SOFC stack, and the Design-spec function is applied to split the anode output stream at different steam-to-carbon (S/C) ratios. The mixed fuel stream enters the SOFC anode chamber following the

fuel preheater. The main electrochemical reaction that takes place at the SOFC anode is the oxidation of the hydrogen produced from the fuel-rich combustion process. The inlet air is sent to the SOFC cathode and separated to achieve the required oxygen molar flow rate. The required molar flow rate of oxygen ($n_{O_2, req}$) based on the fuel utilisation factor (U) can be estimated with Eq. (3):

$$n_{O_2, req} = U \times (0.5n_{H_2} + 0.75n_{NH_3}) \quad (3)$$

where n_{H_2} and n_{NH_3} represent the molar flow rate (in $\text{mol}\cdot\text{s}^{-1}$) of hydrogen and ammonia contained in the fuel stream, respectively.

As shown in Fig. 1, the oxygen is heated in an oxygen preheater with the heat from the electrochemical reaction. Therefore, there is no energy output from the SOFC power generation unit at the SOFC cathode (Sep), which means that the only energy output of the unit is at the SOFC anode (RGibbs block).

The current of the SOFC can be calculated using Eq. (4):

$$I = F \times U \times (2n_{H_2} + 3n_{NH_3}) \quad (4)$$

where F is the Faraday constant of $96,485 \text{ C}\cdot\text{mol}^{-1}$.

The current density of the SOFC (i_c) can be obtained using Eq. (5):

$$i_c = \frac{I}{A_{Act}} \quad (5)$$

where A_{Act} is the active surface area of the SOFC power generation unit in m^2 .

The actual SOFC voltage (V_{SOFC}) can be estimated by applying semi-empirical correlations that display the variations in cell voltage between the actual operating conditions and the reference state operating conditions (Eq. (6)):

$$V_{SOFC} = V_{ref} + \Delta V_p + \Delta V_T + \Delta V_{an} + \Delta V_{cat} \quad (6)$$

where V_{ref} represents the reference voltage in mV, ΔV_p , ΔV_T , ΔV_{an} , and ΔV_{cat} represent the variance of voltage (in mV) by the operating pressure, operating temperature, flowing composition in the anode, and flow composition in the cathode on cell voltage. These parameters can be calculated using the equations below (Eqs. (7)-(11)):

$$V_{ref} = 0.72988 + 2.0014 \times 10^{-4}i_c - 9.668 \times 10^{-7}i_c^2 + 2.626 \times 10^{-10}i_c^3 \quad (7)$$

$$\Delta V_p = 0.76 \times \log\left(\frac{P_{SOFC}}{P_{ref}}\right) \quad (8)$$

$$\Delta V_T = 8.00 \times 10^{-6} \times (T_{SOFC} - T_{ref})i_c \quad (9)$$

$$\Delta V_{an} = 0.172 \times \log\left[\frac{(P_{H_2}/P_{H_2O})}{(P_{H_2}/P_{H_2O})_{ref}}\right] \quad (10)$$

$$\Delta V_{cat} = 0.092 \times \log\left(\frac{P_{O_2}}{P_{O_2,ref}}\right) \quad (11)$$

where P_{SOFC} is the actual operating pressure (in bar) of the SOFC of both electrodes, T_{SOFC} is the operating temperature (in K) of the SOFC power generation unit, P_{H_2}/P_{H_2O} is the ratio of the hydrogen and steam partial pressures in the anode outlet, P_{O_2} is the average partial pressure (in bar) of oxygen in the cathode. The reference values are collected from literatures: the reference operating pressure (P_{ref}) is 1 bar, the reference

operating temperature (T_{ref}) is 1000°C , the ratio of the hydrogen and steam partial pressures in the anode outlet at the reference conditions ($(P_{H_2}/P_{H_2O})_{ref}$) is 0.15 and the oxygen partial pressure at the reference conditions ($P_{O_2,ref}$) is 0.164 [21,22].

It is assumed that the reactions inside the SOFC power generation unit are adiabatic. The net heat duty of the SOFC anode can be calculated using the heat balance, as the heat generated from the reactions includes the net heat duty and the heat required to maintain the operating temperature of the SOFC. This net heat duty consists of the thermal loss from the unit and the output power. The required air flow can then be determined using an Aspen Plus Design-spec that satisfies the following equation (Eq. (12)), applying the calculation hierarchy shown in Fig. 2, where Q_{loss} represents the total thermal loss of the unit, taken as 2% of Q_{net} in this calculation.

$$Q_{net} = IV_{SOFC} + Q_{loss} \quad (12)$$

A direct current to alternating current (DC-AC) transmitter is installed at the output of the SOFC, and the power output of the SOFC (W_{SOFC}) can be obtained using Eq. (13):

$$W_{SOFC} = IV_{SOFC}\eta_{DC-AC} \quad (13)$$

where η_{DC-AC} is the efficiency of direct current converting to alternating current and set to 0.97.

2.2.4. Main operating parameters

The Peng-Robinson equation of state was selected to calculate the global physical properties of the various streams in the GT-SOFC process. The pressure loss due to material conveying between different pieces of equipment was ignored. The main operating parameters are listed in Table 1.

2.3. System evaluation

The first and second laws of thermodynamics are used to evaluate the energy performance of the GT-SOFC hybrid system. The first law of thermodynamics is used to calculate the electrical efficiency, while the second law of thermodynamics is used to calculate the exergy efficiency and exergy destruction.

2.3.1. Energy analysis

The energy efficiency ($\eta_{en,sys}$) was calculated using the following equation (Eq. (14)) [29].

$$\eta_{en,sys} = \frac{W_{net}}{Q_{input}} = \frac{W_{SOFC} + W_{GT} + W_{ST} - W_{comp} - W_{pump}}{m_{fuel}LHV_{fuel}} \quad (14)$$

where W_{SOFC} , W_{GT} , W_{ST} , W_{comp} , and W_{pump} are the power generated in the SOFC, GT, ST, compressors, and pumps, respectively. m_{fuel} is the mass flow rate of the fuel in $\text{kg}\cdot\text{h}^{-1}$, and LHV_{fuel} is the lower heating value of the fuel.

2.3.2. Exergy analysis

The maximum working capacity of the process consumption can be defined as the exergy use of the system. Exergy efficiency can be calculated based on exergy destruction due to irreversible processes throughout the system and the exergy input. The energy efficiency

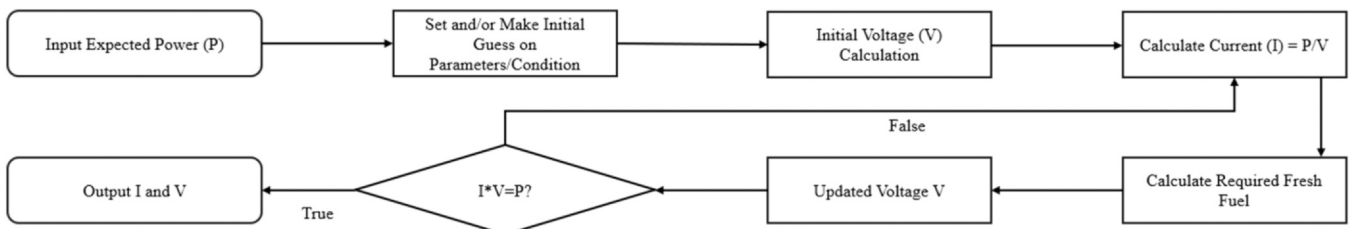


Fig. 2. Hierarchy of cell voltage calculation.

Table 1
Main operating parameters

Items	Description
Feedstocks	-
Fuel input (NH ₃)	Lower heating value (LHV): 18603.6 kJ·kg ⁻¹ . Temperature and pressure of fuel input: -33 °C and 1.2 bar [23,24].
Gas input (O ₂)	Temperature and pressure of fuel input: 25 °C and 1.013 bar.
Compressors	-
NH ₃ fuel compressor	25 bars.
O ₂ compressor	25 bars.
Units	-
Combustor	Adiabatic; pressure: 25 bars.
Gas turbine	Input pressure: 1.013 bar. Exhaust pressure: 25 bars. Isentropic efficiency: 92% [25].
SOFC	Operating temperature: 910 °C. Operating pressure: 1.013 bar. Fuel utilisation factor: 85%. Faraday constant: 96,485 C/mol. Efficiency of DC/AC conversion: 97%. Heat exchanger O ₂ stream outlet temperature: 895 °C [26,27].
PSA system	Compressor outlet pressure: 20 bar; hydrogen recovery ratio: 90%; hydrogen purity: 99%.
Rankine cycle system	Pump isentropic efficiency: 95% [26,28].

AC = alternating current; DC = direct current; SOFC = solid oxide fuel cell.

($\eta_{ex,sys}$) was calculated using the following equations (Eqs. (15) or (16)):

$$\eta_{ex,sys} = \frac{W_{SOFC} + W_{GT} + W_{ST} - W_{comp} - W_{pump}}{m_{fuel} ex_{fuel}} \quad (15)$$

where W_{SOFC} , W_{GT} , W_{RC} , W_{comp} , and W_{pump} are the power generated in SOFC, GT, ST, compressors, and pumps, respectively. m_{fuel} is the mass flow rate of the fuel in kg·h⁻¹, and ex_{fuel} is the exergy of the fuel.

$$\eta_{ex,sys} = 1 - \frac{\text{Total irreversibility of cycle}}{\text{Total exergy input to the cycle}} \quad (16)$$

The equation above (Eq. (16)) is based on irreversibility and fuel input, which is preferred to be applied when the irreversible process of the system is optimised through the reduction of the exergy destruction theoretically.

3. Results and discussion

3.1. Parametric studies

Based on the block programme (Fig. 1), an Aspen Plus model was developed, and the schematic diagram is presented in Fig. 3. The temperature, pressure, and mass flowrate of each stream are summarised in Table 2. The composition of each stream is detailed in the Supplementary Information. The component names and code in the GT-SOFC hybrid system Aspen Plus model are summarised in Table 3. Four key parameters were chosen to evaluate their effects on the model performance: the ER, the pressure in the combustor, the current density, and the fuel utilisation ratio in the SOFC.

3.1.1. Effect of equivalence ratio (ER)

The ER in the combustor was set from 4.5 to 6 as the combustor works at fuel-rich conditions. Fig. 4 shows the power output, power generation efficiency, and energy input of the GT-SOFC hybrid system. As the ER increases, the net power output (P_{net}) and the power generation efficiency (η_p) decrease. The power output from the combustor (P_{com}) decreases significantly, while the power output from the SOFC and heat recovery unit (HRSG) remains stable. At higher ERs, the fuel is in excess, leading to a lower combustion efficiency and more heat losses. The overall power generation efficiency is therefore reduced.

3.1.2. Effect of combustor pressure

The pressure in the combustor varied from 4 bars to 20 bars. As shown in Fig. 5, the total power output slightly increases due to the rise in the power output of the combustor. On the other hand, the power generation efficiency of the GT-SOFC system is significantly improved as the pressure in the combustor increases. This is attributed to a higher combustion efficiency inside the combustor at high pressures, leading to lower heat losses at this step. Additionally, the expansion ratio in the combustor becomes higher at higher pressure conditions, enhancing the mechanical power output.

3.1.3. Effect of current density in the SOFC

The current density of the SOFC varied from 600 A·cm⁻² to 1650 A·cm⁻². As shown in Fig. 6(a), the actual current of the SOFC and the energy input increase as the current density increases, while the cell voltage decreases. Fig. 6(b) shows that the total power output increases

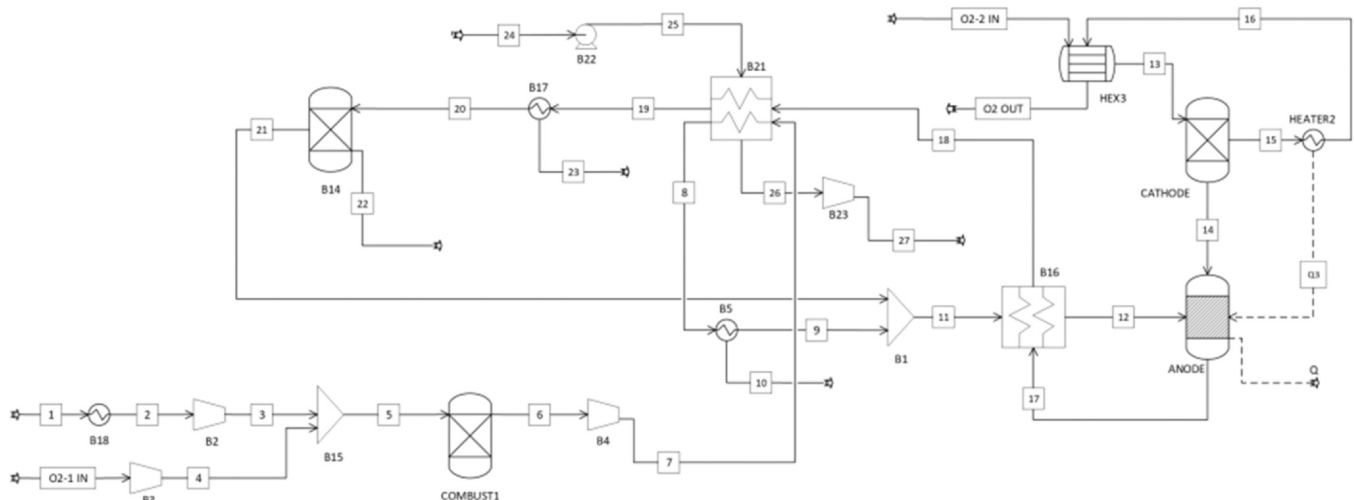


Fig. 3. Schematic diagram of the GT-SOFC hybrid system model using Aspen Plus. GT = gas turbine; SOFC = solid oxide fuel cell.

Table 2

Temperature, pressure, and mass flowrate of the streams

Stream	1	2	3	4	5	6	7	8	9	10
Temperature (°C)	-33	25	332	456	344	816	269	100	40	40
Pressure (bar)	1	1	20	20	20	20	1	1	1	1
Mass flowrate (kg.h ⁻¹)	761.68	761.68	761.68	238.52	1000.2	1000.2	1000.2	1000.2	734.4	265.8
Stream	11	12	13	14	15	16	17	18	19	20
Temperature (°C)	40	800	892	892	892	910	910	225	100	40
Pressure (bar)	1	1	1	1	1	1	1	1	1	1
Mass flowrate (kg.h ⁻¹)	823.53	923.53	135285	817.56	134468	134468	1741.1	1741.1	1741.1	822.17
Stream	21	22	23	24	25	26	27	O ₂ -1 IN	O ₂ -2 IN	O ₂ -OUT
Temperature (°C)	40	40	40	40	41	255	48	25	25	40
Pressure (bar)	1	1	1	0.097	6	6	0.097	1	1	1
Mass flowrate (kg.h ⁻¹)	189.13	633.04	918.92	381.81	381.81	381.81	381.81	238.52	135285	134468

Table 3

Names and codes of the main components in the Aspen Plus model

Component Name	Code
Mixer	B1
Compressor	B2, B3, B23
Gas turbine	B4
Cooler	B5, B17
Heater	B18, HEATER2
Separator	B14
Pump	B22
Heat exchanger	B16, B21, HEX3
Combustor	Combust1

significantly as the current density of the SOFC increases. Compared with the heat recovery unit and the combustor, the power output of the SOFC contributes the most. On the other hand, the power generation efficiency decreases as current density increases, which can be attributed to the decline of cell voltage in the SOFC and the increasing overpotential. The energy losses become greater at higher overpotential, the internal heat generation is great, and more energy is lost as heat instead of being converted to electricity. The number of cells required for the system can be reduced due to the higher power density at higher current density.

3.1.4. Effect of fuel utilisation ratio (U)

In the SOFC, as a portion of fuel is recycled, the recycling ratio (R) can be calculated with the fuel conversion ratio (X_C) and the fuel utilisation ratio (U). The relationship between the fuel conversion ratio (X_C) and the fuel utilisation ratio (U) is defined by Eq. (17):

$$X_C = \frac{U}{1 - (1 - U) \cdot R} \quad (17)$$

When the fuel utilisation ratio (U) varied from 0.1 to 0.9, the fuel conversion ratio (X_C) increased continuously to approach 100% when the recycling ratio (R) was adopted as 99%. As shown in Fig. 7, a fuel conversion ratio of 95% can be achieved at a very low fuel utilisation ratio of 0.15 in the SOFC.

As shown in Fig. 8(a), at a fixed current density, the voltage of the SOFC decreases significantly as the fuel utilisation ratio (U) increases, while the current and energy input are only slightly affected. The total power output decreases when the fuel utilisation ratio increases (shown in Fig. 8(b)), as the power output of the

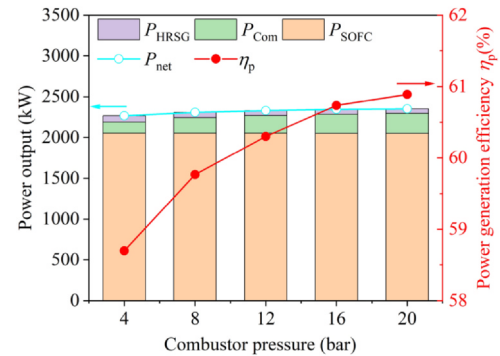


Fig. 5. Power output and power generation efficiency at an equivalent ratio (ER) of 4.5 with a current density of 900 A·cm⁻² and fuel utilisation ratio (U) of 0.85. HRSG = heat recovery steam generator; SOFC = solid oxide fuel cell.

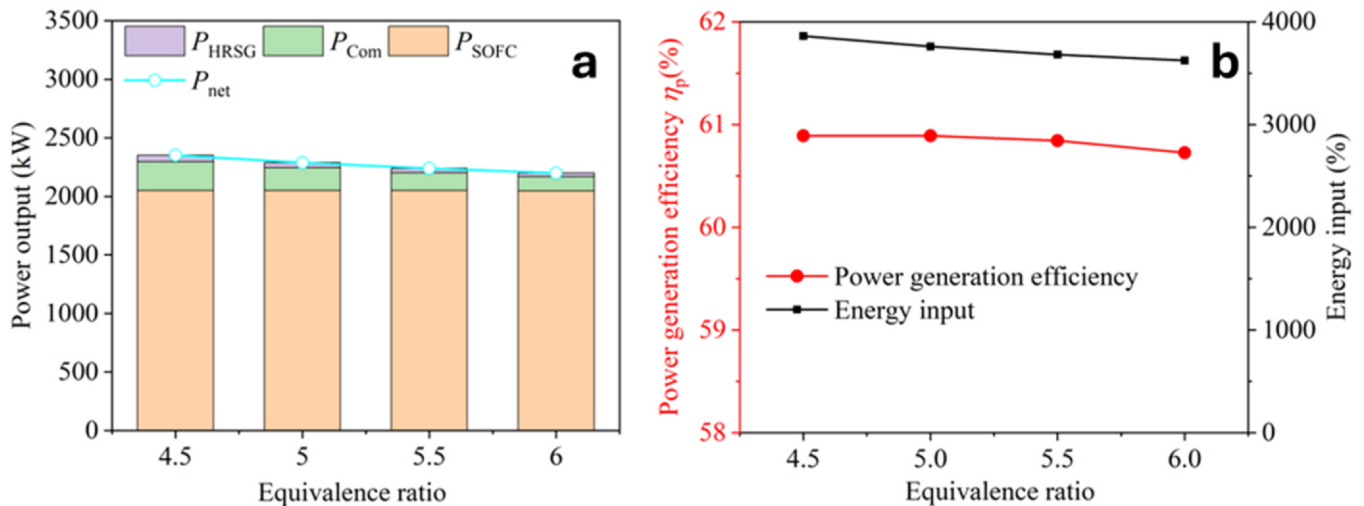


Fig. 4. Power output, power generation efficiency, and energy input at a current density of 900 A·cm⁻² with an operating pressure of 20 bar and fuel utilisation ratio (U) of 0.85. HRSG = heat recovery steam generator; SOFC = solid oxide fuel cell.

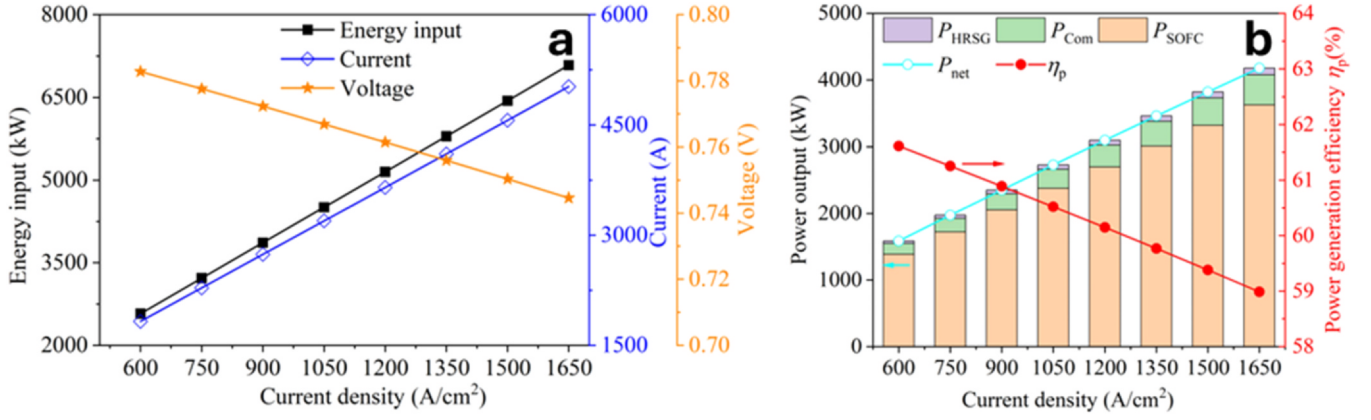


Fig. 6. (a) Energy input, current, and voltage, and (b) power output and power generation efficiency at an operating pressure of 20 bar, with an equivalence ratio (ER) of 4.5 and fuel utilisation ratio (U) of 0.85. HRSG = heat recovery steam generator; SOFC = solid oxide fuel cell.

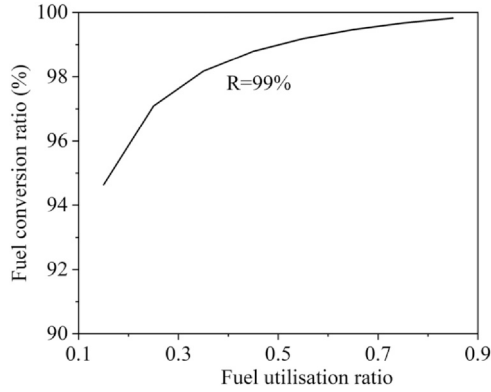


Fig. 7. Relation between fuel conversion ratio (X_c) and the fuel utilisation ratio (U) under conditions of unreacted fuel recycling.

SOFC decreases. However, the power generation efficiency significantly reduces at a high fuel utilisation ratio. In fact, the GT-SOFC hybrid system is able to convert the chemical energy of the fuel into electrical energy effectively, even when the fuel utilisation ratio is low. Unlike conventional SOFCs without fuel recycling, the system reduces energy loss through fuel recovery. In conventional SOFC units, a low fuel utilisation ratio indicates the waste of fuel's chemical energy. However, in the novel GT-SOFC system, the chemical energy of unused fuel is recycled, which minimises the overall energy losses. With a fixed current density, the voltage of the SOFC increases as the fuel utilisation ratio lowers, leading to a higher power generation efficiency.

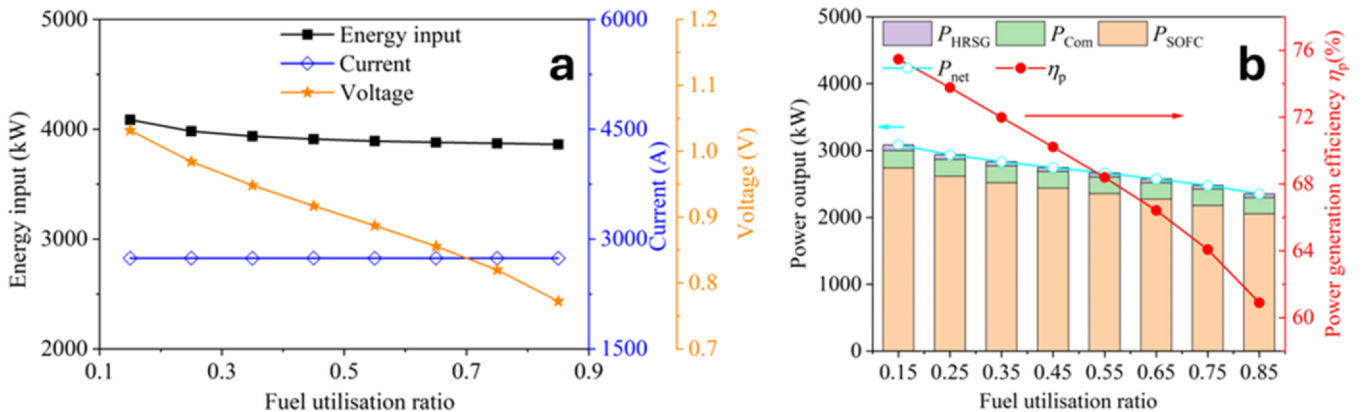


Fig. 8. (a) Energy input, current, and voltage and (b) power output and power generation efficiency at an operating pressure of 20 bar, with a current density of 900 A cm^{-2} and an equivalence ratio (ER) of 4.5. HRSG = heat recovery steam generator; SOFC = solid oxide fuel cell.

3.2. Thermodynamic performance comparison

3.2.1. Energy analysis

Based on the results of the parametric study, it is concluded that the highest power generation efficiency for the GT-SOFC hybrid system can be achieved with a low fuel utilisation ratio of 0.15. The following operating conditions were chosen to establish the detailed energy balance: an equivalent ratio (ER) of 4.5, a combustor pressure of 20 bar, a current density of 900 A cm^{-2} , and a fuel utilisation ratio of 0.15.

A SOFC power generation unit with 3800 kW energy input was applied and integrated into the GT-SOFC hybrid system. According to the Aspen Plus model, the fuel (ammonia) mass flow rate is 0.22 kg s^{-1} . Table 4 shows the detailed calculations of the energy balance under the above conditions.

From Table 4, the power output of the SOFC, GT, and ST and the power consumption of the compressors and pump can be determined: $W_{\text{SOFC}} = 2740.99 \text{ kW}$, $W_{\text{GT}} = 445.14 \text{ kW}$, $W_{\text{ST}} = 84.22 \text{ kW}$, $W_{\text{comp}} = 185.38 \text{ kW}$, and $W_{\text{pump}} = 0.79 \text{ kW}$. Based on Eq. (14), the energy efficiency of the GT-SOFC system can reach 75.5% at the operating conditions studied, which exceeds the 60.96% energy efficiency achieved by the conventional ammonia SOFC-GT system [30].

3.2.2. Exergy analysis

The total exergy input from the fuel can be determined by the following equation: $Ex_{\text{fuel}} = m_{\text{fuel}} \times ex_{\text{fuel}} = 4277.37 \text{ kW}$. Therefore, using Eq. (15), the exergy efficiency ($\eta_{\text{ex,sys}}$) of the GT-SOFC system is calculated to be 72.1%, which outperforms the conventional ammonia SOFC-GT system with an exergy efficiency of 57.79% [30].

Table 4Detailed energy balance at an operating pressure of 20 bar, current density of $900 \text{ A}\cdot\text{cm}^{-2}$, equivalence ratio (ER) of 4.5, and fuel utilisation ratio of 0.15

Energy input		NH ₃ mass flow rate ($\text{kg}\cdot\text{s}^{-1}$)	0.22
		Lower heating value ($\text{MJ}\cdot\text{kg}^{-1}$)	18.60
Energy output	NH ₃ fuel-rich combustion unit	Energy input (kW)	4092.0
		Power consumption of NH ₃ compressor (kW)	156.39
		Power consumption of O ₂ compressor (kW)	28.99
		Power consumption of compressors (kW)	185.38
		Power output of gas turbine (kW)	445.14
		Net power output in NH ₃ fuel-rich combustion unit (kW)	259.76
	Heat recovery unit	Power consumption of the pump (kW)	0.79
		Power output of steam turbine (kW)	84.22
		Net power output in heat recovery unit (kW)	83.43
	SOFC power generation unit	Power output in the SOFC power generation unit (kW)	2740.99
		Net power output (kW)	3084.18

SOFC = solid oxide fuel cell.

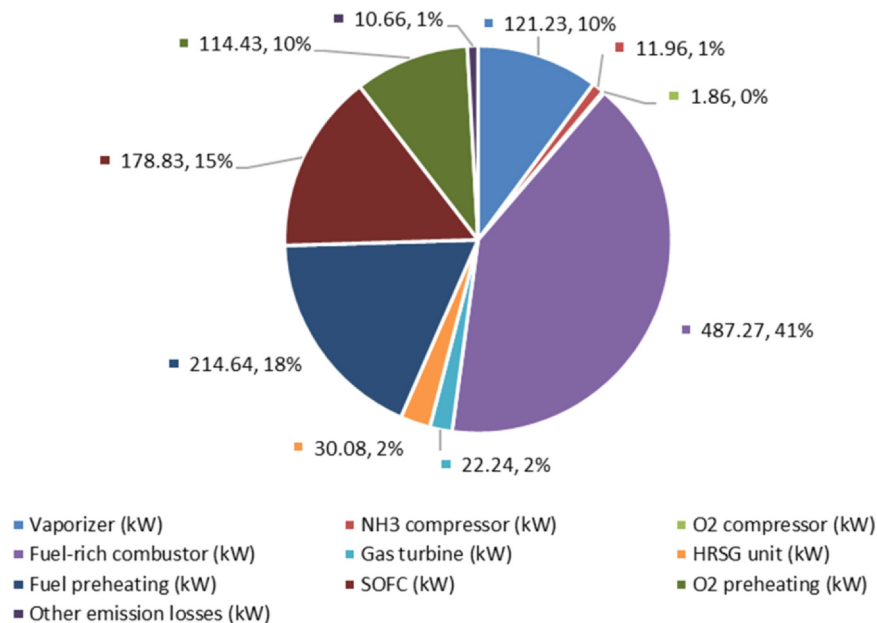
**Fig. 9.** Exergy destruction by each component of the GT-SOFC hybrid system. GT = gas turbine; HRSG = heat recovery steam generator; SOFC = solid oxide fuel cell.

Fig. 9 shows the exergy destruction by components of the GT-SOFC hybrid system. The components with the most exergy destruction are the fuel-rich combustor (burner), the fuel preheating, and the SOFC. The loss from these 3 components accounts for about 75% of the exergy destruction of the system. The fuel-rich combustor contributes to the most exergy destruction (about 41%) due to the incomplete conversion of chemical energy into thermal energy when the ER significantly deviates from 1 [31]. Approximately 18% of exergy destruction is from the fuel preheating. External heat is required to preheat ammonia and oxygen before entering the combustor, and the exergy destruction occurs at the heat exchanger due to its limited efficiency. Approximately 15% of exergy destruction comes from the SOFC. The SOFC operates at high temperature conditions, and heat dissipation is inevitable. Typically, the SOFC includes multiple components and units, and the loss from every single component can accumulate and result in a compensation in energy conversion.

4. Conclusions

In this study, a novel GT-SOFC hybrid system using ammonia as the fuel was designed and modelled via Aspen Plus. The thermodynamics of the energy system was analysed to understand the effect of key operation parameters on the energy efficiency and exergy efficiency. The novel GT-SOFC hybrid system has negligible NO_x emissions and utilises the waste heat efficiently. An energy efficiency of up to 75.5% and an exergy

efficiency of up to 72.1% can be achieved by controlling the operating condition, which outperforms the conventional SOFC-GT system with a similar power output. Although the fuel-rich combustor contributes to the most exergy destruction due to the incomplete conversion of chemical energy into thermal energy, it eliminates the NO_x formation and also avoids the use of any ammonia cracking unit for SOFC, as used in the conventional SOFC-GT system. This work represents a thermodynamic feasibility study of the proposed GT-SOFC system. As the proposed system fundamentally differs from conventional SOFC-GT systems, there are no readily available experimental data for the direct validation of this specific configuration. Future research will focus on the experimental validation of the system, including fuel-rich ammonia combustion characteristics, hydrogen production, and SOFC performance under realistic operating conditions. In addition, a techno-economic analysis will be carried out to evaluate the cost and scalability of the GT-SOFC system, which will provide further insight into its practical viability and commercial potential.

CRediT authorship contribution statement

Siqi Wang: Writing – review & editing. **Song He:** Writing – review & editing, Methodology. **Ziqi Shen:** Writing – review & editing. **Mingming Zhu:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Chia-Sheng Shih:** Writing – original draft, Formal analysis.

Data availability

All data underlying the results are available as part of the article, and no additional source data are required.

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.

Acknowledgement

This research was funded by the EPSRC (EP/X03593X/1).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.nxener.2026.100574](https://doi.org/10.1016/j.nxener.2026.100574).

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2026-04

Elsevier

<https://doi.org/10.1016/j.nxener.2026.100574>

Shih C-S, Wang S, He S, et al., (2026) Thermodynamic analysis of a novel hybrid gas turbine – solid oxide fuel cell power generation system using ammonia as a zero-carbon fuel. Next Energy, Volume 11, April 2026, Article number 100574