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Proposal and assessment of a novel combined heat and power system based on solar photothermal methane dry reforming#

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ABSTRACT

A novel combined heat and power (CHP) system based on solar photothermal methane dry reforming is proposed. Methane is reformed with carbon dioxide by a combination of light and heat to produce syngas. Compared to traditional solar thermochemical reforming, which requires a reaction temperature as high as 900°C, photothermal reforming has been demonstrated to be performed at much lower temperatures. Solid oxide fuel cell (SOFC) and micro gas turbine (MGT) are combined for power generation, while the waste heat is used to supply domestic hot water (DHW). The energy and exergy efficiencies of the novel CHP system reach up to 86.8% and 47.3%, respectively. For the same share of solar energy, the net solar power generation efficiency of the system based on photothermal reforming is 17.8%, which is significantly higher than that of the system based on thermochemical (9.1%). Finally, the Energy Utilized Diagram (EUD) is applied to analyze the exergy destruction of the SOFC, where the main exergy destruction occurs.

Keywords: solar photothermal reforming, SOFC-MGT, energy and exergy efficiency, EUD

NOMENCLATURE

Abbreviations	
STC	Solar Thermochemistry
SMR	Steam Methane Reforming Reaction
CRM	CO_2 Reforming of CH_4
CCHP	Combined Cooling, Heating, and Power System
CHP	Combined Heat and Power System
SOFC	Solid Oxide Fuel Cell
MGT	Micro Gas Turbine
STF	Solar-to-Fuel Efficiency
DHW	Domestic Hot Water
EUD	Energy Utilized Diagram
Symbols	
Q	Energy (kW)
n	Molar mass flow rate (kmol/s)
η	Efficiency
Ex	Exergy (kW)
I	Current (A)
V_{SOFC}	Voltage of SOFC (V)
P_{SOFC}	Power of SOFC (kW)
T	Temperature (K)
W	Work (kW)
h	Enthalpy (kJ/kmol)
S	Shadow area
A	Energy level

1. INTRODUCTION

In recent years, the use of traditional energy sources has led to serious global climate warming. Enhancing the development of clean and renewable energy can effectively reduce carbon emissions and dependence on fossil fuels. Solar energy is an abundant renewable resource. However, due to its variable and intermittent nature, it is difficult to store and often asynchronous with user demands (K Oshiro & S Fujimori, 2022). Combining solar energy with fossil fuels can reduce carbon emissions while increasing solar power generation efficiency. By promoting the effective utilization of solar energy, we can decrease the consumption of fossil fuels, lower greenhouse gas emissions, and contribute to achieving carbon neutrality goals and sustainable development.

Utilizing solar reforming for hydrogen production effectively converts solar energy into chemical energy. A study on the steam methane reforming reaction (SMR) based on full-spectrum solar energy was carried out. (J Sui et al., 2020) The Solar-to-hydrogen efficiency was 54.6% using a combination of solar thermochemistry (STC) and electrochemistry processes and 53.5% using single thermochemical processes. A solar-driven methane dry reforming reactor by developing an optical-thermal-chemical model was designed, (W Zhang, Q Li, & Y Qiu, 2024) which can achieve quite high methane conversion ratio, solar-to-chemical efficiency, and solar-to-thermal efficiency of 36.71%, 30.88%, and 59.05%, respectively. Photothermal reforming of methane to

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hydrogen exhibits higher solar-to-fuel efficiency compared to single thermochemistry. An ultra-efficient solar-to-fuel efficiency of 36.51% was achieved by using Ni/MgAlOx-LDH catalysts loaded Ni foam reactor with heat recovery to drive CO_2 reforming of CH_4 (CRM) (Z Mu et al., 2022).

Since solar energy is widely distributed, it can be used in distributed energy systems. A novel combined cooling, heating, and power system (CCHP) system by combining concentrated photovoltaic/thermal technology with an advanced air-handling process exhibits lower fuel consumption and emissions than a single fossil fuel system (B Su, W Han, W Qu, C Liu, & H Jin, 2018). A parabolic trough collector was used to collect low-temperature solar energy for supplementary refrigeration and heating, achieving the cascade utilization of solar energy (Q Wang, L Duan, Z Lu, & N Zheng, 2023). A CCHP system integrated with a full-spectrum hybrid solar energy device was proposed. (J Wang, Z Han, Y Liu, X Zhang, & Z Cui, 2021) The results indicated that the solar energy share reaches 45.07%, and the energy and exergy efficiencies in cooling mode are 70.65% and 26.59%, respectively.

In this paper, solar energy and methane chemical energy will be combined, breaking through the traditional thermochemical methane dry reforming, using solar photothermal reforming methane to produce hydrogen. Based on the reforming reaction, a novel combined heat and power system (CHP) is proposed, which combines the photothermal reforming of hydrogen with a solid oxide fuel cell (SOFC) and micro gas turbine (MGT) to realize the cascade utilization of energy. The system performance mainly includes energy efficiency, exergy efficiency, and net solar power generation efficiency. Finally, the impact of different reforming methods on the system is analyzed by comparing the single thermochemical and photothermal reforming.

2. SYSTEM DESCRIPTION

Our designed CHP system is illustrated in Fig. 1. The whole system consists of three parts: solar-driven photothermal reforming reaction unit, SOFC-MGT unit, and heating unit.

As shown in Figure 1, the system flow is as follows. CH_4 (stream 1) and CO_2 (stream 2) enter the reforming reactor, where a photothermal reforming reaction driven by solar energy occurs to produce syngas (stream 3). The SOFC is composed of the Anode, Cathode, and Heater1. The syngas enter the anode of the SOFC and electrochemically react with oxygen (stream 12) from the cathode. The air (stream 9) is compressed by a compressor (AC) and then preheated by a heat exchanger (HE1) to form high-temperature air (stream 11). The cathode of the SOFC is a separator that separates the required oxygen to be supplied to the anode. The remaining syngas (stream 4) and air (steam 14) enter the combustion chamber (AB) for an oxidation reaction. The combustion chamber outlet gas (stream 6) enters the turbine (MGT) to expand and then preheats the compressed air. Finally, the heat of the MGT gas is recovered to provide heat for tap water (stream 15) to make domestic hot water (stream 16).

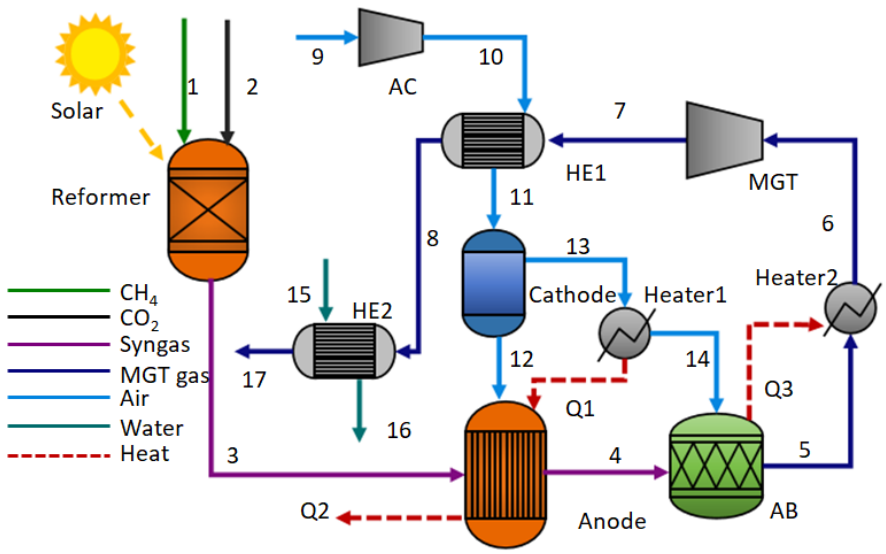

Fig. 1 System schematic

Q1 represents the heat provided for heating the air during the electrochemical reaction occurring at the anode. Q2 is the energy released from the anode, including electrical energy and lost heat. Q3 represents the energy released from the reaction occurring in the combustion chamber, providing heat for the outlet gas. The values of the main parameters of the system are shown in Table 1.

Table 1

Parameters of CHP System

Parameter	*Value*
Input solar energy kW	75
Proportion of solar energy %	14
Methane dry reforming reaction temperature °C	574
Methane conversion rate %	20
Solar-to-fuel efficiency %	37
Operating temperature of SOFC °C (H Zhao & Q Hou, 2019)	900
Operating pressure of SOFC MPa	0.4
Fuel utilization % (ZM Zheng, TX Liu, QB Liu, J Lei, & J Fang, 2021)	85
Heat loss of SOFC %	2
DC-AC conversion efficiency % (M Mehrpooya, M Sadeghzadeh, A Rahimi, & M Pouriman, 2019)	92
Turbine output pressure MPa	0.1
Adiabatic efficiency of compressor %	80
Mechanical efficiency of compressor %	95
Adiabatic efficiency of turbine %	84
Outlet temperature of exhaust gas °C	60

3. CALCULATION METHOD

3.1 Photothermal reforming unit

Under design conditions, the chemical reaction occurring in the reforming unit is the dry reforming reaction of methane. Solar-to-fuel (STF) efficiency is defined as

$$\eta_{sol-che} = \frac{nH_2 \times LHV_{H_2} + nCO \times LHV_{CO} - nCH_{4,rec} \times LHV_{CH_{4,rec}}}{Q_{sol}} \quad (1)$$

nH_2 and nCO represent the molar mass flow rate of reforming product H_2 and CO. $nCH_{4,rec}$ represents the molar mass flow rate of methane which is involved in the reforming reaction. Q_{sol} is the input solar energy.

The input energy of the photothermal reforming unit is composed of methane chemical energy and solar energy, which can be expressed as

$$Q_{input} = Q_{CH_4} + Q_{sol} \quad (2)$$

Similarly, Ex_{CH_4} and Ex_{CO_2} represent the exergy of CH_4 and CO_2, the input exergy can be expressed as follows (Q Wang, L Duan, N Zheng, & Z Lu, 2023).

$$Ex_{input} = Ex_{CH_4} + Ex_{CO_2} + Ex_{sol} \quad (3)$$

3.2 SOFC-MGT unit

The chemical reaction occurs at the anode of the SOFC as follows

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (4)$$

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (5)$$

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad (6)$$

SOFC current, voltage and power are calculated in Ref. (K Yu, H Feng, Y Zhang, D Liu, & Q Li, 2023) The output electrical energy of SOFC is simply expressed as follows, where the efficiency of DC to AC is 0.92.

$$P_{SOFC} = \frac{I \cdot V_{SOFC} \cdot \eta_{DC/AC}}{1000} \quad (7)$$

The expression for the work done by the turbine is as follows. η_{mec} is the mechanical efficiency of the turbine. n and h is the molar mass flow rate and enthalpy of the gas entering the turbine.

$$W_{GT} = n\Delta h \eta_{mec} \quad (8)$$

3.3 Heating unit

The waste heat of exhaust gas is recovered in a heat exchanger to heat the tap water. The heat exergy for domestic hot water is calculated as

$$Ex_h = (1 - \frac{T_0}{T_h})Q_h \quad (9)$$

Ex_h is the heat exergy. T_h and T_0 is the temperature of heating and ambient temperature. Q_h is the heating supplied for DHW.

3.4 Evaluation Criteria

Energy efficiency and exergy efficiency are used to evaluate system performance. The energy efficiency of the novel SOFC-MGT system is defined as

$$\eta_{CHP} = \frac{P_{SOFC} + W_{GT} - W_0 + Q_h}{Q_{CH_4} + Q_{sol}} \quad (10)$$

The energy efficiency of the system is represented by η_{CHP}. The work done by the turbine is denoted by

W_{GT} ,and the power consumed by compression is indicated by W_0.

The electrical energy and exergy of SOFC and GT are numerically equal. The exergy efficiency of the system is represented by ExE . The exergy efficiency is expressed as follows.

$$ExE = \frac{EE_{SOFC} + EE_{GT} - EE_{AC} + Ex_h}{Ex_{CH_4} + Ex_{sol}} \tag{11}$$

The net efficiency of solar energy to electricity is used to evaluate the level of solar energy utilization and the expression is shown, where Q_{syn} is the lower heating of the syngas produced by the reforming reaction.

$$\eta_{sol-ele} = \eta_{sol-che} \times \frac{P_{SOFC} + W_{GT} - W_0}{Q_{syn}} \tag{12}$$

4. RESULTS AND DISCUSSION

4.1 Performances under design conditions

4.1.1 Energetic performance

Under the design conditions, the methane input chemical energy is 439.9 kW and the solar energy input is 74.6 kW. The output electrical energy is 237 kW and the output thermal energy is 209 kW. The novel CHP system has an energy efficiency of 86.8%, with a SOFC electrical efficiency of 31.9%, the GT work efficiency of 14.2%, and a thermal efficiency of 40.7%.

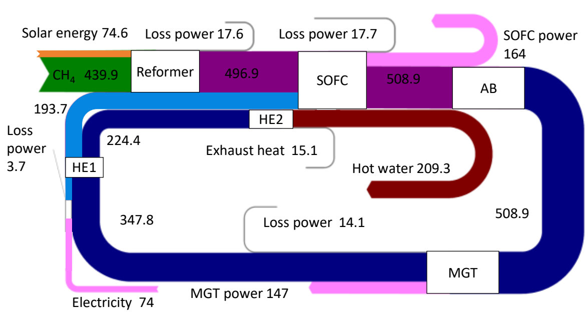

Fig. 2 Energy flow Sankey diagram of the proposed CHP system

In Fig. 2, the energy loss of the reforming unit is 17.6 kW and part of the solar energy is lost. The energy loss of the SOFC unit is 17.7 kW, which is divided into two parts, the heat loss of the SOFC and the DC-AC conversion. Due to the high gas flow rate at the GT outlet, more heat energy is output.

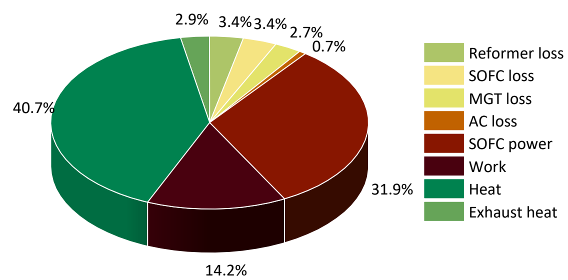

Fig. 3 Energy destruction distribution of main components

4.1.2 Exergetic performance

The input methane exergy is 458.4 kW and solar exergy is 68.4 kW. In Fig. 4, the exergy efficiency of the proposed new system is 47.3%. The SOFC outputs 164 kW with 31% exergy efficiency. The GT outputs 73 kW with 13.8% exergy efficiency. The thermal exergy output is just 13.1 kW and the thermal exergy efficiency is 2.5%.

In Fig. 5, exergy destructions are mainly in the heat exchanger, SOFC, combustion chamber, and reforming reaction. The maximum exergy destruction occurs in the heat exchanger with an exergy destruction of 78.6 kW. Due to the larger gas-liquid flow rate, the exergy destruction is large. There are four parts of the SOFC exergy destruction causes, which are from the chemical reaction process, the air heating, the wasted heat, and the DC-AC conversion. Since the inlet air flow is large, the exergy destruction of heat is correspondingly large. The reason for the smaller losses in the reforming unit compared to the SOFC unit is that the share of solar energy is smaller, and minor amounts of solar energy are lost.

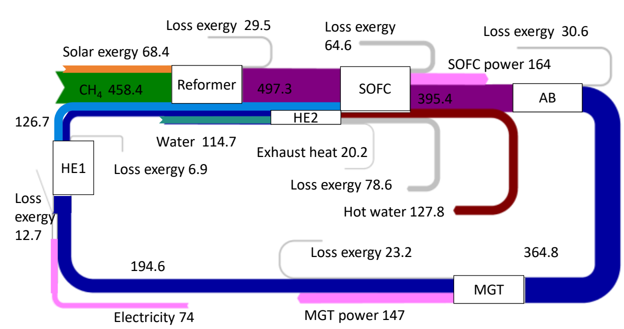

Fig. 4 Exergy flow Sankey diagram of the proposed CHP system

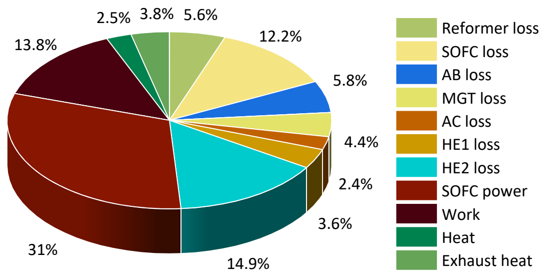

Fig. 5 Exergy destruction distribution of main components

4.2 Comparison of the performance of photothermal and thermochemical reforming systems

The photothermal reforming temperature is 847 K and the thermochemical reforming temperature is 947 K for the same solar energy share. In Fig. 6, the thermochemical is compared to the photothermal system. Since the input methane flow rate is the same, the system outputs the same SOFC electrical energy. The GT in the thermochemical system does 71 kW of work and outputs 205 kW of thermal energy. The GT in the photothermal reforming system does 73 kW of work and outputs 207 kW of thermal energy.

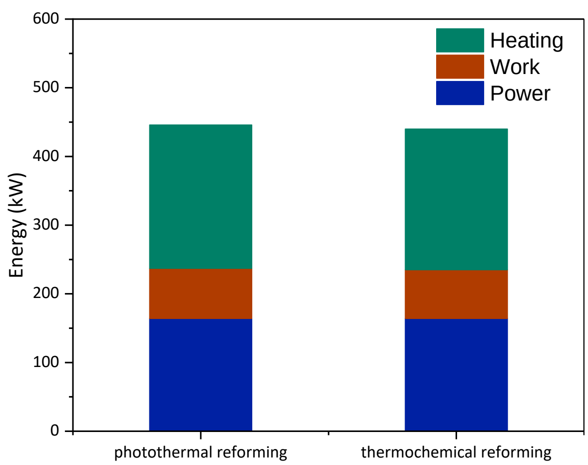

Fig. 6 Energy composition with the same share of solar energy

In Fig. 7, the energy efficiency of the photothermally coupled reforming system is 86.8% and the exergy efficiency is 47.3%. The energy efficiency of the single thermochemical reforming system is 85.5% and the exergy efficiency is 47.1%. However, the difference in net solar power efficiency is significant. The net solar power generation efficiency of the photothermal reforming system is 17.8% and the net solar power generation efficiency of the thermochemical reforming system is 9.1%. The STF efficiencies of the thermochemical reforming system and the photothermal reforming system are 19% and 37%, respectively, and the efficiencies of syngas chemistry to electricity are 48% and 47.7%, respectively, so the STF efficiency leads to the difference in the net efficiency of solar energy to electricity.

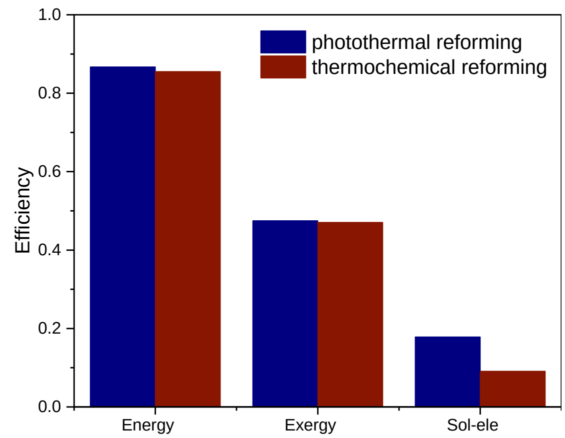

Fig. 7 Different efficiencies with the same share of solar energy

4.3 Analysis of the causes of SOFC losses

The SOFC exergy destruction is larger than the reforming unit, to verify and specifically analyze the exergy destruction of the SOFC unit, Fig. 8 shows the EUD diagram of the SOFC unit, which consists of endothermic energy acceptors and exothermic energy donors. ΔH refers to the amount of work output(S Peng, Z Wang, H Hong, D Xu, & H Jin, 2014). The shaded area S is formed by energy level A. The pre-reforming reaction in the SOFC unit is SMR(W Zhang, E Croiset, PL Douglas, MW Fowler, & E Entchev, 2005). In Figure 8, A1 is the exothermic process of the syngas, so the energy level A is decreasing. A2 is SMR process. A3 is the hydrogen oxidation process, A5 and A6 are the reactant heating processes, and A7 is the water-gas shift reaction.

The shaded area S1 is the exergy destruction from the pre-reforming reaction, which is 9.6 kW. S2 and S3 are the exergy destruction from the fuel and air heating processes. S4 is formed as the exergy destruction from the water-gas shift process. Since the anode generates electrical energy, the right side of the shaded area should contain two kinds of exergy destruction, which are from the wasted heat of the SOFC and the DC-AC conversion, combining them with S2, S3, and S4 to form the anode exergy destruction, which is 55 kW. Therefore, the exergy destruction of SOFC unit is 64.6 kW, a large part of which is generated by the preheating of the air.

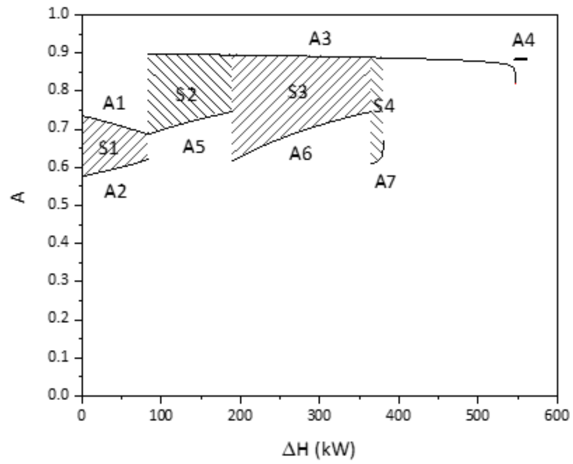

Fig. 8 EUD of SOFC unit

5. CONCLUSIONS

A novel CHP system is proposed, which consists of a photothermal reforming unit, a SOFC-MGT unit and heat recovery. Under the design conditions, the novel system can achieve energy efficiency of 86.8% and exergy efficiency of 47.3%. The energy and exergy efficiencies of the system based on photothermal reforming and the system based on thermochemical reforming are similar, but the net efficiency of solar energy to electricity for the photothermal reforming system is 17.8%, higher than the efficiency of only 9.1% for the thermochemical system. Finally, the EUD was used to specifically analyze the exergy destruction of the SOFC unit, and the results show that heating of the reactants leads to significant exergy destruction of SOFC.

ACKNOWLEDGEMENT

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