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Investigation on the operation strategy for a complementary system of solar energy and natural gas

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ABSTRACT

This paper designs a combined cooling, heating and power system based on the complementary conversion of solar energy and natural gas. An operation strategy based on the energy storage characteristics of the system is developed. The performance of the system under the new operation strategy is evaluated based on three indicators including the operation cost saving rate, the carbon dioxide emission reduction rate and the relative energy saving rate. The annual system performance is analyzed on typical days throughout different seasons. The results show that the developed operation strategy can achieve significant improvements in energy efficiency and economic benefits. Compared to the reference system, the designed system achieves considerable annual cost saving, CO_2 emission reduction rate and relative energy saving rate of 15.12%, 31.51% and 28.52%, respectively. These promising results provide guidance for the integrated design and operational regulation of solar and fuel complementary systems.

Keywords: complementary system, hybrid energy conversion, energy storage, operation strategy, seasonal variation

NONMENCLATURE

Abbreviations	
STC	Solar Thermochemistry
CCHP	Combined Cooling, Heating, and Power System
SOFC-MGT	Solid Oxide Fuel Cell and Micro Gas Turbine
STF	Solar-to-Fuel Efficiency
ABS	Absorption chillers
EC	Electric chiller
Symbols	
E_{ec}	Electricity requirements for EC (kW)
P, C, H	User power, cooling, and heating loads (kW)

1. INTRODUCTION

There is an urgent need to promote the revolution of energy production and consumption (Liu et al., 2022). Under the pressure of energy and environmental problems, the rational utilization of energy has become the focus of attention of all countries (Li et al., 2020; Hou et al., 2016). Promoting the development of new energy sources, improving the comprehensive cascaded utilization rate of energy, realizing emission reduction are of far-reaching strategic significance for economic development and environmental protection. An efficient, flexible, and clean multi-energy complementary system is precisely the new method proposed to address these challenges (Liu et al., 2019).

Renewable energy systems are challenged by unstable and uncontrollable energy inputs and mismatches between supply and demand. Energy storage and system regulation are essential to ensure the reliability and stability of renewable energy systems, while increasing system complexity and economic costs (Liu et al., 2022; Ren et al., 2024). The user cooling, heating and power loads have random fluctuations on multiple time scales, and the use of key energy storage devices to achieve stable operation and matching of supply and demand of the multi-energy complementary system is a key point in the research of multi-energy complementary system (Liu et al., 2023). Various multi-energy complementary systems have been investigated, including the development of key components, system integration design, and thermodynamics analysis.

Solar-fuel hybrid systems are almost always operated under off-design conditions, where input solar energy and user load demand fluctuate in real time (Wu et al., 2019; Wang et al., 2023). Their thermodynamic and economic performance is significantly affected by system configuration parameters and operation strategies. Suitable operation strategies can ensure that the energy system achieves optimal performance during actual operation (Liu et al., 2020). Under different supply

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and demand scenarios of solar input and thermoelectric output, the system output and user load balance cannot be the focus only, and a novel operation strategy that considers the impact of solar energy needs to be proposed (Fani & Sadreddin, 2017).

This study addresses the source load fluctuation and supply-demand mismatch problems of the solar-natural gas complementary CCHP system. Firstly, the framework of a multi-energy system with coordinated supply of cooling, heating and electricity cogeneration based on complementary solar energy and natural gas is established. Secondly, a new operation strategy considering solar energy input and regulating by storage is proposed, which improves the efficiency of solar energy and fuel utilization under the new operation mode, and achieves the purpose of high efficiency, economy, and environmental protection. Finally, the operation pattern of the system under seasonal changes and different user loads is described, and the system is analyzed in terms of energy, environment, and economy. These promising results provide useful guidance for the integrated design and operation regulation of the multi-energy complementary system, thus contributing to the efficient, economic, and low CO_2 emission utilization of solar and fuel energy.

2. SYSTEM DESIGN AND MODELING

2.1 System description

In this study, solar energy and natural gas are complementarily input and converted by photothermal coupling for energy cascaded utilization, thus constructing a complementary CCHP system. Based on the theory of energy-potential matching, the solid oxide fuel cell is combined with a micro-gas turbine to achieve order release and cascaded utilization of the fuel chemical energy from solar energy and natural gas, thus improving the energy utilization efficiency. Fig. 1 shows the detailed flow of the solar-natural gas complementary CCHP system.

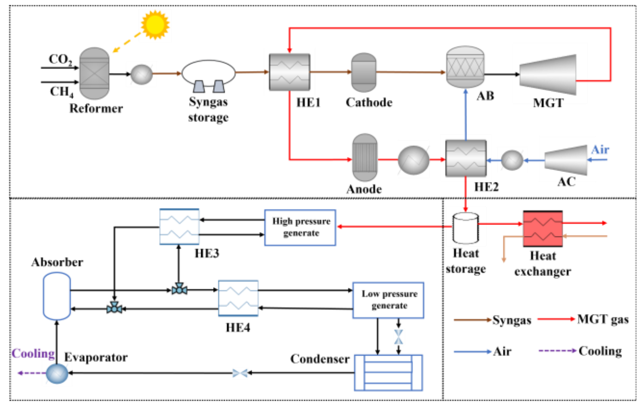

Fig. 1 Schematic diagram of the solar-natural gas complementary CCHP system

The solar-natural gas complementary CCHP system is user oriented and operates according to load demand. Due to the time-varying load demand and the intermittent and unstable nature of solar radiation, the integrated system alone is unable to meet the user's load demand in a timely manner. To ensure a secure and stable energy supply, the proposed system is integrated with the grid, an electric chiller (EC), and a standby boiler, thus forming a microgrid energy system. Fig. 2 shows the flowchart of the microgrid energy system with solar energy, methane, and grid power as energy inputs, and a solar and natural gas complementary system as the core to satisfy the user's electric, heating, and cooling loads in a timely manner. Grid power plays the role of power supplementation in the microgrid energy system. The cooling load is first supplied by absorption chillers (ABS), and the insufficient part is supplied by EC. When the heat generated by the heating recovery system cannot meet the heating load demand, the backup boiler outputs heat to supplement.

2.2 System modeling

2.2.1 The solar-natural gas complementary CCHP system

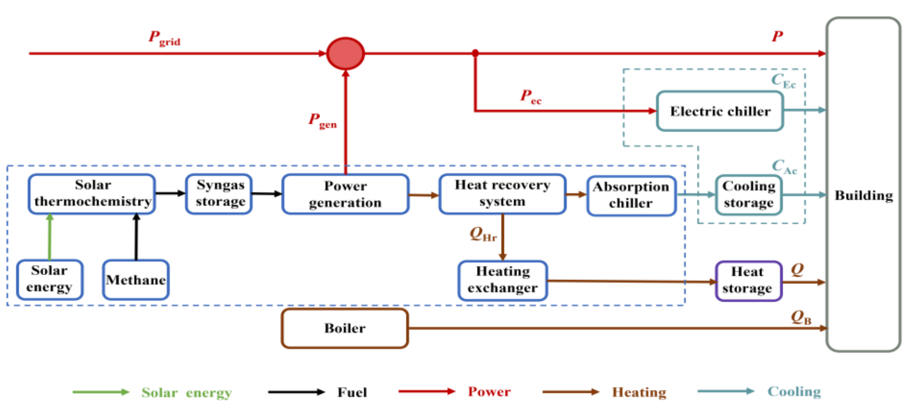

Fig. 2 Flowchart of the proposed microgrid system

The system shown in Figure 1 consists of five key components, namely the photothermal chemical reforming reactor, syngas storage, SOFC-MGT, ABS and heating storage system. The components were modelled by Aspen plus v12.

2.2.2 Cooling storage units

The cooling storage system consists of an EC and a cooling storage tank. When the user's cooling demand exceeds the cooling capacity generated by ABS, the electric chiller is turned on for cooling. The formula for calculating the refrigeration power of the EC and the relationship between the power of the cooling storage and the cooling storage capacity are as follows (Heidari et al., 2020).

$$C_{\mathrm{ec}}(t)=COP_{\mathrm{ec}}\cdot E_{\mathrm{ec}}(t) \tag{1}$$

$$V_{\mathrm{cs}}(t)=V_{\mathrm{cs}}(t-1)\cdot(1-\sigma_{\mathrm{cs}})+\left(C_{\mathrm{cs}}^{\mathrm{c}}(t)\cdot\eta_{\mathrm{cs}}^{\mathrm{c}}-\frac{C_{\mathrm{cs}}^{\mathrm{d}}(t)}{\eta_{\mathrm{cs}}^{\mathrm{d}}}\right)\cdot\Delta t \tag{2}$$

$$0\le\alpha_{\mathrm{cs}}^{\mathrm{c}}\cdot C_{\mathrm{cs}}^{\mathrm{c}}(t)\le C_{\mathrm{cs,max}}^{\mathrm{c}} \tag{3}$$

$$0\le\alpha_{\mathrm{cs}}^{\mathrm{d}}\cdot C_{\mathrm{cs}}^{\mathrm{d}}(t)\le C_{\mathrm{cs,max}}^{\mathrm{d}} \tag{4}$$

$$S_{\mathrm{csc}}(t)=\frac{V_{\mathrm{csc}}(t)}{V_{\mathrm{csc,max}}} \tag{5}$$

$$S_{\mathrm{cs,min}}\le S_{\mathrm{cs}}(t)\le S_{\mathrm{cs,max}} \tag{6}$$

$$\alpha_{\mathrm{cs}}^{\mathrm{c}}\cdot\alpha_{\mathrm{cs}}^{\mathrm{d}}=0 \tag{7}$$

In the formula, $V_{\mathrm{cs}}(t)$ and $V_{\mathrm{cs}}(t-1)$ are the cooling capacity of the tank at time t and time t-1 respectively, kwh; $C_{\mathrm{cs}}^{\mathrm{c}}(t)$ and $C_{\mathrm{cs}}^{\mathrm{d}}(t)$ are the cooling and cooling power, kW; $S_{\mathrm{csc}}(t)$ indicates the state of the tank; $V_{\mathrm{csc,max}}$ is the capacity of the tank, taken as 201 kWh. COP_{ec} is the efficiency of EC, 4.2.

2.2.3 Heating storage units

A heating storage device is used to store the waste heat. The stored heat is used to supplement the deficient heat. The mathematical model of the heating storage unit is like that of the cooling storage unit (Heidari et al., 2020). $V_{\mathrm{hs,max}}$ is the capacity of the tank, 471 kWh.

2.2.4 Boiler

When the user heating demand exceeds the capacity of the waste heat recovery system and the heating storage tank, the make-up boiler will start to operate. The mathematical model is shown (Heidari et al., 2020).

$$Q_{\mathrm{gb}}(t)=Q_{\mathrm{gb}}^{\mathrm{r}}\cdot PLR_{\mathrm{gb}}(t) \tag{8}$$

$$F_{\mathrm{gb}}(t)=\frac{Q_{\mathrm{gb}}(t)}{\eta_{\mathrm{gb}}\cdot HV_{\mathrm{ng}}}\cdot\Delta t \tag{9}$$

$$\eta_{\mathrm{gb}}=\eta_{\mathrm{gb}}^{\mathrm{r}} \tag{10}$$

In the formula, $Q_{\mathrm{gb}}(t)$ is the thermal power generated by the gas boiler, kW; $Q_{\mathrm{gb}}^{\mathrm{r}}$ is the rated thermal power, kW; $PLR_{\mathrm{gb}}(t)$ is the load factor; $F_{\mathrm{gb}}(t)$ is the consumption of standard coal in a certain period, kg. η_{gb} is the boiler efficiency, taken as 0.83.

3. SYSTEM OPERATION AND EVALUATION

3.1 System operation strategy

A solar-natural gas complementary CCHP system outputs multiple energy products to satisfy the customer's electricity, heating, and cooling loads. The overall performance of the system is influenced by factors such as solar irradiation resources, customer energy load demand, and operating strategy. The fact that it is affected by intermittent solar input makes the traditional operation strategy less suitable for solar natural gas complementary systems. So, we added syngas storage tank, heating storage tank and cooling storage unit to propose a new operation strategy as shown in Fig. 3.

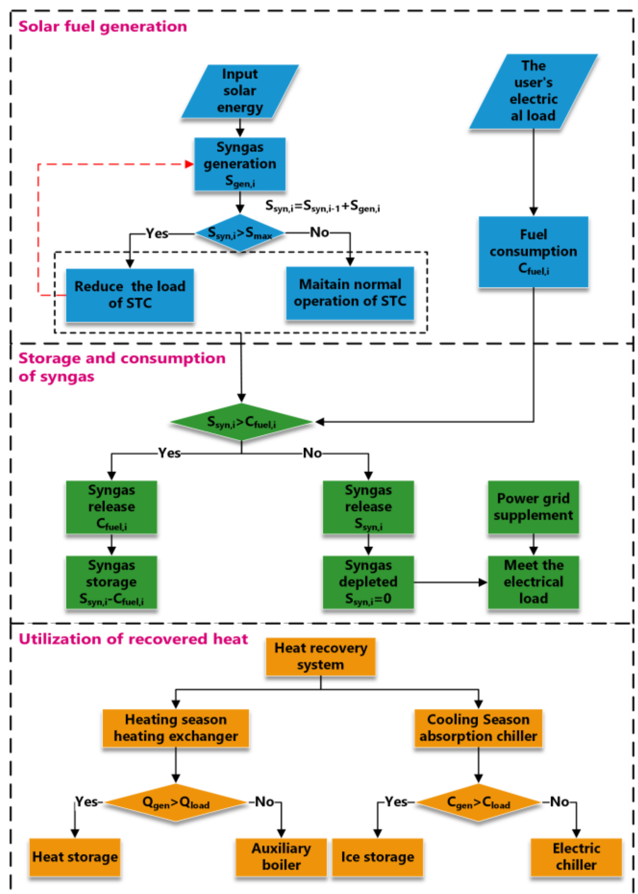

Fig. 3 Proposed new operation strategy

Specifically, solar fuel is generated through the STC and the resulting syngas is stored. When the stored solar fuel reaches the maximum storage capacity, the operating load of the STC is reduced by giving up some of the incoming solar energy. When the syngas stored in the system is not sufficient to meet the amount of fuel required by the electrical load, it is replenished through the grid. The users' cooling demand is satisfied by the ABS, and the deficit is supplemented via EC. Similarly, the heating demand is satisfied via heat recovery, and the heating gap is provided by the back-up boiler. The solar-fuel hybrid system fulfills multiple energy demands through the proposed strategy.

3.2 Performance evaluation criteria

The performance of CCHP system is evaluated through the operating cost saving rate, CO_2 emission saving rate and relative energy saving rate compared to the system using grid power extraction and coal-fired boiler for heat extraction.

3.2.1 The operating cost saving rate

Annual operating costs of the system primarily involves the cost of the fuel consumption, electricity trading, and boiler heating.

$$CT = CT_{\text{fuel}} + CT_{\text{ele}} + CT_{\text{boiler}} \tag{11}$$

$$S_{\text{cost}} = 1 - \frac{CT_{\text{ME}}}{CT_{\text{RS}}} \tag{12}$$

In the formula, CT_{fuel}, CT_{ele} and CT_{boiler} are the annual costs of system fuel consumption, electricity trading and boiler heating extraction, respectively; CT_{RS} is the cost of purchasing electricity from the grid and taking heat from the boiler to match the customer's load.

3.2.2 CO_2 emission saving rate

In the prototype system, the net CO_2 emissions are generated by the input methane.

$$m_{\text{ME}} = F_{\text{m}} \times \Delta t \tag{13}$$

$$S_{CO_2} = 1 - \frac{m_{\text{ME}}}{m_{\text{RS}}} \tag{14}$$

F_{m} is the mass flow rate of methane, kg/s. m_{RS} is CO_2 emissions from coal-fired power plants for electricity and coal-fired boilers for heating.

3.2.3 Relative energy saving rate

The relative energy efficiency of the system is calculated according to the calculation method provided by the national standard.

$$\eta_{\text{ME}} = \frac{E_{\text{a}} - E_{\text{r}}}{E_{\text{a}}} \times 100\% \tag{15}$$

$$E_{\text{a}} = P \times \text{e}_{\text{ref,p}} + C \times \text{e}_{\text{ref,c}} + H \times \text{e}_{\text{ref,h}} \tag{16}$$

In the formula, η_{ME} is the relative energy saving rate of the system; E_{r}, E_{a} are the energy consumption and the calibration energy consumption, kgce; $\text{e}_{\text{ref,p}}$, $\text{e}_{\text{ref,c}}$ and $\text{e}_{\text{ref,h}}$ are the value of power consumption, cooling consumption, and heating consumption, kgce/kWh.

3.3 Reference system

The reference system has the same setup as the designed system, except for the absence of the energy storage unit. The system outputs directly to the user.

4. RESULTS

4.1 Modeling case

The dynamic loads of a small office building in Nanjing, China are simulated. A typical hourly cooling, heating and power load are shown in Figs. 4. It is evident that the heating and cooling loads are significant, while the power load is relatively small. But the power load distribution remains stable.

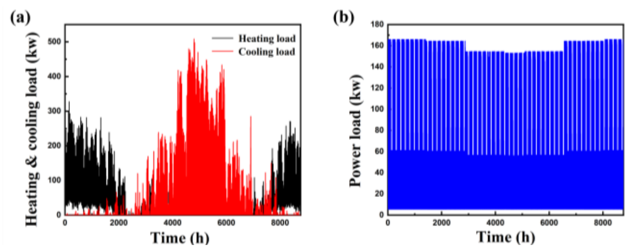

Fig. 4 (a) Heating and cooling loads; (b) power load

4.2 Solar thermochemical process

Solar energy and methane thermochemical conversion is a key hybrid process for upgrading solar energy into the chemical energy of syngas. The system proposed in this paper is driven by solar energy and chemical energy of methane and the variation of energy input to the system is shown in Fig. 5(a). The input of methane maintains the same trend as that of solar energy, with methane accounting for 29.89% of the total energy input. Figure. 5(b) shows the variation of DNI and STF at different hours under a typical day, during the operation STF remains around 0.4 when there is sufficient light and decreases significantly when there is insufficient light.

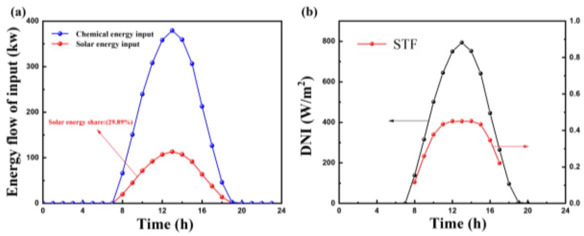

Fig. 5 (a) System Inputs; (b) STF and DNI changes

4.3 System energy supply analysis

Considering the variability of solar irradiation and changing user load demand, it is necessary to design energy storage units in the system, which utilizes syngas as a storage medium for solar energy and adds a cooling and heating storage unit.

In a representative typical week, the regulation of the syngas storage tanks shown in Figure. 6. Take a syngas storage tank for example. The more solar energy input, the more syngas is produced. When there is sufficient solar irradiation, only part of the syngas needs to be consumed to meet the electrical load of the user, while the remaining syngas is stored. When there is insufficient solar irradiation, the stored syngas is released to meet the user's energy demand. Due to the regulation of syngas storage, the system can supply electricity to the user throughout the day.

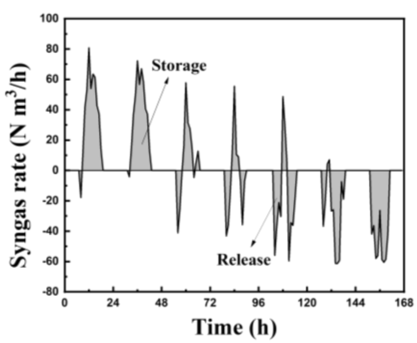

Fig. 6 Syngas storage regulation in a typical week

The balance of supply and demand for cooling and heating of the system is shown in Fig. 7. Fig. 7(a) illustrates the summer electricity balance, the user needs the electricity load in addition to the basic electricity load, but also includes the electricity load required for refrigeration. Users are mainly supplied by the system output power, and the shortfall is obtained from the grid. Fig. 7(b) shows the heat balance in winter, during 15:00 - 17:00 hours, the flue gas waste heat is enough to drive the refrigeration unit to meet the user's heating load demand, but in the other hours cannot meet the user's heating load demand, then the heating storage tank is needed to release heat to supplement.

4.4 Performance analysis

The annual performance of the system is shown in Figure. 8, which shows that the system performs superiorly under the new operation strategy and achieves high efficiency, economy, and environmental protection. The results of the monthly operating cost savings, CO_2 emission savings and relative energy savings of the system are shown in Fig. 9, which compared with the reference system. The three evaluation indexes of the system under the new operation strategy are significantly better than the reference system, with S_{CO_2} and η_{ME} remaining between 19.06% ~ 47.68% and 18.21% ~ 43.47%, respectively. Besides, the operating cost savings of the system ranged from 8.87% to 24.47%.

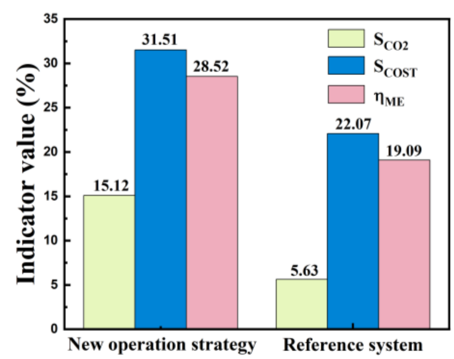

Fig. 8 Annual Performance Comparison

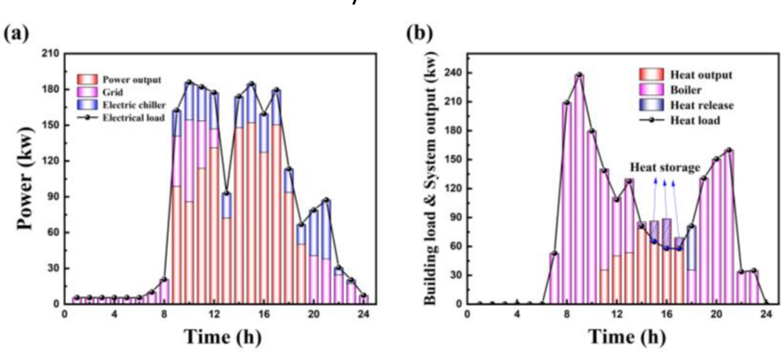

Fig. 7 User load matching under a typical day

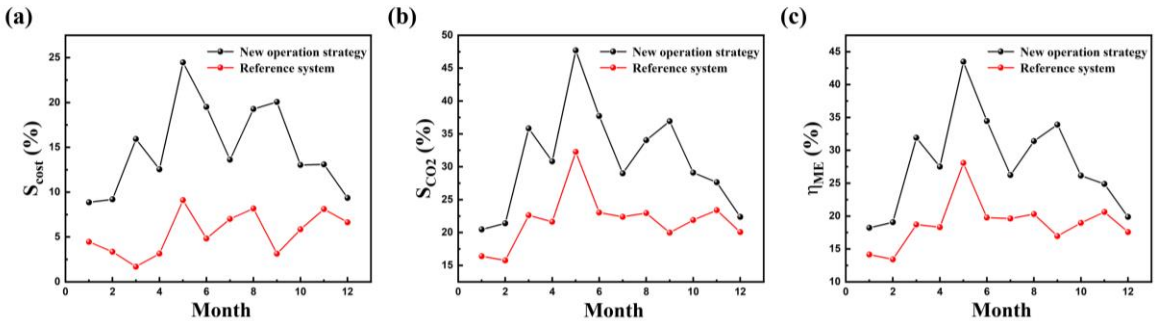

Fig. 9 Monthly performance evaluation

5. CONCLUSIONS

In this paper, a novel CCHP system integrating complementary solar energy and natural gas is designed. A new operation strategy for considering energy storage and solar input is developed. Based on the CCHP system and the new operating strategy, the designed system achieves considerable annual cost saving, CO_2 emission reduction rate and relative energy saving rate of 15.12%, 31.51% and 28.52%, respectively. The flexibility of the system is improved through integrating the energy storage unit, so that the system can stabilize fluctuations and better meet the loads on a typical day. We addressed the effects of unstable solar energy and fluctuating loads, which achieves a balance between system output and user load.

ACKNOWLEDGEMENT

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