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Multi-energy thermochemical hybrid CHP system integrated two-stage energy storage

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ABSTRACT

A multi-energy thermochemical hybrid heat and power (CHP) system with two-stage storage is presented and analyzed in this study. The proposed system includes parabolic trough solar collectors, a thermochemical reactor, an internal combustion engine (ICE) and a two-stage storage of thermal energy and chemical energy, which uses solar energy and methanol as input and outputs power and thermal energy. With the two-stage storage, solar energy and exhaust heat are stored as thermal energy in the first stage and further converted into chemical energy in the second stage, which is stored in the syngas tank. Due to the two-stage energy storage, the heat-to-power ratio (HPR) of the proposed system can be adjusted and controlled between 0.67 and 2.02 under rated working conditions. The load match between energy supplier and receiver is improved, reducing additional energy input and energy waste. Compared to the reference CHP system, the fuel saving ratio (FSR) of the proposed system is further improved from 34% to 52% under the design conditions. The methanol decomposition driven by the combination of solar energy and exhaust heat increases the power generation efficiency for methanol fuel. The fuel source conversion reduces the irreversible loss of fuel combustion. Solar thermal energy is upgraded into syngas chemical energy. A high net solar-to-electric efficiency (22.85%) is achieved at a low heat-collecting temperature (538.15 K). This study provides a promising approach for the active regulation of solar-fuel hybrid distributed systems.

Keywords: Combined heat and power, solar energy, energy storage, thermochemistry, heat-to-power ratio

1. INTRODUCTION

Combined heat and power (CHP) systems, as one of typical distributed energy systems (DES), are adjacent to users to meet the demand for electricity and heating loads, and play an important role in reducing fossil fuel consumption and CO_2 emission. However, the heating and electrical output of the CHP are highly coupled and difficult to adjust independently[1]. The conflict between supply and demand promotes new technologies for the CHPs. For thermal supplementation in case of heat storage, as well as for reducing CO_2 emission simultaneously, the integration of CHP and renewable energy sources (RES) is a promising strategy[2]. For excess heat production, waste heat recovery technologies, especially thermal power generation technologies, are studied intensively. Mago et al.[3] analyzed and optimized the use of CHP–ORC systems for small commercial buildings. Liu et al.[4] proposed a hybrid solar-clean fuel distributed energy system with solar thermochemistry of methanol decomposition and chemical recuperation. This study proposes a novel CHP system based on solar-exhaust heat co-driven fuel reforming with two-stage energy storage to achieve the active regulation for matching supply and demand.

2. SYSTEM CONFIGURATION AND OPERATION

2.1 System description

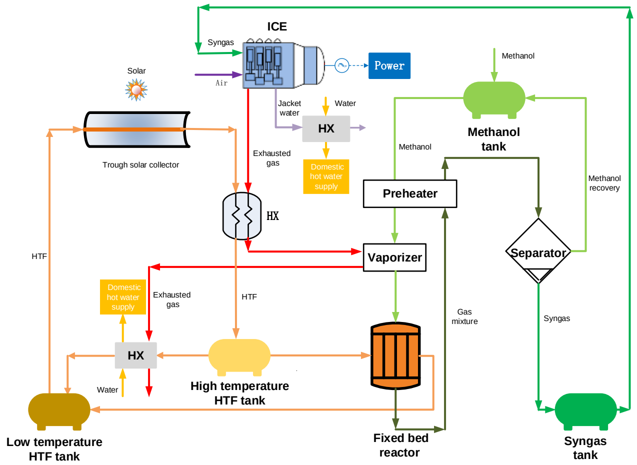


Fig. 1. Scheme diagram of the proposed system

The proposed system inputs solar energy and methanol fuel and outputs power and thermal energy. The configuration of the proposed system is shown in Fig.1. It is mainly composed of five parts, i.e., parabolic trough solar collectors, a thermochemical reactor, an ICE power block, a domestic hot water production unit and a two-stage energy storage unit.

The heat transfer fluid (HTF) from a low-temperature HTF tank stores solar energy provided by parabolic trough solar collectors and further harvests exhaust heat from the ICE. A part of it is stored in a high-temperature HTF tank for heating. In this way, solar energy and exhaust heat are stored as thermal energy, namely the first stage energy storage. The other stored energy in the HTF drives fuel reforming.

After a series of specific operations, including preheating, vaporizing, decomposition, heat recovery, and gas liquid separation, the methanol is converted into syngas and stored in a syngas tank for power generation. Solar and exhaust thermal energy are further stored as chemical energy, namely the second stage energy storage in this study.

A typical CHP system with the direct methanol combustion technology is selected as the reference system.

Compared to the reference system, the ICE burns syngas produced by methanol decomposition, instead of methanol, for power generation in the proposed system[5-7]. The first stage energy storage takes the place of the fuel-fired heating device for heat shortage in the reference system.

The nominal operation parameters are summarized in Table 1.

2.2 System operation strategy

The operational strategy of the proposed system aims to match supply and demand for heat and electricity under various operation conditions by the active regulation (see Fig. 2 for more details).

Table 1. Nominal parameters for the proposed system

Items	Value	Items	Value
Solar collection		**ICE Power generation**	
Aperture area of solar flied	1381.82 m^2	Rated power	767 kW
Designate optical efficiency	0.741	Power generation efficiency	37.30%
Solar collection temperature	508.15-538.15 K	Exhaust gas temperature(K)	733.15 K
Thermochemical reaction		**Domestic hot water supply**	
Reaction temperature	523.15 K	Domestic hot water temperature	368.15 K
Reaction pressure	1 MPa	**Others**	
Conversion rate	0.9	Ambient temperature	298.15 K
Reaction capacity	0.269 kg/s	Heat loss rate of pipeline	10%

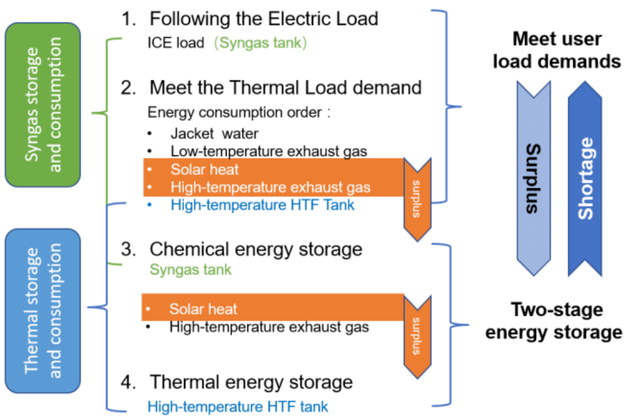


Fig. 2. Operation strategy of the proposed system

3. SYSTEM EVALUATION METHODS

This study introduces the HPR to measure the adjustability of the proposed system, and chooses the overall energy efficiency, the exergy efficiency, the solar energy share, the net solar-to-electric efficiency and the FSR as the main system performance evaluation indices.

The HPR is defined as the ratio of the thermal output (load) to the electrical output(load):

$$HPR = \frac{\dot{Q}}{P} \tag{1}$$

HPR_{sys}, $HPR_{sys,ref}$, $HPR_{ICE,}$ and HPR_{users} are the HPR for the proposed system, the reference system, the ICE, and the users, respectively.

The user thermal demand coefficient ω is used to characterize the deviation between the user thermal demand and the ICE thermal output under the FEL strategy, which is formulated by:

$$\omega = \frac{HPR_{users}}{HPR_{ICE}} = \frac{HPR_{users}}{HPR_{sys,ref}} = \frac{\dot{Q}_{user}}{\dot{Q}_{ICE}} \tag{2}$$

The overall energy efficiency η_{th} is used to evaluate the energy utilization of the whole system, which has the following formula:

$$\eta_{th} = \frac{P+\dot{Q}+\dot{Q}_{th,eq}+\dot{Q}_{ch,eq}}{\dot{Q}_{sol}+\dot{N}_m h_m+\dot{Q}_{th}+\dot{Q}_{ch}} \tag{3}$$

where P and $\dot{Q}$ represent the electric and thermal output, respectively; $\dot{Q}_{th,eq}$ and $\dot{Q}_{ch,eq}$ represent the equivalent output of the thermal and chemical energy storage, respectively; $\dot{N}_m$ and h_m represent the molar input rate and low heating value (LHV) of methanol, respectively; $\dot{Q}_{th}$ and $\dot{Q}_{ch}$ represent the energy released from the thermal and chemical energy storage, respectively.

The exergy efficiency η_{ex} is implemented to evaluate the irreversible loss of the whole energy conversion process in a system, which can be expressed as:

$$\eta_{ex} = \frac{\dot{E}_e+\dot{E}_h+\dot{E}_{th,eq}+\dot{E}_{ch,eq}}{\dot{E}_{sol}+\dot{N}_m e_m+\dot{E}_{th}+\dot{E}_{ch}} \tag{4}$$

The solar energy share F_{sol}, which stands for the solar energy proportion of the total energy input, can be defined as:

$$F_{sol} = \frac{\dot{Q}_{sol}}{\dot{Q}_{sol}+\dot{N}_m h_m} \tag{5}$$

The net solar-to-electric efficiency $\eta_{\mathrm{sol-ele}}$ is used to evaluate the solar power generation efficiency in the proposed system, which is formulated as:

$$\eta_{\mathrm{sol-ele}} = \eta_{\mathrm{sol-th}} \cdot \eta_{\mathrm{th-ch}} \cdot \eta_{\mathrm{ICE}} \tag{6}$$

where $\eta_{\mathrm{sol-th}}$, $\eta_{\mathrm{th-ch}}$, and η_{ICE} represent the efficiency of the solar heat collection, the thermal-to-chemical energy thermochemical conversion, and the ICE power generation efficiency, respectively.

The FSR is calculated as the rate of fuel saving compared to the fuel consumption of conventional separated energy systems:

$$FSR = \frac{\dot{F}_{sep}-\dot{F}_{DES}}{\dot{F}_{sep}} \tag{7}$$

where $\dot{F}_{sep}$ and $\dot{F}_{DES}$ are given by

$$\dot{F}_{sep} = \dot{N}_{m,e} + \dot{N}_{m,th} \tag{8}$$

$$\dot{F}_{DES} = \dot{N}_m + \left(\dot{N}_{syn,discharge} - \dot{N}_{syn,storge}\right) \cdot \frac{h_{syn}}{h_m} \tag{9}$$

4. RESULTS AND DISCUSSION

In this section, the on-design and off-design system performances of the proposed system and the reference system are evaluated. The energy storage and release analysis of the proposed system with the consideration of user demands is carried out. The performances of the proposed system based on user demands are investigated.

The on-design operation condition is DNI=700w/m^2 and the ICE load rate is 100%. The comparison is based on the two systems with the same amount of power. For the conventional separated energy systems, the efficiencies of electricity and heat are 0.38 and 0.83, respectively [8].

4.1 On- and off-design system performance analysis

Table 2. On-design system performances

Items	Value	
	The proposed	The reference
R	0.67-2.03	1.21
η_{th}	75.17%	82.26%
η_{ex}	36.80%	36.23%
F_{sol}	16.69%	0%
$\eta_{sol\text{-}ele}$	22.85%	0%
FSR	*58.62%*	*34.26%*

4.1.1 Heat-to-power ratio

The HPR can be adjusted between 0.67-2.03 in the proposed system, which is wider than that (only 1.21) in the reference system under the on-design condition, as shown in Table 2. The HPR adjustment range under variable working conditions is shown in Fig. 3. The results show that the HPR of the proposed system under a certain ICE load rate can be massively adjusted and controlled, especially when the solar energy share is high. The upward adjustment ability of the HPR stems from the first stage energy storage, while its downward adjustment ability due to the second stage energy storage.

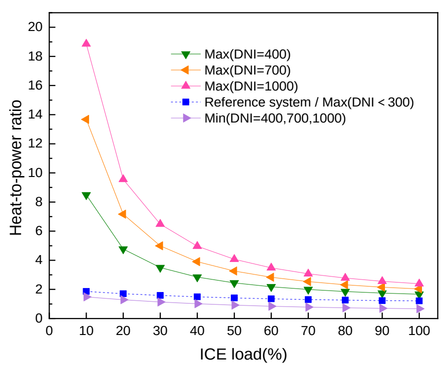


Fig. 3. HPR adjustment range under the off-design operation conditions

4.1.2 Overall energy efficiency

The overall energy efficiency of the proposed system is 75.17%, which is slightly lower than that of the reference system (82.26%) under the on-design condition, as shown in Table 2. In Fig. 4, the significant heat loss in the solar collection process is the main reason for the decrease of the efficiency of the proposed system. Each energy in the proposed system, especially the thermal energy of the high-temperature exhaust gas, is efficiently utilized in a cascading manner, addressing the temperature mismatch problem on the energy utilization in the reference system.

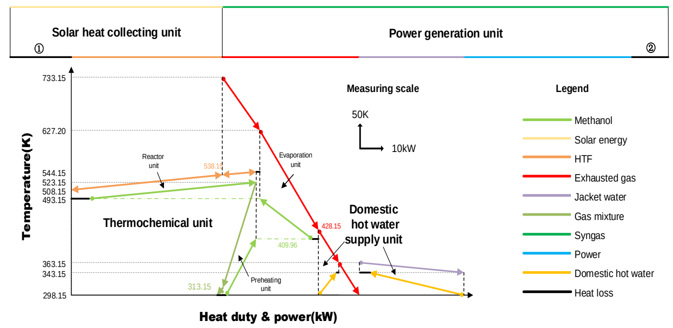


Fig. 4. T-Q diagram of the proposed system under the designate condition

4.1.3 Exergy efficiency

The exergy efficiencies of the proposed and reference systems under the on-design condition are 36.80% and 36.23%, respectively. The exergy analysis result reveals the inherent differences between them. In the proposed system, and there is a significant exergy destruction in the solar collection process, as shown in Fig. 5. Due to hybrid thermochemistry, the exergy loss of the power generation decreases from 1200kW to 900kW, down by 25%, producing the same electricity. The exergy efficiency under the off-design condition is shown in Fig. 6(a). The result shows that the chemical recuperation of the exhaust thermal energy is the key to the improvement of the exergy efficiency.

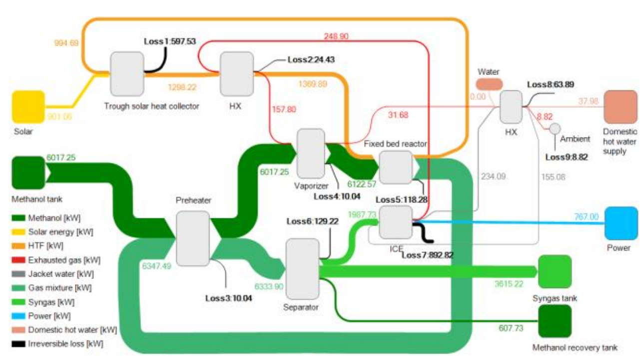
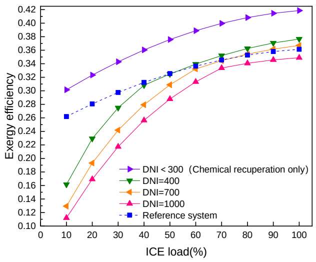
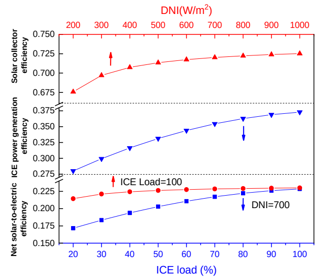


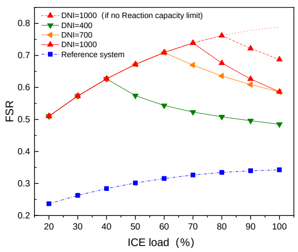
Fig. 5. Sankey diagram of the system exergy flow of the proposed system under the on-design condition.



(a)



(b)



(c)

Fig. 6.
(a)Exergy efficiency,
(b)Net solar-to-electric efficiency, and
(c)FSR
under varying conditions

4.1.4 Solar energy share and net solar-to-electric efficiency

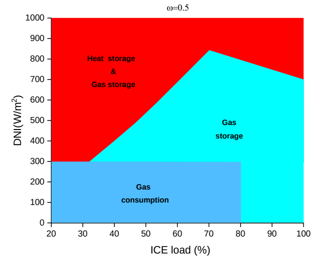
Solar energy is introduced and utilized in the proposed system, whose proportion reaches to about 16.69% of the total input energy under the on-design condition. Owing to the use of solar thermochemical power generation technologies, a high net solar-to-electric efficiency (22.85%) is achieved at a low heat-collecting temperature (538.15 K). The off-design net solar-to-electric efficiency is shown in Fig. 6(b). The result shows that the net solar-to-electric efficiency is positively correlated with the ICE load and the solar collector efficiency.

4.1.5 Fuel saving ratio

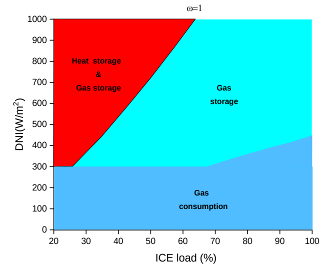
Under the on-design condition, the proposed system has a FSR of 58.62%, which is higher than that of the reference system (34.26%), mainly due to the introduction of solar energy. Under the off-design conditions, the FSR of the proposed system is still much higher than that of the reference system. The FSR has a decline trend after the initial ascent, due to the reduction of the solar energy share and the surplus solar energy for thermochemistry, respectively, as shown in Fig. 6(c).

4.2 Energy storage and consumption

Fig. 8 shows the energy storage and consumption of the proposed system under varying working conditions and user demands, with ω=0.5, ω=1, and ω=2.



(a)



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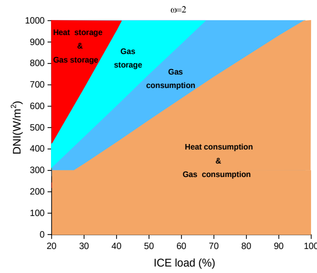
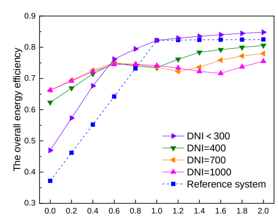


(c)

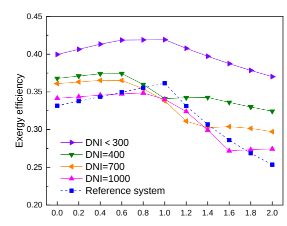
Fig. 8.
Energy storage and consumption under varying operation conditions and user load demands

With the increase of ω, any certain section will undergo a specific sequence of changes in whole or in part, i.e., heat and gas storage, gas storage only, gas consumption only, and gas and heat consumption in that order. The region with heat and gas storage includes two cases of the solar thermal storage: too little exhaust thermal energy for vaporizing methanol and too small reactor capacity for decomposing methanol.

4.3 System performances based on user demands



(a)



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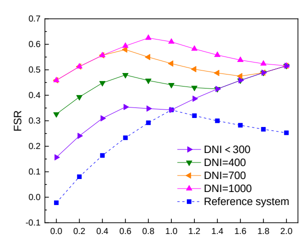

(c)

Fig. 9.

Overall energy efficiency(a), Exergy efficiency(b), and FSR(c) under varying user load demands.

Fig.9 shows the overall energy efficiency, exergy efficiency, and the FSR under varying user load demands at the full load rate on ICE, respectively. The results show that, owning to the active regulation, the proposed system can achieve a high energy efficiency, exergy efficiency, and the FSR under varying working conditions and user load demands. Especially, using solar thermal energy for direct heating shows great advantages on the exergy efficiency and the FSR in case of a shortage of heat supply from ICE ($\omega > 1$), and the chemical recuperation improves the performance of the proposed system by reducing or avoiding energy waste caused by excess heat production($\omega < 1$).

5 CONCLUSIONS

In this work, we proposed a multi-energy thermochemical hybrid CHP system with two-stage energy storage. The multi-energy thermochemical hybrid process offers multiple benefits. The chemical recuperation of the high-temperature exhaust gas alleviates the temperature mismatch problem in energy utilization in the reference system. It improves the exergy efficiency and fuel power generation efficiency of the proposed system. The fuel source conversion reduces the irreversible loss of fuel combustion. The solar thermochemical process upgrades solar thermal energy into syngas chemical energy, by which a high net solar-to-electric efficiency (22.85%) is achieved at a low heat-collecting temperature (538.15 K). With the two-stage energy storage, the HPR of the proposed system can be adjusted and controlled between 0.67 and 2.02 under the on-design conditions. Due to the active regulation, it is possible to maintain high energy efficiency, exergy efficiency, and the FSR under varying working conditions and user demands.

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REFERENCE

[1] Feng L, Dai X, Mo J, Ma Y, Shi L. Analysis of energy matching performance between CCHP systems and users based on different operation strategies. Energy Conversion and Management. 2019;182:60-71.
[2] Bagherian MA, Mehranzamir K. A comprehensive review on renewable energy integration for combined heat and power production. Energy Conversion and Management. 2020;224.
[3] Mago PJ, Hueffed A, Chamra LM. Analysis and optimization of the use of CHP–ORC systems for small commercial buildings. Energy and Buildings. 2010;42:1491-8.
[4] Liu TX, Liu QB, Lei J, Sui J, Jin HG. Solar-clean fuel distributed energy system with solar thermochemistry and chemical recuperation. Applied Energy. 2018;225:380-91.
[5] Leung P, Tsolakis A, Rodríguez-Fernández J, Golunski S. Raising the fuel heating value and recovering exhaust heat by on-board oxidative reforming of bioethanol. Energy & Environmental Science. 2010;3.
[6] Tartakovsky L, Sheintuch M. Fuel reforming in internal combustion engines. Progress in Energy and Combustion Science. 2018;67:88-114.
[7] Verhelst S, Turner JWG, Sileghem L, Vancoillie J. Methanol as a fuel for internal combustion engines. Progress in Energy and Combustion Science. 2019;70:43-88.
[8] Liu T, Liu Q, Lei J, Sui J. A new solar hybrid clean fuel-fired distributed energy system with solar thermochemical conversion. Journal of Cleaner Production. 2019;213:1011-23.