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Dynamic Operation Investigation of the Solar Thermochemical Polygeneration System Based on Methane Dry Reforming

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ABSTRACT

The solar thermochemical technology as a promising method can effectively convert concentrated solar thermal energy into the chemical form of syngas, and then realizes efficient renewable energy utilization. In this work, a solar-driven polygeneration system with the methane dry reforming based solar thermochemical process is developed, and the generated syngas is further utilized by the methanol synthesis module and the gas-steam combined power cycle, to achieve diverse energy outputs of methanol and electricity. Meanwhile, within the fluctuating solar irradiation, the fed methane can be flexibly adjusted to promote reasonable solar energy utilization and comprehensive system operation performances. Through the system off-design analysis, the favorable concentrating solar heat to chemical energy conversion effects can be achieved with the optimal system energy efficiency of 63.0%. During the typical day operation process, the solar share can reach to 25.1% with the real-time regulation complementation of solar energy and fossil fuel. While the annual system operation efficiency is up to 54.4% with a solar share of 21.0%, the system surplus solar energy can be readily stored by the liquid methanol fuel, and the system monthly methanol outputs capacity is 6.65-26.88 GWh. With the flexible regulation and combination of solar energy and chemical energy, efficient multi-energy generation can be achieved, which provides an alternative way to optimize solar conversion performances.

Keywords: solar thermochemical, polygeneration system, regulation complementation, dynamic operation

NONMENCLATURE

Symbols	
η	Efficiency
ω	Energy upgrade factor
Q	Heat
A	Area
W	Generated power
X	Energy share
Abbreviations	
CEI	Comprehensive Evaluation Index
DNI	Direct Normal Irradiance
LHV	Low Heat Value
HRSG	Heat Recovery Steam Generator
MDR	Methane Dry Reforming

1. INTRODUCTION

The complementary utilization of renewable energies and fossil fuels in an energy system is reliable method that can promote clean energy supply and carbon neutrality [1]. Among them, solar thermochemistry is one of the promising complementary technology, such as by driving the methane reforming with the high-temperature concentrated solar energy, and the introduced solar energy achieve stable storage with form the chemical fuel of H_2-enriched syngas [2, 3].

Designing rational energy utilization systems based on solar thermochemistry is a significant research direction in the field of solar energy. Sheu et al. [4] combined methane redox reforming with solar energy to develop a power generation system complementary to solar energy and fuel. Li et al. [5] proposed a solar combined cycle system, which uses solar radiation heat energy to drive methane reforming reaction to produce syngas for the power cycle, and the system efficiency is increased to 51.6 %. Based on the solar methane steam reforming and chemical recovery, Ni et al. [6] presented

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a solar thermochemical generation system, and the thermal efficiency of the system reach 47.7%. Bai et al. [7] developed a solar polygeneration system through the complementary of solar and biomass fuel, the energy efficiency can reach 51.89%. System integration has the potential to promote efficient complementarity between solar energy and fuel.

Whereas, during the practical application, the fluctuating irradiation deteriorates the efficiency of the solar system. It is important to explore the optimization methods to improve the ability of system to cope with variable conditions. To enhance the variable operating efficiency, Diaz et al. [8] used carbon fuel energy storage to realize the flexible energy scheduling of a concentrated solar hybrid power generation system. Liu et al. [9] adopted the multi-objective optimization method to optimize the equipment capacity configuration of a solar CCHP system under different operation strategies, which improved the system comprehensive utilization efficiency. Li et al. [10] proposed the operation strategy of following battery state and optimized the configuration of a hybrid system with solar thermal utilization, thus achieving better primary energy saving ratio and carbon dioxide emission reduction ratio. The research on system integration and optimization has proved the changeable solar energy conversion process can be adapted by adjusting the system structure, capacity configuration and operation strategy. However, the active regulation of complementary fuel scheduling to improve thermochemical efficiency and system performance is also essential and worth discussing. The operating characteristics of the system are affected by both solar energy resources and complementary strategies, which makes the dynamic conditions of the system more complicated.

In this paper, a solar thermochemical polygeneration system that outputs methanol and electricity is developed, this system promotes the diversified conversion of solar energy to electricity and methanol. Then the dynamic operation of the variable working condition and full working condition with a real-time energy scheduling strategy are studied.

2. SYSTEM DESCRIPTIONS

The solar thermochemical polygeneration system based on methane reforming achieves multiple conversion of energy to methanol and electricity, which enhances scheduling flexibility of stored solar energy.

2.1 System configuration

The solar polygeneration system consists of solar reforming section, a methanol synthesis section, and a power cycle. Apart from the H_2-enriched syngas through the solar reforming, the valuable energies of electricity and liquid methanol also can be obtained, and the schematic configuration of the system is shown in Fig. 1.

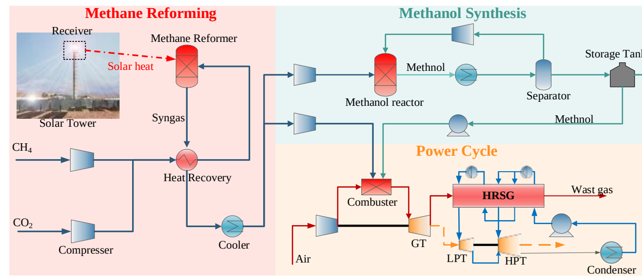


Fig. 1 Layout of the solar polygeneration system

In the solar reforming section, the endothermic reaction of methane dry reforming is adopted, and the incident solar irradiation is concentrated by the heliostats and then reflected to the cavity-type solar reforming reactor. The produced high-grade gaseous fuel comprising CO, H_2 syngas, and unreacted CH_4 and CO_2 will be utilized for power generation via the Brayton-Rankine cycle. The surplus syngas will be then utilized for methanol synthesis, achieving the long-term solar thermal liquefied storage. In addition, the released waste heat from the exothermic methanol synthesis will be recovered to generate additional steam and also approve the power generation.

Whereas, due to the fluctuant nature of solar irradiation, according to the energy balance, the flow rate of the fed methane for solar reforming should be regulated, and the integrated subsystem should correspondingly coordinate their individual operating parameters. Concerning the off-design operation of the power cycle, except for the syngas, the methanol can be directly used as supplemental fuel under insufficient solar conditions.

2.2 System modeling

Within the solar reforming process, the required reaction heat is supplied by point focus type solar collection technology of solar tower, its collection efficiency η_c can be formulated by Eq. 1.

$$\eta_c = \eta_{opt} - \frac{Q_l}{Q_s} = \eta_{opt} - \frac{Q_l}{DNI \cdot A_a} \quad (1)$$

where η_{opt} is the optical efficiency of the solar collection facilities, Q_s and Q_l are the incident solar radiation and heat loss of the receiver/reactor, respectively; *DNI* and A_a mean the total area of the heliostat and the direct solar irradiation.

As for the solar tower collection, it mainly includes the thousands of heliostats and the solar tower with a top-mounted solar receiver/reactor, its optical efficiency will be affected by the cosine effect, attenuation by the long collection radius, and the mirror reflectance, as expressed by Eq. 2.

$$\eta_{\rm opt}=\eta_{\rm cos}\cdot\eta_{\rm ref}\cdot\eta_{\rm s\&b}\cdot\eta_{\rm att}\cdot\eta_{\rm int} \tag{2}$$

where $\eta_{\rm cos}$, $\eta_{\rm ref}$ and $\eta_{\rm s\&b}$ represent the cosine efficiency, reflectivity and shading efficiency of heliostats, respectively; $\eta_{\rm att}$ and $\eta_{\rm int}$ mean the atmospheric attenuation efficiency and the interception efficiency, respectively.

The calculation methods for these efficiencies are as follows:

$$\eta_{\rm cos}=\vec{n}\cdot\vec{S} \tag{3}$$

$$\eta_{\rm att}=\begin{cases}0.99321-0.000176d+1.97\times10^{-8}d^2,\ d\le 1000\text{m}\\ \exp(0.0001106d),\ d>1000\text{m}\end{cases} \tag{4}$$

$$\eta_{\rm int}=\frac{1}{2\pi\sigma^2_{\rm tot}}\int_x\int_y \exp(-\frac{x^2+y^2}{2\sigma^2_{\rm tot}})dydx \tag{5}$$

$$\sigma_{\rm tot}=\frac{\sqrt{D^2(\sigma^2_{\rm sun}+\sigma^2_{\rm bq}+\sigma^2_{\rm ast}+\sigma^2_{\rm track})}}{\sqrt{\cos rec}} \tag{6}$$

The incident radiation will be first intercepted and absorbed by the solar receiver/reactor which is installed at the top of the tower, and then drive the internal high-temperature thermochemical reaction of methane reforming. The energy balance of the solar receiver/reactor is given as follows:

$$Q_{\rm s}=Q_{\rm r}+Q_{\rm l}=Q_{\rm r}+Q_{\rm lk}+Q_{\rm lc}+Q_{\rm rad} \tag{7}$$

where $Q_{\rm r}$ is the endothermic reaction, which is determined by the enthalpy change of the reaction process; $Q_{\rm l}$ means the total heat loss of the reactor, including three parts: the conduction heat loss $Q_{\rm lk}$ of the reactor, the convective heat loss $Q_{\rm 1c}$ and the radiation heat loss $Q_{\rm rad}$.

There are two types of main reactions that take place in the reactor, including methane dry reforming (MDR) and a reverse water-gas shift reaction, as expressed by Eqs. 8-9.

$$\text{CH}_4+\text{CO}_2\rightarrow 2\text{CO}+2\text{H}_2,\Delta H^0_{298}=+247.0\ \text{kJ/mol} \tag{8}$$

$$\text{CO}_2+\text{H}_2\rightarrow \text{CO}+\text{H}_2\text{O},\Delta H^0_{298}=+41.7\ \text{kJ/mol} \tag{9}$$

Within the methanol synthesis process (with the material of CO, CO_2 and H_2), the main reactions are formulated by Eqs. 10-11.

$$\text{CO}+2\text{H}_2\rightarrow \text{CH}_3\text{OH},\Delta H^0_{298}=-90.5\ \text{kJ/mol} \tag{10}$$

$$\text{CO}_2+3\text{H}_2\rightarrow \text{CH}_3\text{OH}+\text{H}_2\text{O},\Delta H^0_{298}=-49.5\ \text{kJ/mol} \tag{11}$$

As for the power generation, a gas-steam combined cycle with the capacity of 63 MW is adopted, and it mainly consists of a gas turbine, a heat recovery steam generator (HRSG) and a steam turbine. The main operating parameters of the system is listed in Table 1.

Table 1 Main operation parameters of the system

Item	Value
Heliostat field area	19000 m^2
Receiver pressure	0.1 MPa
Receiver temperature range	500-1000℃
Synthesis reactor temperature / pressure	260℃/ 5.5 MPa
Gas turbine inlet temperature	1093℃
Gas turbine inlet/Discharge pressure	1.166/0.1038 MPa
HRSG gas discharge temperature	115℃

2.3 System evaluation methods

In order to evaluate the performance of the solar thermochemical process and discuss the solar energy enhancement effect on chemical energy. The thermochemical efficiency $\eta_{\rm th}$ and the energy upgrade factor ω are used as evaluation criteria:

$$\eta_{\rm th}=\frac{m_{\rm syngas}\cdot LHV_{\rm syngas}}{Q_{\rm s}+m_{\rm methane}\cdot LHV_{\rm methane}} \tag{12}$$

$$\omega=\frac{m_{\rm syngas}\cdot LHV_{\rm syngas}}{m_{\rm methane}\cdot LHV_{\rm methane}} \tag{13}$$

Taking into account the solar energy and methane in the polygeneration system, the performance and solar energy effect were comprehensively discussed from the thermodynamic aspect. Taking energy efficiency $\eta_{\rm sys}$ and solar energy share $X_{\rm solar}$ as the basic thermodynamic evaluation criteria:

$$\eta_{\rm sys}=\frac{W+m_{\rm methanol,\,out}\cdot LHV_{\rm methanol}}{Q_{\rm s}+m_{\rm methane}\cdot LHV_{\rm methane}+m_{\rm methanol,\,in}\cdot LHV_{\rm methanol}} \tag{14}$$

$$X_{\rm solar}=\frac{Q_1+Q_{\rm methanol,solar}}{Q_1+m_{\rm methane}\cdot LHV_{\rm methane}+m_{\rm methanol,\,in}\cdot LHV_{\rm methanol}} \tag{15}$$

where W means generated power, respectively; $m_{\rm methanol,in}$ and $m_{\rm methanol,out}$ are supplemental fuel and output methanol; $Q_{\rm methanol,solar}$ represents the solar energy stored in methanol.

3. RESULTS AND DISCUSSION

The solar thermochemical polygeneration system based on methane reforming is designed to sustain the stable operation of a 63 MW gas-steam combined cycle, with a rated solar collection capacity of 60 MW and a methane reforming rate of 0.2 kmol/s. The system operating characteristics are revealed by the variable operating condition study, and the full operating conditions performances based on formulated strategies are discussed.

3.1 Thermochemical characteristics of solar methane reforming

The methane reforming process is composed of multiple reversible reactions, which will be affected by various factors such as reactor temperature and pressure. Based on the chemical equilibrium, the solar methane reforming characteristic is evaluated, as shown in Fig. 2.

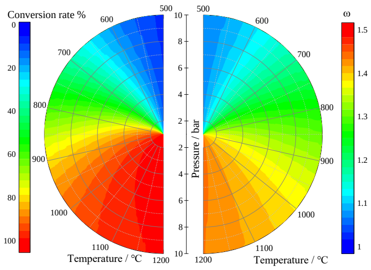


Fig. 2 Effect of temperature and pressure on reaction characteristics of MDR

Since methane reforming is an endothermic reaction, as the temperature increase, the reaction equilibrium is shifted toward a positive direction. Pressure will have an adverse impact on solar reforming and the energy upgrade factor of the reaction will follow the same trend as the conversion rate. Meanwhile, the characteristics of the reactor energy conversion under different heat collection conditions and methane flow conditions were simulated, and the results are shown in Fig. 3.

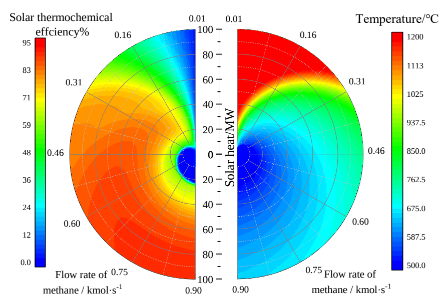
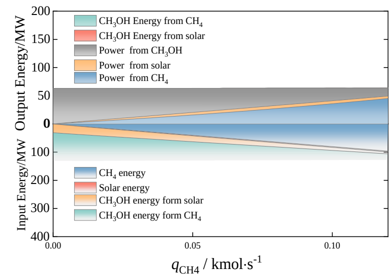


Fig. 3 Effect of methane flow and solar heat on reaction characteristics of solar MDR

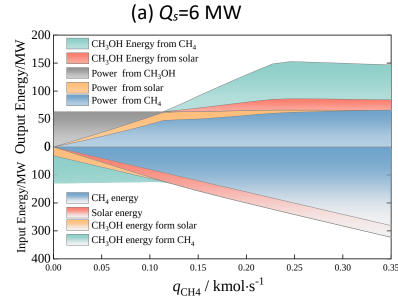
With the solar radiation increasing, the high temperature of the reactor leads to more heat loss. Under the same solar heat conditions, the increase of methane input can decrease the temperature of the reformer, which reduces the heat loss of the heat collector and improves the thermochemical conversion efficiency.

3.2 System energy conversion and operation strategy

As a dispatchable energy, methane is used to complement the fluctuation of solar energy. The solar reforming can be flexibly adjusted in order to match the subsequent combined power generation cycle and methanol synthesis process. Under two different concentrating solar heat conditions (10% and 80% of the rated solar heat of the system), the effect of fossil fuel dispatch on the system energy output characteristics is shown in Fig. 4.



(a) Q_s=6 MW

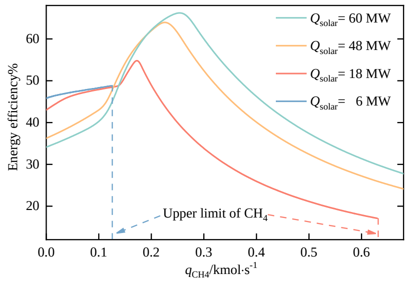


(b) Q_s=48 MW

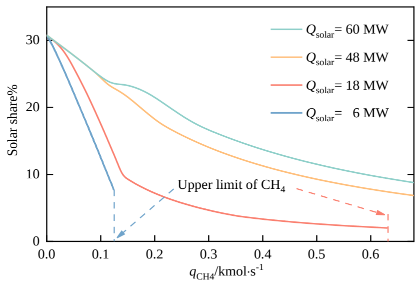
Fig. 4 Effect of methane flow on energy output

The energy output under 6 MW solar radiation shows that even under maximum fossil fuel replenishment, the syngas cannot meet the requirements of heat value to maintain stable operation of the power cycle. In this regard, as the supplementary fuel, a certain amount of methanol stored by the synthesis part needs to be delivered to the power cycle to maintain power generation. Under the condition of sufficient radiation (80% of the rated solar heat), When the methane input is 0.12 kmol/s, the system is at an equilibrium point where neither methanol is produced nor supplementary methanol is supplied as fuel.

In addition, energy efficiency and solar energy share under more working conditions are calculated, as is shown in Fig. 5. According to the results of the parameter analysis, when the methane flow rate is adjusted under different solar conditions, the changes of system efficiency and solar energy share are inconsistent. Although adjusting the complementary amount of methane can obtain the highest overall energy utilization efficiency at a specific operating point, the corresponding solar energy utilization share is decreased, which is not conducive to improving the solar energy share and the saving rate of fossil fuels. And when a large amount of methanol is used for supplemental fuel, it will indirectly reduce the overall energy utilization efficiency.



(a) energy efficiency



(b) solar share

Fig.5 Effect of methane flow on energy characteristics

Considering the asynchrony of evaluation indexes such as system efficiency and solar share, a comprehensive evaluation method is adopted in this work to develop an energy scheduling strategy that can improve the system comprehensive performance. Comprehensively considering the energy efficiency, solar energy share, and methanol supplementary ratio, a comprehensive evaluation index (*CEI*) for system operation is established as shown in Eq. 14:

$$CEI = \eta_{sys} + X_{solar} - \frac{m_{methanol,in} \cdot LHV_{methanol}}{m_{methane} \cdot LHV_{methane}} \tag{14}$$

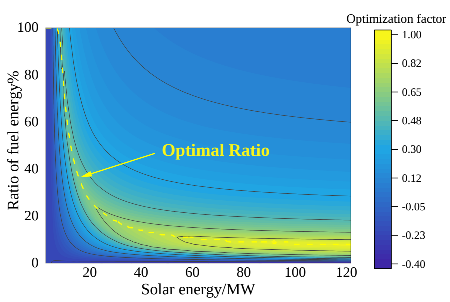


Fig. 6 The comprehensive evaluation index under different operation conditions

The *CEI* under different energy complementary conditions is shown in Fig. 6. The optimal ratio of methane fuel can be determined to give the optimized energy scheduling strategy under full operating conditions.

3.3 System dynamic operation performances

By adopting the scheduling strategies, the system dynamic operation process under full conditions is simulated. Based on meteorological data of Hotan in China, the daily, monthly, and yearly results are presented to show the system adaptability under different time scales.

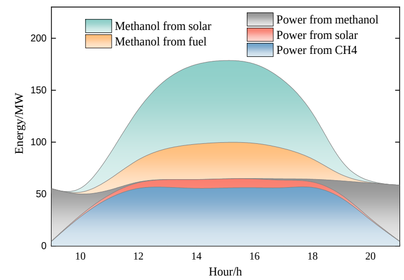


Fig. 7 The hourly energy output of the typical day

With the annual average data as a typical day, the hourly power and methanol output are shown in Fig. 7. In order to stabilize its output, three parts of the energy are collaborate used as the fuel source of the power cycle, including methane fossil fuel, synthetic methanol, and solar energy. The solar energy is eventually converted into electricity and chemical energy of methanol and the solar energy proportion of the output energy can reach 25.1% when the heat collection is sufficient.

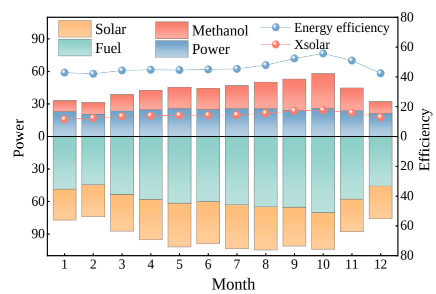


Fig. 8 The monthly energy output of the system

The energy input and output characteristics of each month are shown in Fig. 8. The solar share is basically maintained at 18.3%-20.1% and the system energy efficiency is varied between 40.2%-58.3%, which shows the monthly complementarity between solar energy and fossil fuels. In the months when solar energy is relatively sufficient, the proportion of fossil fuel replenishment in the system is relatively low. Especially in October, the solar heat reaches the maximum value of 22.4 GWh, the energy of complimentary methane fuel is 26.88 GWh, and the fuel complementation ratio reaches the lowest.

From the perspective of the whole year, the energy stream of the solar thermochemical polygeneration system is shown in Fig. 9. The ratio of the solar energy in the solar field to the methane fossil energy is 0.54, due to the limitation of solar energy collection efficiency, the ultimate the solar share of the system is only 21%. Meanwhile, the system efficiency can reach 54.4%. In addition, methanol for the fuel supplement of the power cycle only accounts for 46.3% of the total annual methanol production.

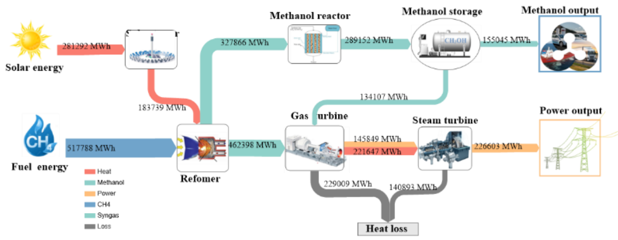


Fig. 9 The annual energy stream diagram of the system

4. CONCLUSIONS

A new solar thermochemical polygeneration system based on solar methane reforming is developed. The solar thermochemical process and the whole system performance under different operating conditions and fuel scheduling are analyzed, and then the full operating conditions characteristics under the formulated strategy are investigated. The main conclusions are as follows:

The thermochemical process is researched under the different solar collection temperatures, and the high-temperature concentrated solar is beneficial to improve the reforming energy upgrade factor and the conversion rate, but it also tends to increase heat loss and then reduce system efficiency. Adjusting the scheduling of fuels can change reaction temperature and enhance the system efficiency to 63%, but with a low solar share.

With the goal of optimizing the comprehensive evaluation index, the real-time scheduling strategy is determined and the full operation condition is studied. The typical daily output shows that the solar share can reach 25.1%, still maintaining a high proportion of solar energy. The annual investigation verifies the excellent performances of the system in practical operations the monthly system efficiency varied between 40.2%-58.3%, with the annual efficiency of 54.4%. Meanwhile, 26.7 kt methanol is outputted yearly to store solar energy. The polygeneration system with the real-time energy scheduling strategy exhibits favorable thermodynamic and energy complementary performance.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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