Energy Proceedings
Vol 32, 2023
ISSN 2004-2965

A new distributed energy system coupled with solar thermochemistry and wind power generation

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ABSTRACT

A new solar-wind-fuel complementary distributed energy system (DES) is proposed, which is integrated with solar-fuel thermochemical conversion for efficient utilization of solar and wind energy. To address the source-load mismatch caused by intermittent and unstable solar and wind energy, a new multi-energy system consisting of solar, wind and fuel is proposed to maintain the energy supply, with the consideration of the characteristics of day-night and seasonal complementation of solar and wind energy. Through solar-driven methanol decomposition, solar energy is upgraded to high-quality chemical energy in the form of syngas for storage. The results show that the new DES can promote the integrated use of wind and solar energy, increase the proportion of renewable energy in the system and reduce CO_2 emissions. Compared to conventional power grid and fuel direct combustion, the new DES achieves a 42.12% reduction in CO_2 emission.

Keywords: solar thermochemistry, carbon reduction, solar-wind hybrid, distributed energy system, system integration

NONMENCLATURE

Abbreviations	
DES	Distributed energy system
DNI	Direct normal irradiation
STC	Solar thermochemical conversion
Symbols	
P	Instantaneous wind power
ρ	Air density
v	Wind speed
A	Cross-sectional area

1. INTRODUCTION

With the development of global economy and increasing demand for energy, achieving efficient and clean utilization of energy has become an urgent issue. Distributed energy systems are considered to be energy-saving and environment-friendly approaches with the potential in the hybrid cascade utilization of fuel and renewable energy sources [1,2]. Due to its high efficiency, stability and low emission, DES coupled with renewable energy has attracted extensive attention[3,4]. In particular, solar energy and wind energy are considered to be two most promising energy sources for solving energy shortage and have been applied to DESs[4].

Due to spatial and temporal differences and environmental conditions, solar energy can only be used during the day, while wind energy is mainly distributed in the early morning or late evening when temperatures change considerably. Existing complementary forms of wind and solar power focus on combining photovoltaic and wind power generation, which can improve the stability of energy supply to a certain extent[3]. However, photovoltaic and wind power do not have the function of energy storage and are subject to real-time fluctuations in renewable energy sources, resulting in a mismatch between supply and demand. It is necessary to further enhance the supply-demand matching performance of the system by energy storage, which places high requirements on electricity storage.

This is a paper for Applied Energy Symposium 2023: Clean Energy towards Carbon Neutrality (CEN2023), April 23-25, 2023, Ningbo, China.

Solar thermochemical conversion (STC) has been identified as a promising method for utilizing solar energy because it can convert unstable solar energy into fuel chemical energy, improving power output and facilitating energy storage. Many researchers[5,6] have conducted numerous studies on solar-driven thermochemistry, such as splitting carbon dioxide and water, methane dry and wet reforming[7], and high-temperature thermochemical energy storage. The papers[8,9] used solar thermochemical cycles to split water or carbon dioxide through metal oxides to produce high-quality fuels. However, in those mentioned solar thermochemical reactions, higher reaction temperatures often require higher concentration ratios, increasing the complexity of the system.

Our team has investigated the mid-and-low temperature solar thermochemistry using solar energy collected by commercial parabolic trough collectors to drive methanol decomposition for producing high-quality syngas[10,11]. The lower reaction temperature reduces the complexity of the solar thermochemical process and is conducive to improving the solar thermochemical efficiency[12]. Considering the complementarity of wind and solar energy and the efficient utilization and stable storage of solar energy through the mid-and-low STC, this study proposes a new DES with solar thermochemistry to enhance and renewable energy proportion, and reduces CO_2 emission.

2. SYSTEM AND METHODS

This section describes the new DES, establishes solar thermochemistry and wind power generation models, as well as gives the calculation method for energy balance between user loads and system supply.

2.1 System description

Figure 1 describes the structure and workflow of the proposed DES, which mainly includes four parts: solar thermochemical conversion, syngas storage and internal combustion engine power generation, wind power generation and grid replenishment, and auxiliary boiler heating. The composition and function of the system units are described as follows:

(1) Solar thermochemical conversion unit. In Figure 1, the evaporated methanol vapor is decomposed into syngas through the solar receiver/reactor driven by concentrated solar thermal energy using parabolic trough collectors.

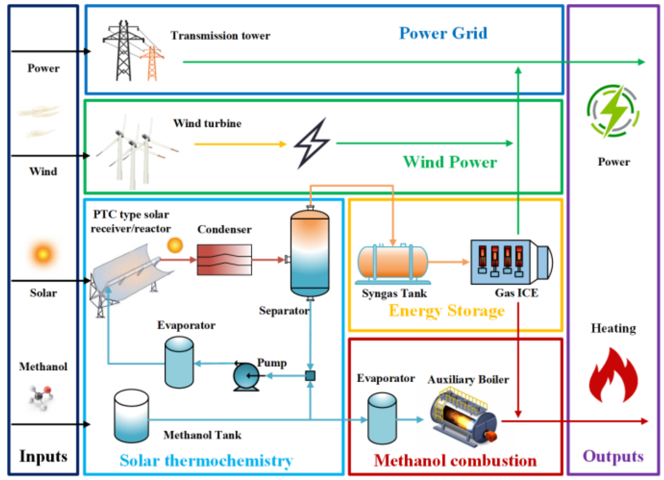

Fig. 1. Structure and workflow of the new system

(2) Energy storage device and internal combustion engine unit. The energy storage device can store the syngas generated by the solar thermochemical unit, thus enabling the storage and utilization of solar energy. The internal combustion engine unit allows the flow of syngas into the internal combustion engine to be adjusted in time to meet the user's demand for electric loads.

(3) Wind power generation and grid replenishment unit. In periods of sufficient wind resources, wind turbines can be used to convert wind energy into electrical energy. When the wind turbines do not generate enough electricity to meet the electrical load of the user, an internal combustion engine is used to convert the chemical energy in the form of syngas into electricity.

(4) Auxiliary boiler heating unit. When the thermal energy provided by the internal combustion engine is insufficient to meet the needs of the user, the additional heat required is provided by burning methanol in the boiler.

2.2 System model

2.2.1 Solar thermochemistry

The solar thermochemical system mainly consists of collectors for solar energy collection and receivers/reactors for chemical reactions. Parabolic trough solar collectors can collect and concentrate solar energy with low energy density at the focal line of the parabolic collector. The reaction equation of methanol decomposition is as follows:

$$CH_3OH(g) \rightarrow CO(g)+2H_2(g) \tag{1}$$

The solar thermochemical receiver/reactor is mainly composed of two parts: the outer transparent glass tube and the inner selectively coated absorption tube. The structure is shown in Figure 2. The sunlight can pass through the outer glass tube and directly reach the inner absorption tube.

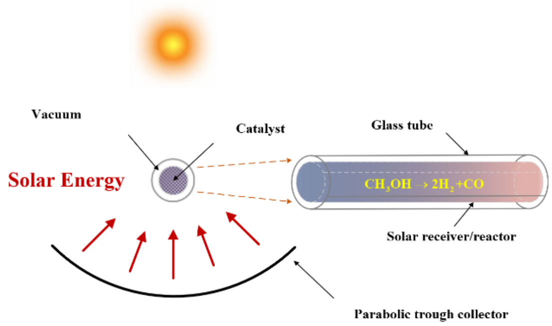

Fig. 2. Schematic of the solar receiver/reactor

Considering heat and mass transfer processes of the system and reaction kinetics characteristics, it is possible to propose the following model for methanol decomposition [13].

$$r_D = \frac{k_D K^*_{CH_3O^{(2)}}\left(\frac{P_{CH_3OH}}{P^{0.5}_{H2}}\right)\left(1-\frac{P^2_{H_2}P_{CO}}{k_D P_{CH_3OH}}\right)C_{S_2}C_{S_{2a}}}{\left[1+K^*_{CH_3O^{(2)}}\left(\frac{P_{CH_3OH}}{P^{0.5}_{H2}}\right)\right]\left(1+K^{0.5}_{H^{(2a)}}P^{0.5}_{H_2}\right)} \quad (2)$$

<u>2.2.2 Wind turbine</u>

During the generation of electricity, the amount of power generated by a wind turbine will vary with the wind speed during the day. The mathematical model of the wind turbine power and wind speed can be expressed as[14]:

$$P(v)=\begin{cases} 0 & \text{if } v \le v_{\text{in}} \\ \frac{1}{2}\eta\rho A v^3 & \text{if } v_{\text{in}} < v \le v_{\text{rated}} \\ P_{\text{rated}} & \text{if } v_{\text{rated}} < v \le v_{\text{out}} \\ 0 & \text{if } v > v_{\text{out}} \end{cases} \quad (3)$$

where the instantaneous wind power P can be expressed by the air density ρ, the wind speed $v(\text{m/s})$, the total efficiency η, and the cross-sectional area A perpendicular to the wind speed.

The output power curve of a wind turbine is the relationship curve between the output power and the wind speed established to reflect the characteristics of the wind turbine. The wind speed and power data of the known wind turbine were corrected using the above mathematical model, and thus the wind power curve in Figure 3 was obtained.

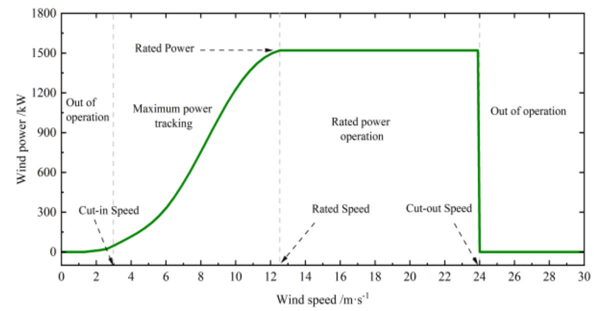

Fig. 3. Power curve of the wind turbine

2.3 *Calculation and method*

The calculation flow diagram of the new DES is shown in Figure 4. Firstly, the wind turbine is used to supply power to users. When electricity demands of the user exceed the amount generated by the wind turbine, the stored syngas is used to generate electricity by an internal combustion engine. Finally, the combustion of methanol in the boiler and the purchase of electricity from the grid are used to supplement heat and electricity.

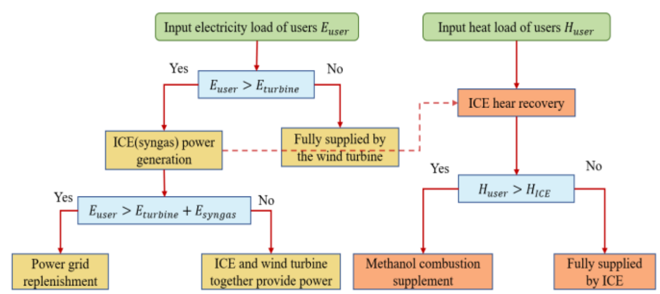

Fig. 4. The calculation flow diagram

In order to describe the changes in energy intensity and complementarity of the two renewable energy sources in the new DES, an energy intensity factor is defined. It refers to the ratio of instantaneous intensity to maximum intensity over some time.

$$\text{Energy intensity factor}=\frac{\text{Instantaneous intensity}}{\text{Maximum intensity}} \quad (4)$$

3. RESULTS AND DISCUSSION

This section focuses on analyzing the low-temperature solar thermochemistry performance, calculating the power balance distribution and the heat balance distribution, and comparing the carbon emission reduction performance of the system.

3.1 Complementarity of the system

The daily intensity factor of solar energy and the daily intensity factor of coupling solar energy and wind energy are shown in Figure 5. It can be seen that solar energy is mainly concentrated during the day, and solar energy cannot be utilized due to the lack of sunlight before 7:00 and after 18:00. By combining solar and wind energy, the energy intensity factor of the proposed DES can be almost maintained above 40% throughout the day, avoiding situations where the sole solar energy is not available at night.

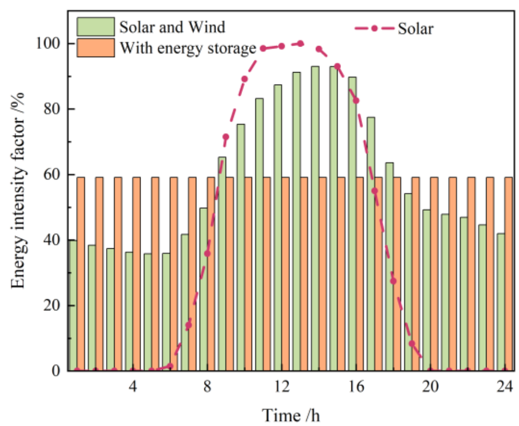

Fig. 5. Average daily intensity factor

3.2 Performances of the STC process

Figure 6 shows the effect of methanol molar flow and solar energy flux on methanol conversion and solar-to-chemical efficiency. Before the solar radiation intensity can achieve complete conversion of methanol, increasing the feed rate will reduce the conversion of methanol under a constant solar flux. When the feed rate of methanol is a constant, the thermochemical efficiency will initially increase and then decrease during the process of solar flux changing from 200 $\mathrm{W/m^2}$ to 900 $\mathrm{W/m^2}$, with the highest solar-to-chemical efficiency corresponding to the complete conversion of methanol.

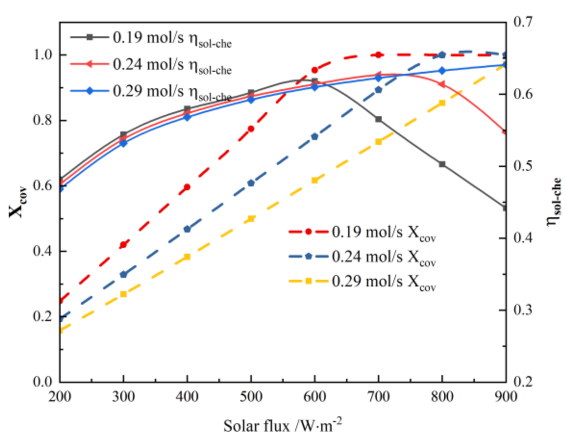

Fig. 6. Effect of DNI and methanol feed on methanol conversion rate and solar thermochemical efficiency

3.3 Power balance distribution

Figures 7 and 8 show the power distribution of the new DES on two typical winter and summer days, respectively. The new DES can convert solar energy into chemical energy during periods of abundant solar energy at noon, and then release the stored chemical energy to users for power supply during peak electricity demand. The proposed DES extends the utilization time of solar energy through energy storage, thus improving the stability and energy utilization efficiency of the system.

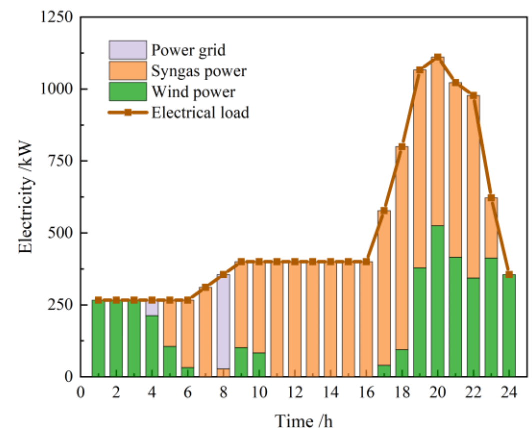

Fig. 7. Electricity distribution in winter

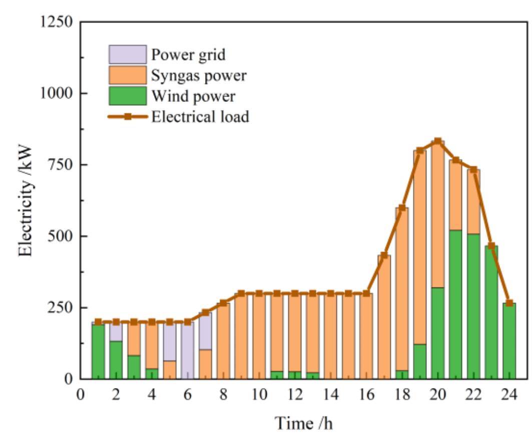

Fig. 8. Electricity distribution in summer

3.4 *Heat balance distribution*

Figures 9 and 10 are the heat balance distribution of the DES on typical winter and summer days, respectively. We can observe that the proportion of waste heat recovery from the internal combustion engine is much higher than that of methanol combustion in the entire system's heat supply. The new DES can increase the proportion of internal combustion engine heat recovery and reduce the proportion of methanol combustion heating, thus improving the energy utilization ratio of the system.

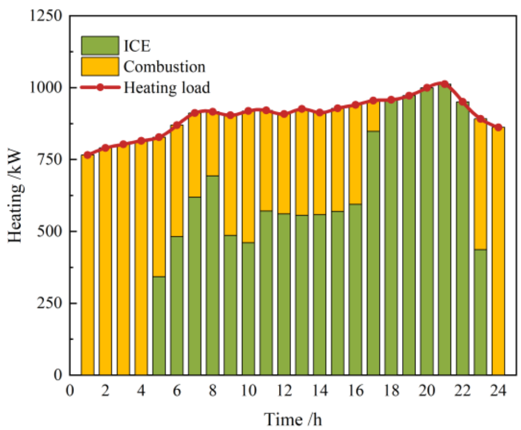

Fig. 9. Heat distribution in winter

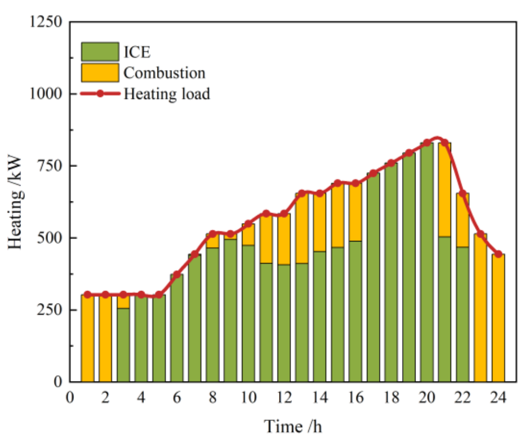

Fig. 10. Heat distribution in summer

3.5 *CO_2 emission reduction*

Table 1 shows carbon emissions and carbon reduction performance of the DES on a typical day. Compared to reference systems of power grid electricity purchase and boiler heating (Reference system 1), photovoltaic and wind power (Reference system 2), the proposed DES achieves carbon reductions of 42.12% and 22.14%, respectively.

Table 1

CO_2 emissions on a typical day

CO_2 emission /kg	Proposed system	Reference system1	Reference system2
Grid power supply	426.69	7065.00	4419.58
Auxiliary heating	795.57	2897.02	2897.02
STC	4510.77	0	0
Total	5697.03	9962.02	7316.61
CO_2 emission reduction rate		42.12%	22.14%

4. CONCLUSIONS

A new DES integrating solar thermochemical conversion and wind power generation is proposed to achieve efficient utilization of solar and wind energy and reduce CO_2 emissions . The main research findings can be summarized as follows:

1. The proposed DES improves the performance of the system in matching supply and demand through efficient utilization of multiple energy sources and the mid-and-low temperature STC.
2. The wind power and STC processes have been modeled and analyzed. By adjusting the methanol feed rate for different solar irradiations, a methanol conversion rate of 85% has been achieved in the system, while the solar-to-chemical efficiency can be maintained at around 60%.
3. The new DES promotes the efficient utilization of wind and solar energy and reduces CO_2 emissions. It reduces CO_2 emissions by 42.12% compared to conventional systems of power grid and boiler heating. Compared to reference systems of a hybrid photovoltaic and wind power system supplemented with grid power, CO_2 emissions are reduced by 22.14%.

ACKNOWLEDGEMENT

The authors appreciate the financial support provided by the National Natural Science Foundation of China (No.52006214), and the Basic Science Center Program for Ordered Energy Conversion of the National Natural Science Foundation of China (No.51888103).

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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