Thermodynamic and economic analyses of a hybrid solar–wind–bioethanol hydrogen generation system via membrane reactor

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ABSTRACT

A novel hybrid solar–wind–bioethanol hydrogen generation system via membrane reactor was proposed in this study. The thermodynamic and economic analyses were conducted at different bioethanol reforming working conditions under the actual weather situation of a year in DunHuang based on numerical simulation. The energy efficiency and standard coal saving rate (SCSR) from 300 °C to 500 °C (reaction temperature) and 0.005 bar to 0.25 bar (separation pressure) were studied. Under the design condition, the energy efficiency and SCSR can reach 52.55% and 1760.94 kg/year at 500 °C, 0.1 bar. Hydrogen generation rate and levelized cost under different photovoltaic area were researched and analyzed. The results showed that the hydrogen generation rate and levelized cost can be 394.15 kg/year and 4.56 $/kg. This study shows the feasibility of bioethanol reforming hydrogen production driven by renewable energy via membrane reactor.

Keywords: bioethanol reforming, hydrogen production system, renewable energy sources, membrane reactor, clean energy conversion

1. INTRODUCTION

The global energy consumption is expected to be doubled by 2050 due to the increasing population and rising living standard [1]. Currently, fossil fuels are the main energy sources of society while the reserves of them are limited and the fossil fuels large–scale utilization leads to global warming due to the massive emissions of carbon dioxide [2]. The renewable energy sources such as solar and wind energy which are abundant, clean and widespread have the potential to solve energy demand problem [3]. Considering the intermittency of solar and wind energy, it is essential to develop the steady energy carrier for providing renewable energy to end users stably [4].

Renewable energy has many storage forms such as thermal (e.g. sensible heat storage), mechanical (e.g. pumped hydroelectric storage), electrical (e.g. electricity), and chemical (e.g. hydrogen) [5]. Hydrogen is one of the most promising renewable energy storing forms due to its low transport loss, high energy conversion efficiency, flexibility of conversion to other forms of energy, and near–zero carbon production during the utilization process [6]. Water electrolysis is a common method to produce hydrogen driven by renewable energy and it can obtain high purity hydrogen to be utilized in fuel cell with no pollution while it has a high cost and low efficiency [7]. Photoelectrochemical method is a clean and sustainable way to produce hydrogen by renewable energy at low operation temperature while it has a low system efficiency and needs high cost materials [8].

In this study, a novel hydrogen production system driven by solar and wind energy based on bioethanol reforming via membrane reactor is proposed. A palladium hydrogen permeation membrane (HPM) which can selectively remove hydrogen under the pressure difference to shift the equilibrium of bioethanol reforming forwards is used to improve the hydrogen yield and obtain high purity hydrogen. In this paper, the energy efficiency and standard coal saving rate (SCSR) from 300 °C to 500 °C (reaction temperature) and 0.005 bar to 0.25 bar (separation pressure) were studied under the actual weather condition of the year in DunHuang. The hydrogen generation rate and levelized cost under different photovoltaic area were researched.

2. SYSTEM AND MODEL DESCRIPTIONE

2.1 System description

A conceptual hybrid solar–wind–bioethanol hydrogen generation system via membrane reactor is illustrated in Fig 1. The chamber between HPM and impermeable tube is filled with Ni/Al_2O_3 catalyst to catalyze bioethanol reforming. The thermal energy for enthalpy change and preheat reactants can be provide by parabolic trough solar collector or electric heater. A vacuum pump is used to maintain a negative separation pressure inside the HPM for hydrogen separation. Photovoltaic array and wind turbine generate electricity for electric heater and vacuum pump, and residual energy can be stored in battery. An inverter is used to convert alternating current

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to direct current for further utilization. A mixture of bioethanol and water vapor flow into the reactor at a constant rate (150 cm^3/s) in a ratio of one to three and the reactor tube length is taken as 1000 cm. The energy flow mode under different weather conditions is shown in Fig 2. In times when there is sufficient renewable energy, the surplus electricity generated by photovoltaic array and wind turbine after meeting the demand of electric heater and vacuum pump is stored in battery, and supply to electric heater and vacuum pump in the absence of adequate renewable energy. With the flow of energy, the renewable energy is converted into the chemical energy of hydrogen.

2.2 Model description

2.2.1 Bioethanol reforming kinetic model

According to the previous studies about bioethanol reforming reaction catalyzed by Ni/Al_2O_3, the reaction process and kinetic reaction rate can be expressed as follow [10]:

$$C_2H_5OH \rightarrow CH_4 + CO + H_2 \tag{1}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{2}$$

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \tag{3}$$

$$CH_4 + 2H_2O \rightleftharpoons CO_2 + 4H_2 \tag{4}$$

$$r_1 = k_1 \cdot \mathrm{P} \cdot X_\mathrm{e} \tag{5}$$

$$r_2 = \frac{k_2 \cdot \mathrm{P} \cdot \left[X_\mathrm{m} \cdot X_\mathrm{w} - \dfrac{X_\mathrm{d} \cdot X_\mathrm{h}}{K_2} \right]}{X_\mathrm{h} \cdot den^2} \tag{6}$$

$$r_3 = \frac{k_3 \cdot \left[X_\mathrm{me} \cdot X_\mathrm{w} - \dfrac{X_\mathrm{m} \cdot X_\mathrm{h}^3 \cdot \mathrm{P}^2}{K_3} \right]}{X_\mathrm{h}^{2.5} \cdot den^2 \sqrt{\mathrm{P}}} \tag{7}$$

$$r_4 = \frac{k_4 \cdot \left[X_\mathrm{me} \cdot X_\mathrm{w}^2 - \dfrac{X_\mathrm{d} \cdot X_\mathrm{h}^4 \cdot \mathrm{P}^2}{K_4} \right]}{X_\mathrm{h}^{3.5} \cdot den^2 \sqrt{\mathrm{P}}} \tag{8}$$

$$den = 1 + \mathrm{P} \cdot (K_\mathrm{m} \cdot X_\mathrm{m} + K_\mathrm{h} \cdot X_\mathrm{h} + K_\mathrm{me} \cdot X_\mathrm{me}) + \frac{K_\mathrm{w} \cdot X_\mathrm{w}}{X_\mathrm{h}} \tag{9}$$

where r_i (mol $s^{-1} g_{cat}^{-1}$) is the reaction rate of Eq. (i); P (Pa) is the reaction pressure; X_e, X_m, X_w, X_d, X_h, and X_{me} are the mole fraction of bioethanol, carbon monoxide (CO), water (H_2O), carbon dioxide (CO_2), hydrogen and methane. The detailed calculation method for other parameters of Eq. (5)–Eq. (9) can be seen in [10].

2.2.2 Hydrogen separation model

The HPM reactor is utilized to separate hydrogen and the hydrogen flux of palladium HPM can be expressed as [3]:

$$J_{\mathrm{H_2}} = \frac{k\left(P_{\mathrm{H_2,in}}^{\mathrm{n}} - P_{\mathrm{H_2,out}}^{\mathrm{n}}\right)}{d_\mathrm{M}} \tag{10}$$

$$k = 3.85 \times 10^{-7} \exp\left(-\frac{18560}{8.314 \times T_\mathrm{H}}\right) \tag{11}$$

where J_{H_2} (mol H_2 m^{-2} s^{-1}) is the hydrogen flux; n is an exponent, taken as 0.5; $P_{H_2,in}$ and $P_{H_2,out}$ are the hydrogen partial pressures (Pa) on the reaction side and the separation side of palladium HPM; d_M (m) is the thickness of HPM; T_H (K) is the reaction temperature.

2.2.3 Renewable energy power generation model

The power generated by photovoltaic cells is given as:

$$E_\mathrm{PV}(T_\mathrm{i}) = DNI \cdot A_\mathrm{PV} \cdot \eta_\mathrm{opt} \cdot \eta_\mathrm{mod} \cdot \eta_\mathrm{PV}(T_\mathrm{i}) \tag{12}$$

where DNI is direct normal irradiance (W/m^2); A_{PV} is the area of PV to receive solar energy; η_{opt} is the optical efficiency, which can be taken as 73%; η_{mod} is module efficiency defined as the ratio between the efficiency of a PV module and that of constituent PV cell; T_i is the temperature of PV module; $\eta_{PV}(T_i)$ is the PV efficiency which depends on T_i.

Choosing a suitable model for wind turbine is significance for power output simulation. A widely used wind turbine power output model can be expressed as:

$$P_\mathrm{w}(V) = \begin{cases} P_\mathrm{R} \cdot \left[(V^2 - V_\mathrm{C}^2) / (V_\mathrm{R}^2 - V_\mathrm{C}^2) \right] & V_\mathrm{C} \le V \le V_\mathrm{R} \\ P_\mathrm{R} & V_\mathrm{R} \le V \le V_\mathrm{F} \\ 0 & V \ge V_\mathrm{F}, V \le V_\mathrm{C} \end{cases} \tag{13}$$

where P_R is the rated electrical power of wind turbine; V, V_C, V_R, and V_F are actual wind speed, cut–in wind speed, rated wind speed, and cut–off wind speed, respectively.

2.2.4 Thermodynamic and economic calculation model

In order to convert and utilize renewable energy efficiently, the total energy efficiency which can be defined as the ratio of hydrogen chemical energy output to the renewable energy input (solar, wind, and bioethanol energy) of this novel system needs to be studied and analyzed. The total energy efficiency can be expressed as:

$$\eta_\mathrm{tot} = \frac{n_\mathrm{h} \cdot \mathrm{HHV_h}}{n_\mathrm{e} \cdot \mathrm{HHV_e} + \int_0^{8760} DNI \cdot A_\mathrm{solar} \mathrm{d}h + \int_0^{8760} \frac{1}{2} \cdot A_\mathrm{wind} \cdot \rho \cdot V^3 \mathrm{d}h} \tag{14}$$

where n_h and n_e are the total hydrogen production amount and the bioethanol consumed amount of a year;

HHV_h and HHV_e are the mole higher heating value of hydrogen and bioethanol; A_{solar} and A_{wind} are the area for receiving sun light and wind of the system.

In addition to energy efficiency, environmental performance is also a significant indicator of the system. The system energy sources are renewable energy so lots of fossil fuel can be saved and the SCSR is given as:

$$m_{coal} = \frac{n_h \cdot HHV_h}{q_{coal} \cdot \eta_{c \to h}} \tag{15}$$

where $\eta_{c \to h}$ is the conversion efficiency from standard coal to heat, taken as 80%; q_{coal} is the heating value of standard coal, taken as 2.931×10^4 kJ/kg.

For the future application of the system, the levelized cost of hydrogen production needs to be taken into consideration. The levelized cost for hydrogen production in this system can be calculated as:

$$C_h = \frac{n_h \cdot N}{C_{PV} + C_{collector} + C_{wind} + C_{reactor} + C_{inverter} + C_{battery} + C_{heater} + C_{pump} + C_{O\&M}} \tag{16}$$

where N is the lifetime of this system, taken as 20 year; C_i is the capital cost of component i; $C_{O\&M}$ is the operation and maintenance cost of the system in the lifetime.

3. RESULTS AND DISCUSSION

The partial pressures of gases and hydrogen selectivity under 400 °C, 0.01 bar is shown in Fig 1 as a

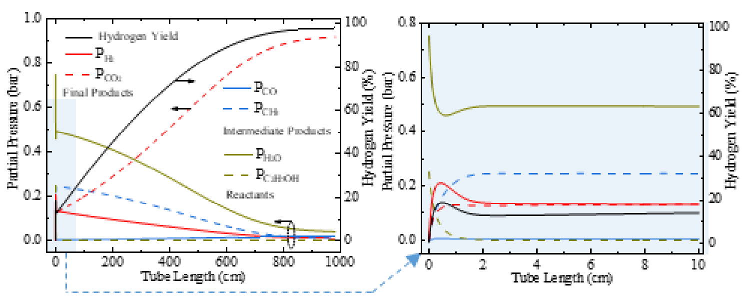

Fig 1 Variation of partial pressures of gases and hydrogen yield under 400 °C, 0.01 bar for separation pressure

case to exhibit the compoent change when a certain amount of gas flowing through the reactor. The hydrogen partial pressure increases initially and then decreases to the separation pressure due to the hydrogen separation process. Hydrogen yield can be improved because the remove of hydrogen shifts the equilibrium of bioethanol reforming forward and the final hydrogen yield can be 97.84% at 981 cm tube length. It needs to be noted that the water vapour partial pressure has a slight rise at about 1 cm due to a reverse methane steam reforming process near the reactor entrance under the relatively low reaction temperature.

The system performance under actual weather condition is vital because renewable energy is usually intermittent. Fig 2 shows the *DNI* and *V* of DunHuang in a year, which are used as a case to analyze system performance in this work.

The energy efficiency defined by Eq.(14) under different temperatures (300 °C to 500 °C) and separation pressures (0.005 bar to 0.25 bar) of a year in DunHuang

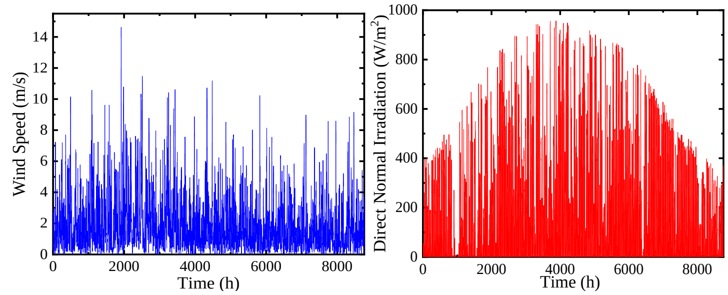

Fig 2 Annual *DNI* and *V* data in DunHuang

is exibited in Fig 3. The biggest energy efficiency reaches 52.55% under 500 °C, 0.1 bar because high temperature and low separation pressure correspond to high hydrogen yield which means high efficiency. However, as the decrease of separation pressure, vacuum pump efficiency goes down quickly so the energy consumed for separating hydrogen increase rapidly which has negative effect to the efficiency and when the separation pressure changes, 0.1 bar corresponds to the highest efficiency. Raising temperature will increase the enthalpy change and preheat thermal energy while the increment is not huge and the negative effect on efficiency is less than the positive effect of hydrogen yield improvement at the same time.

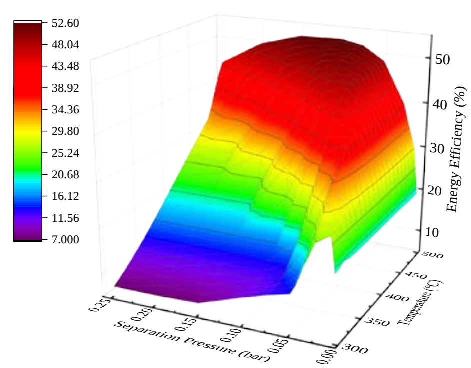

Fig 3 Energy efficiencies under different working condition

As the system in this paper is driven by renewable energy, lots of fossil fuel can be saved. The SCSR defined by Eq. (15) at different working conditions of a year in DunHuang is shown in Fig 4. Higher energy efficiency means bigger amount of renewable energy can be

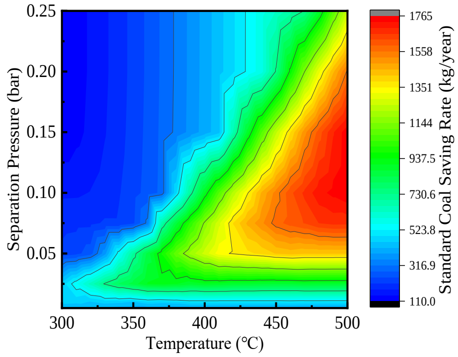

Fig 4 SCSR under different working condition

utilized and converted to hydrogen energy. The bigger hydrogen generation rate per year corresponds to more standard coal can be saved and the biggest SCSR in this system under the design condition can reach 1760.94 kg/year under 500 °C, 0.1 bar.

The economic performance of this system is significance for system application prospect. The hydrogen generation rate and levelized cost under different PV area at 500 °C, 0.1 bar are shown in Fig 5. As the PV area increases, more solar energy can be utilized so the hydrogen generation rate of a year goes up, which reaches 394.15 kg/year at 30.5 m^2 PV area. However, it has the best PV area for hydrogen levelized cost because on the one hand, small PV area means small amount of hydrogen production and lots of capital cost cannot recovered. On the other hand, as the PV area increases, the amount of wasted solar energy which cannot be stored by battery goes up so the hydrogen generation rate changes a little and levelized cost goes up. The smallest hydrogen levelized cost is 4.56 \$/kg at 6.5 m^2 PV area with a 330.14 kg/year hydrogen generation amount.

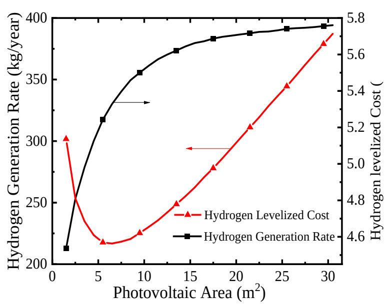

Fig 5 Hydrogen generation rate and levelized cost under different PV area at 500 °C, 0.1 bar

4. CONCLUSION

The proposed system can improve the hydrogen yield of bioethanol reforming due to the remove of hydrogen and the hydrogen yield can reach 97.84% under 400 °C, 0.01 bar. This system converts renewable energy into the chemical energy of hydrogen and a big amount of fossil fuel will be saved. The total energy efficiency and standard coal saving rate can reach 52.55% and 1760.94 kg/year under 500 °C, 0.1 bar. The hydrogen production and levelized cost are related to the capacity of PV, wind turbine and bioethanol reforming reactor and when PV area changes, the smallest hydrogen levelized cost is 4.56 \$/kg at 6.5 m^2 PV area with a 330.14 kg/year hydrogen generation amount.

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