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A polygeneration system for the methanol production and the power generation with the solar–biomass thermal gasification ☆

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ABSTRACT

A polygeneration system of generating methanol and power with the solar thermal gasification of the biomass is proposed in this work. The endothermic reactions of the biomass gasification are driven by the concentrated solar thermal energy in a range of 1000–1500 K. The syngas from the biomass gasification is used to produce the methanol via a synthesis reactor. The un-reacted gas is used for the power generation via a combined cycle power unit. The thermodynamic and economic performances of the polygeneration system are investigated. A portion of the concentrated solar thermal energy can be chemically stored into the syngas, and thus the energy level of the solar thermal energy is improved. Numerical simulations are implemented to evaluate the thermal performances of the proposed polygeneration system. The results indicate that H_2/CO molar ratio of the syngas reaches 1.43–1.89, which satisfies the requirements of the methanol synthesis. The highest energy efficiency and the exergy efficiency of the polygeneration system approximately are 56.09% and 54.86%, respectively. The proposed polygeneration system can achieve the stable utilization of the solar energy and the mitigation of CO_2 emission, and thus a promising approach is introduced for the efficient utilization of the abundant solar and biomass resources in the Western China.

1. Introduction

Fossil energies, including coal and petroleum, are being consumed rapidly, which brings serious environment problem. The limited supply of the fossil energy restricts the sustainable development. In order to address the above challenges, numerous environmental friendly and economical alternative renewable energies, including solar energy and biomass, have attracted increasing attentions [1–3].

The utilization process of the solar energy is clean, and the gross of the solar energy is huge. Solar energy is viewed as an alternative for the alleviation of the current energy and environment concerns. In order to achieve efficient utilization, however, we will face the challenges such as low energy density and intermittent nature.

Similarly, the biomass is a renewable energy consisting of the carbohydrates, and can be utilized by various methods. Compared with other renewable technologies, including solar and wind, the biomass provides a renewable carbon resource, and can produce the biogas and the liquid fuels with CO_2-neutral [4–6]. In particular, the gasification is one of the most important approaches of the utilization of the biomass, which is a thermochemical conversion technology for the production of the syngas (synthesis gas, a mixture composed of H_2 and CO). The syngas can be directly utilized in a Brayton–Rankine combined cycle for the electricity generation [7,8]. Moreover, the syngas also can be converted into various valuable fuels, including H_2 (water–gas shift reaction), diesels (Fischer–Tropsch process) and methanol (synthesis) [9–11].

In conventional biomass gasification technologies, air, oxygen, air–steam or oxygen–steam is chosen as a gasification agent. The conventional gasification is an autothermal reaction process, in which the heat is supplied by the in-situ combustion (oxidation) of the biomass with the air or oxygen. The conventional conversion approaches consist of three main steps: (1) pyrolysis, the biomass is decomposed as tar, gas and char, (2) oxidation, the pyrolysis products and oxygen are reacted and the large amounts of heat are released, (3) gasification, the tar and char are gasified to form the syngas [12].

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Nomenclature

CRF	capital recovery factor
E	exergy (kW)
e	specific exergy (kJ kg^{-1} or kg $kmol^{-1}$)
HHV	high heat value (kJ $kmol^{-1}$ or kJ kg^{-1})
LEC	leveled energy cost ($)
m	mass flow rate (kg s^{-1})
n	molar flow rate (kmol s^{-1})
Q	heat (kW)
S	saving ratio (%)
W	electricity power (kW)

Greek letters

η	efficiency (%)

Subscript

I	first law of thermodynamics
II	second law of thermodynamics
bio	biomass
chem	chemical energy
fresh	fresh syngas
gas	produced syngas
O&M	annual operation and maintenance
ref	reference system
solar	solar energy

One of the main advantages of conventional technologies depends mainly on the simplicity of the reaction system. However, the heat resource from the combustion of the biomass accounts for 25–40% of the input biomass, and the syngas that may be contaminated by the combustion byproducts has a low H_2/CO molar ratio. Studies indicate that the high-temperature solar thermochemical technology is a promising solution for the supply of the process heat, in which the biomass gasification can be driven by the concentrated solar energy [13,14].

The concentrated solar energy is used as the high-temperature process heat source rather than the in-situ combustion of the biomass, and thus more biomass feedstock can be efficiently utilized and CO_2 molar fraction in the syngas may be reduced owing to the fact that the biomass combustion process is removed [15]. Moreover, the concentrated solar energy is converted into the chemical energy of the syngas, the heat value of the syngas from per unit of biomass is improved because of the introduction of the additional solar energy, and thus the solar energy is chemically stored in an amount equal to the enthalpy change of the endothermic reactions. This approach is viewed as a promising pathway of producing valuable and low-carbon chemicals from renewable resources [14–17].

The design of the solar thermochemical reactor is challenging, which plays a crucial role in the commercial utilizations of the solar-driven biomass gasification. According to the approaches of heating the feedstock, the solar thermochemical reactors can be classified into two types: directly irradiated reactors and indirectly irradiated reactors. Presently, several solar thermochemical reactors have been developed [18]. Z'Graggen et al. [19] presented a 5 kW cylindrical cavity-receiver prototype reactor. Piatkowski et al. [20,21] described a packed-bed solar reactor, both reactors had been tested with carbonaceous material feedstock, and a higher chemical conversion of the feedstock was obtained and the high-quality syngas was yielded. Gokon et al. [22] designed an internally circulating fluidized bed reactor for CO_2 gasification of the coal coke, which results in a homogeneous gasification reaction for all bed layers and achieves a favorable reaction kinetics.

Additionally, numerous system configurations were developed for the effective utilizations of the syngas. Hertwich and Zhang [23] presented a 3rd biofuel generation process using the concentrated solar energy as a main energy source. Kaniyal and Ng et al. [24,25] developed different multi-function systems for the production of the F–T diesel and electricity based on the solar thermal gasification of the fossil fuel. Ozturk and Dincer [26] proposed a CCHP system by integrating a Brayton–Rankine combined cycle and the PEM fuel cell.

In order to satisfy the demand of the clean liquid fuel like methanol and to improve the utilization efficiency of renewable energies, in this work we propose a solar-driven biomass gasification based a polygeneration system with the outputs of the methanol and power, and the performances of the system are evaluated. The main contributions can be summarized as follows:

(1) A new polygeneration system of generating methanol and power with the solar thermal gasification of the biomass is proposed to simultaneously achieve the stable utilization of solar energy and biomass, the reduction of the consumption of the fossil fuels and the mitigation of CO_2 emission.
(2) The proposed polygeneration system yields the qualified syngas, which is suitable for methanol synthesis. Especially, the water-shift process can be eliminated, and the un-reacted syngas is directly combusted for the power generation. The thermodynamic performance of the new system can be improved.
(3) The thermodynamic properties of the solar-driven biomass gasification process are investigated, and the thermodynamic and economic performances of the polygeneration system are evaluated.
(4) For the proposed system, the in-situ biomass combustion in the process of gasification is avoid, the solar energy can be converted and stored into the chemical energy of the methanol, and thus an effective approach of utilizing the renewable energies is introduced.

According to the main motivation of the work, we organize the rest of this paper as follows. In Section 2, a new polygeneration system is proposed, and the reference systems are determined. In Section 3, the thermodynamic properties of the solar-driven gasification for the biomass sample are investigated. The effects of the gasification temperature and the recycle ratio of the un-reacted syngas on the system thermodynamic performances are evaluated in Section 4. Section 5 appraises the sensitivity of the system economic performances on the price of the biomass and electricity. Finally, Section 6 summarizes the main conclusions.

2. Polygeneration system and the evaluation criterion of the system

2.1. Polygeneration system

Based on the solar-driven steam-based biomass gasification, the produced qualified syngas can be applied to various processing industries. Seeking an efficient utilization of the qualified syngas is highly desired for practical applications. If the syngas is directly used to generate the electricity by means of combustion, the

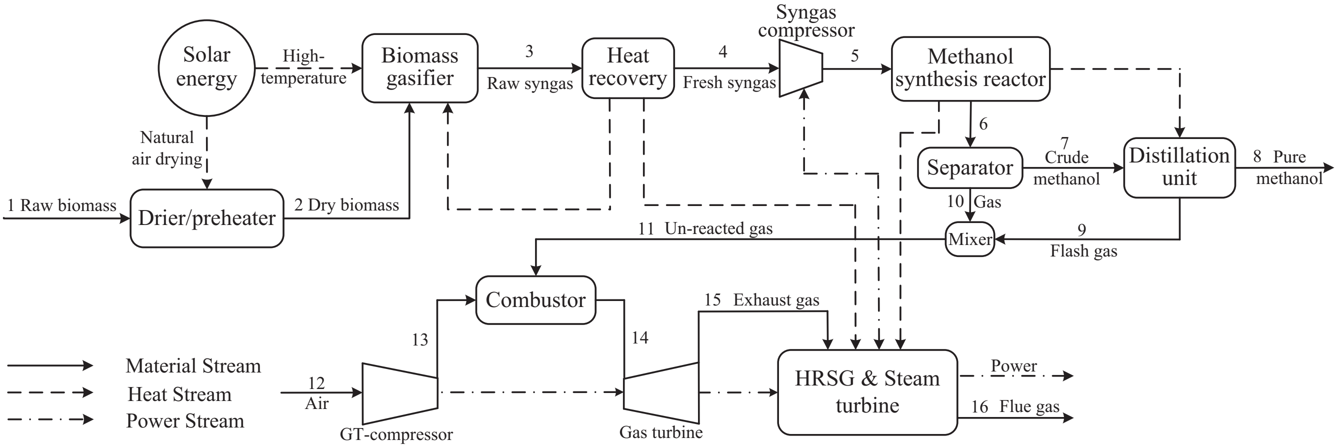

Fig. 1. The flowchart of the polygeneration system with solar–biomass gasification.

chemical energy cannot be efficiently utilized. Thus, in this paper a solar–biomass gasification based polygeneration system for the production of the methanol and the power generation is proposed, which is shown in Fig. 1.

In the polygeneration system, the quailed syngas can be utilized in a cascade way, a part of the solar energy can be stored into the methanol as a valuable liquid fuel, which is convenient for transportation and can be applied in various chemical industries. The released syngas with lower chemical energy can be used for the power generation. Therefore, the efficient utilization of the syngas in this system is achieved.

It can be observed from Fig. 2 that the proposed system consists of three main components, including the gasification subsystem, the methanol production subsystem and the power generation subsystem.

2.1.1. Gasification subsystem

There are abundant solar energy and biomass resources in many places, such as in the Western China. The cotton stalk and superheated steam are selected as the biomass feedstock and the gasification agent, respectively. The raw biomass contains about 35 wt.% moisture, and thus the dry preparation is necessary. The moisture can be removed via the common natural air drying or other auxiliary drying devices, and the dried biomass with a moisture content of 15% is fed into the solar–biomass gasifier.

The solar incident radiation falls on the heliostats around the central solar tower and reflected to the solar–biomass gasifier (i.e. central receiver), the high temperature heat resource in a range of 1000–1500 K is obtained, which will be used to drive the steam-based biomass gasification reactions. It is worth mentioning that the heating method is different from conventional gasification technologies.

Moreover, the raw syngas produced via the gasification should be purified by removing the tar, particle and other liquid fuel production catalyst-poison compound. In order to optimize the methanol synthesis reaction, about 75% amount of CO_2 in syngas will be separated by the Selexol process, and the qualified syngas served as the fresh syngas is used for the methanol production.

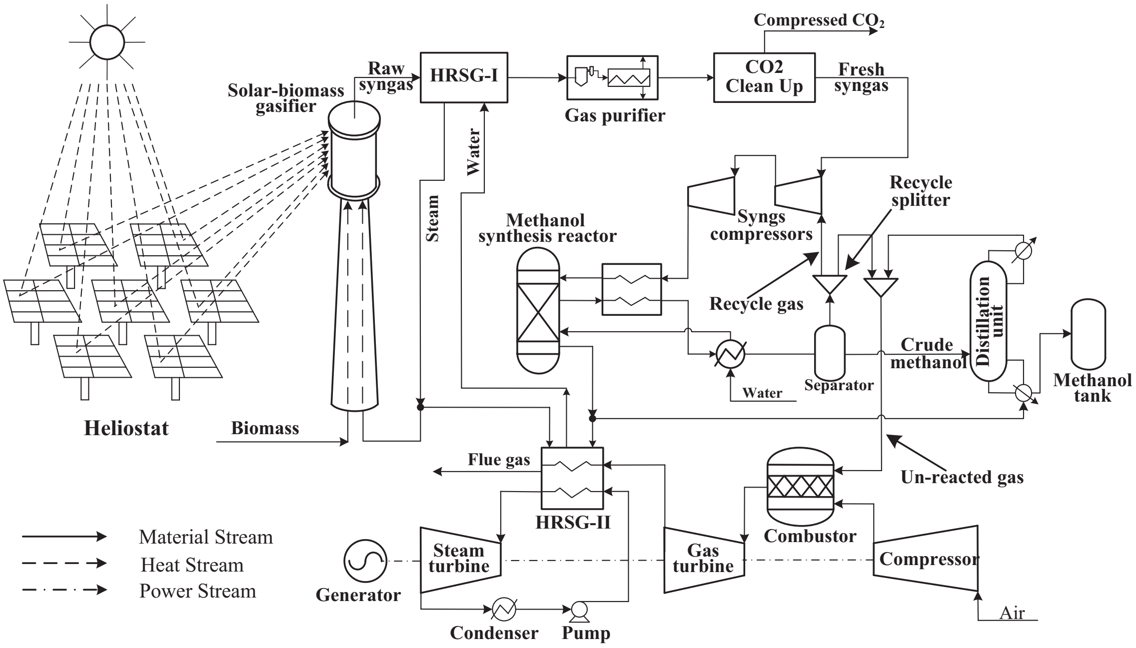

Fig. 2. Schematic diagram of the proposed polygeneration system.

2.1.2. Methanol production subsystem

The fresh syngas exits from the gasification subsystem is firstly fed into the methanol synthesis reactor ($H_2 + 0.5CO \rightarrow 0.5CH_4O$, $\Delta_r H_{298K} = -64.07$ kJ/mol) after it is compressed to 10 MPa. The outlet stream from the reactor is the mixture of the crude methanol and the gaseous product, and the sensible heat of the gas–liquid mixture is used to preheat a stream of water. After the separation process, the raw methanol is pumped into the distillation unit, and achieve the required quality (>99.9 wt.%).

The un-reacted gas released from the synthesis reactor is separated, and then directly enter the power generation subsystem as a gas fuel. In fact, the un-reacted syngas also can be utilized in other approaches. A portion of the un-reacted syngas utilized as the recycle gas will be compressed and be used for the methanol synthesis, while the rests are combusted directly for the power generation. In this work, both of above-mentioned two schemes will be analyzed in Section 4, the former is named as the Once-through scheme, and the latter is Recycle-utilization scheme.

The un-reacted syngas recycle ratio (*r*, recycle ratio for short) is used to specify the recycle fraction of the un-reacted syngas, which is defined as:

$$r = \frac{n_{\mathrm{fresh,gas}} + n_{\mathrm{unreacted,gas}}}{n_{\mathrm{fresh,gas}}} \tag{1}$$

where $n_{\mathrm{fresh,gas}}$ is the molar rate of the feed syngas in the methanol synthesis reactor and $n_{\mathrm{unreacted,gas}}$ represents the molar rate of the released syngas from the reactor. Obviously, *r* is 1 when all the un-reacted syngas directly flow into the power generation subsystem as the gas fuel.

Owing to the fact that the methanol synthesis reaction is an exothermic reaction, in order to maintain a favorable reaction condition, a stream of the preheated water should be pumped into the reactor to remove the reaction heat.

2.1.3. Power generation subsystem

In the polygeneration system, the un-reacted gas will be used as a fuel gas for the power generation, and an advanced Brayton–Rankine combined cycle unit is installed. The gas turbine refers to "LM2500RD" from GE Company, and the HRSG-II employs the dual pressure-reheat steam configuration.

The outlet stream of the gas turbine enters the HRSG-II to provide the exhaust gas sensible heat with the temperature of around 820 K, and the generated steam enters a two-stage steam turbine. In addition, two extra steams utilized by the HRSG-II are obtained by recovering the raw syngas sensible heat and the methanol synthesis reaction heat.

Meanwhile, a portion of the generated power from the combined cycle unit is used to run the compressors in the methanol synthesis subsystem and the Selexol process.

According to the above discussions, we can outline the advantages of the proposed polygeneration system as follows.

(1) The concentrated solar energy is used to provide the process heat of the biomass gasification, which is chemically stored into the chemical energy of the produced syngas. It is worth mentioning that in the proposed system the solar energy can be efficiently and stably utilized, which is distinctly different from common methods.
(2) Compared with conventional biomass gasification technologies, the in-situ biomass combustion process is avoided. In the proposed system, especially, nearly all the feed biomass is gasified into the syngas.
(3) The syngas produced by the solar-driven biomass gasification has higher H_2/CO molar ratio, which is suitable for the methanol synthesis. In particular, the water-shift process can be eliminated, and the exergy destruction can be reduced.

2.2. Reference systems

In order to evaluate the proposed polygeneration system, the reference systems should be predetermined. One of the distinct advantages in the proposed polygeneration system is that the concentrated solar energy is introduced for the biomass gasification. The proposed polygeneration system can be viewed as a combination of two stand-only systems. One is the polygeneration system for the multi-production of the methanol and electricity using conventional biomass gasification methods, the other is the solar thermal energy utilization system. Thus, the proposed system can be evaluated by compared with the above-mentioned two stand-only systems with the same valuable energy output. The two types of the system are named as the reference system I and the reference system II.

In reference system I, which is shown in Fig. 3, the conventional biomass gasification technology is employed, and the biomass is gasified with the mixture of steam and O_2 with a molar purity of 95%. The syngas contains a lower H_2/CO ratio, and thus the syngas should be adjusted via a water-shift reaction process. The subsequent subsystems include the methanol synthesis and the power generation, which are similar with the proposed polygeneration system. To provide an effective comparison, as be listed in Table 1, some of the operating parameters of key devices in reference system I and the proposed system are the same. Additionally, the

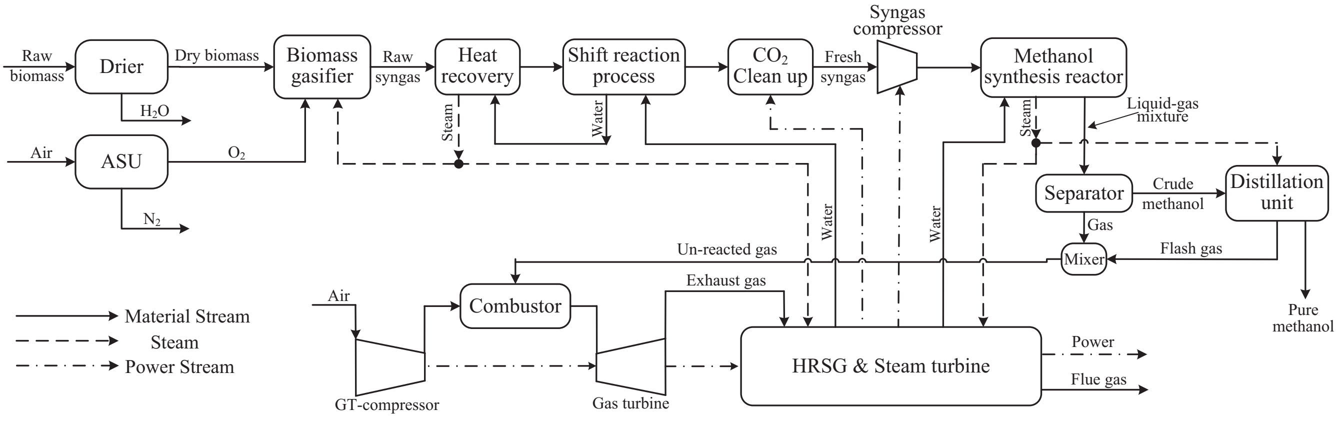

Fig. 3. Schematic diagram of the reference system I.

Table 1
Operating parameters of key devices for the compared systems.

Items	Operating parameters	
	Polygeneration system	Reference system I
O_2 supplied molar purity and pressure (MPa)	–	0.95/1.8
Mass ratio of steam to biomass for gasification	0.55	0.1
Gasification temperature (K) and pressure (MPa)	1000–1500/1.8	1000–1500/1.8
Methanol synthesis temperature (K) and pressure (MPa)	523.15/10	523.15/10
Un-reacted syngas recycle ratio	1–2.8	1.5
Gas turbine inlet temperature (K)	1523.15	1523.15
Pressure ratio	23	23
Temperature (K) and pressure (MPa) of high pressure steam	783.15/12.5	783.15/12.5
Temperature (K) and pressure (MPa) of reheat steam	783.15/3.25	783.15/3.25
Temperature (K) and pressure (MPa) of low pressure steam	505.15/0.72	505.15/0.72
Isentropic efficiency of compressors	0.85	0.85
Isentropic efficiency of gas turbine	0.87	0.87
Isentropic efficiency of steam turbine	0.87	0.87

conventional biomass gasification process in reference system I is viewed as the reference biomass gasification process in Section 3.

The reference system II is a solar thermal energy utilization system, which can be regarded as a solar tower thermal power generation system. The solar energy collection efficiency is similar with the solar collection process of the proposed polygeneration system, and the annual thermal to electricity efficiency of the steam turbine is 30.6% [27].

2.3. System evaluation criteria

Energy and exergy analysis were employed for the evaluation of the system performance. The overall energy efficiency $\eta_{\mathrm{I,sys}}$ and the exergy efficiency $\eta_{\mathrm{II,sys}}$ of the system are served as basic criterions for the evaluation of the thermodynamic performances of the polygeneration system, which can be formulated as:

$$\eta_{\mathrm{I,sys}} = \frac{m_{\mathrm{methanol}} \cdot \mathrm{HHV}_{\mathrm{methanol}} + W_{\mathrm{power}}}{Q_{\mathrm{solar}} + m_{\mathrm{bio}}\mathrm{HHV}_{\mathrm{bio}}} \tag{2}$$

$$\eta_{\mathrm{II,sys}} = \frac{m_{\mathrm{methanol}} \cdot e_{\mathrm{methanol}} + W_{\mathrm{power}}}{E_{\mathrm{solar}} + m_{\mathrm{bio}}e_{\mathrm{bio}}} \tag{3}$$

where m_{metnaol} and m_{bio} are the methanol production flow rate and the biomass feed flow rate, respectively; $\mathrm{HHV}_{\mathrm{methanol}}$ and $\mathrm{HHV}_{\mathrm{bio}}$ represent the high heat value of the methanol and the biomass, respectively; Q_{solar} and E_{solar} stand for the solar thermal energy and the solar thermal exergy, respectively; e_{methanol} and e_{bio} are the specific chemical exergy of the methanol and the biomass, respectively; W_{power} represents the output electricity power.

Compared with reference systems I and II, in the proposed polygeneration system the solar energy is converted into the methanol and the electricity power, and the energy consumption is reduce. In other words, with the same output of the valuable products, the proposed system requires a less input of the biomass feedstock and the solar energy. Therefore, the energy saving ratio (S_{energy}) is used to evaluate the energy conservation potential of the polygeneration system, which is defined as:

$$S_{\mathrm{energy}} = \frac{(Q_{\mathrm{ref,solar}} + m_{\mathrm{ref,bio}}\mathrm{HHV}_{\mathrm{bio}}) - (Q_{\mathrm{solar}} + m_{\mathrm{bio}}\mathrm{HHV}_{\mathrm{bio}})}{Q_{\mathrm{solar}} + m_{\mathrm{bio}}\mathrm{HHV}_{\mathrm{bio}}} \tag{4}$$

where $m_{\mathrm{ref,bio}}$ is the biomass input flow rate of the reference system I and $Q_{\mathrm{ref,solar}}$ represents the solar thermal energy of the reference system II.

Additionally, the ratio of methanol to power k is used to indicate the product distribution (i.e. methanol and electricity) of the polygeneration system, and defined as:

$$k = \frac{Q_{\mathrm{methanol}}}{W_{\mathrm{power}}} = \frac{m_{\mathrm{methanol}} \cdot \mathrm{HHV}_{\mathrm{methanol}}}{W_{\mathrm{power}}} \tag{5}$$

3. Physical properties and chemical equilibrium analysis of the biomass sample

3.1. Physical properties of the biomass

The cotton stalk from Xinjiang in the Western China was selected as a gasification feedstock. The chemical composition of the biomass sample is listed in Table 2. The sample with a mean particle size of 0.2 mm was dried (328.15 K, >8 h). The lower heating value (LHV) and the high heat value (HHV) of the biomass sample are 17564.8 kJ/kg and 19080.11 kJ/kg, respectively.

A high temperature condition is necessary for the biomass gasification reaction, but the melt of the ash produced at the end of the reaction should be avoided. The melted ash may stick on the inner surface of the reactor, reduce the heat transfer and bring the inhomogeneous temperature distribution in the reactor, even clog the slag discharge exit. Therefore, the gasification temperature should be lower than the deformation temperature (start to melt) of the biomass ash. The melting properties of the sample are presented in Table 3.

The solar energy resource in Xinjiang is abundant as well as the biomass resource, the simulated solar assisted polygeneration system is located in Yanqi (E86°34′, N42°05′), while the location of collecting the biomass sample is nearby Yanqi. The solar radiation

Table 2
Chemical compositions of the biomass sample (air-dried basis).

Biomass (cotton stalk)	Content (wt.%)
Moisture (M)	5.525
Ash (A)	2.686
Volatile (V)	80.785
Fixed carbon (FC)	11.004
Carbon (C)	45.011
Hydrogen (H)	6.094
Oxygen (O)	40.04
Nitrogen (N)	0.601
Sulfur (S)	0.043

Table 3
Melting properties of the biomass ash.

Items	Temperature (K)
Deformation temperature (DT)	1399.15
Softening temperature (ST)	1527.15
Hemispherical temperature (HT)	1527.15
Flowing temperature (FT)	1615.15

was obtained from the annual solar incident radiation data. The calculated average incident radiation value of 611.15 W/m^2 is used as the mean date of estimating optical performance throughout the year. Meanwhile, for a typical work condition, the nominal heliostat field collection efficiency η_{field} and the solar receive efficiency of the gasifier $\eta_{gasifier}$ are selected as 54.91% and 94%, respectively.

3.2. Chemical equilibrium analysis

The biomass gasification is a complex process involving several intermediate reactions. The concentrated solar energy provides the heat for the gasification without the introduction of air or oxygen, and thus the biomass combustion reactions are avoided. The main intermediate reactions in the solar–biomass gasifier are outlined as follows:

Steam gasification	$C + H_2O \rightarrow CO + H_2$	$\Delta_r H_{298K} = 131.29$ kJ/mol
Boudouard equilibrium	$C + CO_2 \rightarrow 2CO$	$\Delta_r H_{298K} = 172.46$ kJ/mol
Methanation	$C + 2H_2 \rightarrow CH_4$	$\Delta_r H_{298K} = -74.81$ kJ/mol
Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$	$\Delta_r H_{298K} = 206.10$ kJ/mol
Water–gas shift	$CO + H_2O \rightarrow CO_2 + H_2$	$\Delta_r H_{298K} = -41.17$kJ/mol

For a specific biomass sample, the above-mentioned reactions depend mainly on the temperature, pressure and steam flow rate. The chemical equilibrium of the air-dried biomass sample was implemented, and the gasification parameters are chosen according to Table 1. The equilibrium mole fractions of the main gas component for the biomass gasification are the function of the solar gasification temperature, which are shown in Fig. 4. When the gasification temperature is lower than 700 K, the components of CO_2, CH_4 and H_2 are thermodynamically stable owing to the fact that the intermediate reactions do not take place. In the temperature range of 700–1200 K, the rates of intermediate reactions are enhanced, and the fraction of H_2 and CO are increased with the increase of the temperature. When the temperature is higher than 1200 K, the gasification process is thermodynamically equilibrium, and the produced syngas consists of H_2, CO_2 and a little CO_2 with a constant H_2/CO ratio.

The comparison of the H_2/CO molar ratio of the produced syngas between the proposed and the conventional biomass gasification technologies is presented in Fig. 5. For the conventional biomass gasification methods, oxygen (O_2) with a molar purity of 0.95 is used as the gasification agent, and the oxygen feed rate is controlled by maintaining the gasification temperature. It should be pointed out that the same gasification condition is used in reference system I.

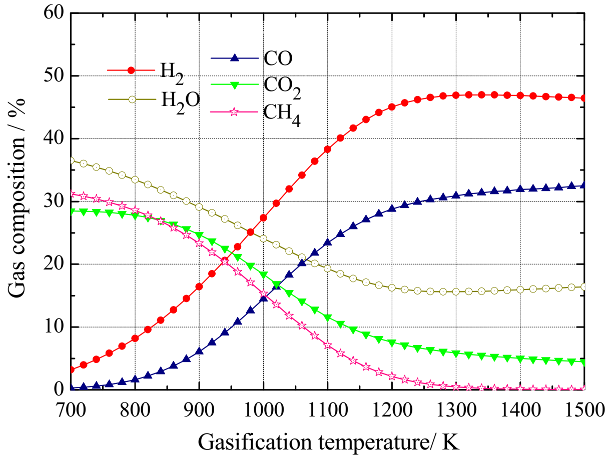

Fig. 4. Equilibrium gas composition of the biomass gasification under different gasification temperatures (gasification pressure: 1.8 MPa, S/B = 0.55).

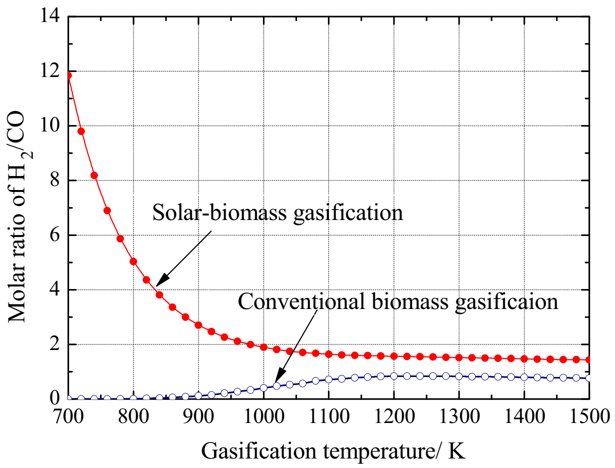

Fig. 5. H_2/CO ratio under different gasification temperatures.

It is worth mentioning that the molar rate of H_2 is higher than that of CO for the solar-driven steam-based biomass gasification, whereas the conventional biomass does not present such phenomena. If the gasification temperature is increased, the H_2/CO ratio of the syngas for the conventional biomass gasification technologies will be increased, the H_2/CO ratio with a range of 0.41–0.84 (>1000 K) is lower than the other, and the H_2/CO ratio of the syngas produced by the solar–biomass gasification is 1.43–1.89 (>1000 K). Generally, the syngas with the higher H_2/CO ratio is more suitable for the methanol synthesis.

4. Results and discussion

The polygeneration system is simulated by the Aspen Plus software with a biomass feed flow rate of 15 kg/s. The generation rate of the methanol and the electricity are calculated, and the energy and exergy performances of the proposed system are evaluated.

According to the utilization scheme, the evaluation process consists of two parts. The impact of the gasification temperature on the system performances for Once-through scheme is firstly analyzed, and then the influence of the recycle ratio (r) is studied.

4.1. The influences of the solar gasification temperature on the polygeneration system

The biomass gasification equilibrium depends mainly on the temperature, which will influence the methanol production subsystem and the power generation subsystem. For the scheme of Once-through, all the un-reacted syngas is directly utilized for the power generation, the steam flow of the gasification is 4.526 kg/s (i.e. the mass ratio of the steam to air-dry biomass reaches to 0.55). The effects derived from the variations of the solar gasification temperature in the range of 1000–1500 K on output products and system performances are investigated.

It can be seen from Fig. 6 that the methanol production is rapidly increased to 5.40 kg/s from 1.89 kg/s when the gasification temperature is lower than 1200 K, and then keeps relatively stable when the methanol output reaches the maximum production of 6.03 kg/s at 1400 K. But, the variation of the power output with the increase of the temperature is opposite, and the generated minimum power drops to 37660.88 kW at 1325 K.

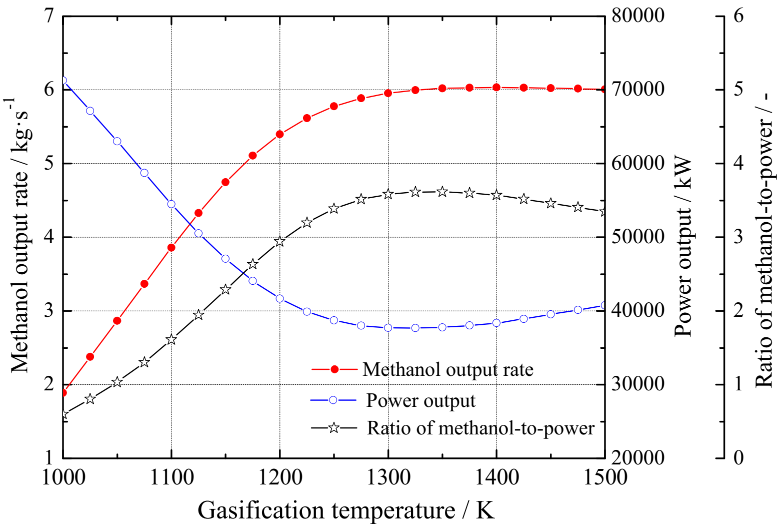

Fig. 6. System products under different gasification temperatures.

Fig. 7 shows the variations of the efficiencies of the polygeneration system under different gasification temperatures, in which the trend of two curves is similar. If the gasification temperature is increased to a range of 1000–1500 K, the overall energy efficiency can be increased to 52.45% from 47.39% with the highest efficiency of 54.16%, while the exergy efficiency is increased to 51.68% from 46.25% with the highest efficiency of 53.17%. There is a highest energy and exergy efficiencies when the solar gasification temperature is about 1200 K.

However, both efficiencies would be reduced in a higher temperature range (>1200 K), which is derived mainly from the irreversible loss. The exergy efficiency of the solar collector will decrease with the increase of the temperature. Meanwhile, the higher solar temperature will bring more irradiative loss and heat transfer loss, and thus the irreversible loss during the heat recovery process will be increased.

The integrated utilization of the biomass and the solar energy will improve the quality of the syngas, and reduce the fuel and energy consumption with the same output as compared with the reference systems. As shown in Fig. 8, the highest energy saving ratio is approximately 31.47%, moreover it also maintain the level of about 30% when the gasification temperature is higher than 1150 K.

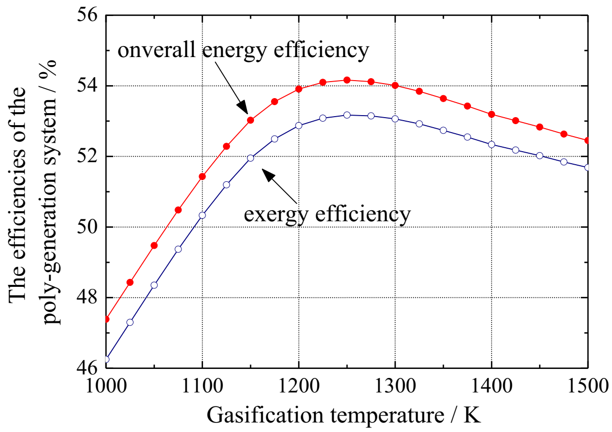

Fig. 7. The system efficiencies under different gasification temperatures.

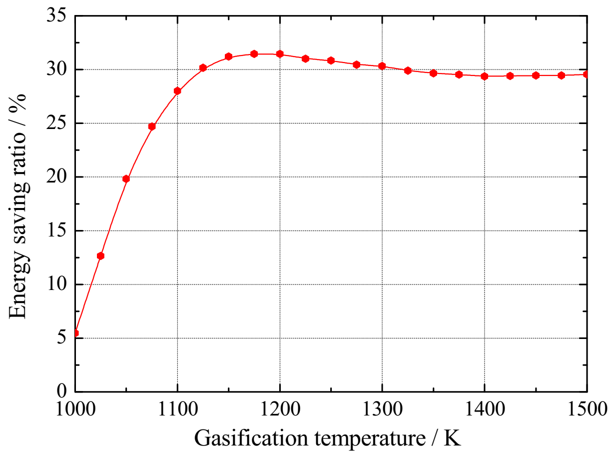

Fig. 8. Energy saving ratio under different gasification temperatures.

4.2. The influences of the un-reacted syngas recycle ratio on the polygeneration system

The Once-through conversion ratio of the syngas into the methanol cannot reach so high, even is assisted by the favorable catalyst, and thus enhancing the synthesis reaction is challenging. The recycle utilization of the un-reacted syngas is an effective approach, in which the syngas can be synthesized more than one time, and the methanol production rate can be improved at the cost of raising the compress power consumption. In the scheme of Once-through, the system can achieve the highest efficiencies when the gasification temperature is around 1200 K. Under this operation condition, the thermodynamic performances can be further improved by the recycling utilization of the un-reacted syngas. Thus, system analysis in this section is based on the gasification temperature of 1200 K, and the product distribution of the polygeneration system by adjusting the recycle ratio (r) is presented in Fig. 9.

It can be found from Fig. 9 that the methanol production rate is increased to 6.70 kg/s from 5.40 kg/s when the recycle ratio is increased to 2.8 from 1 owing to the fact that the conversion rate of the syngas into the methanol is enhanced. Meanwhile, the

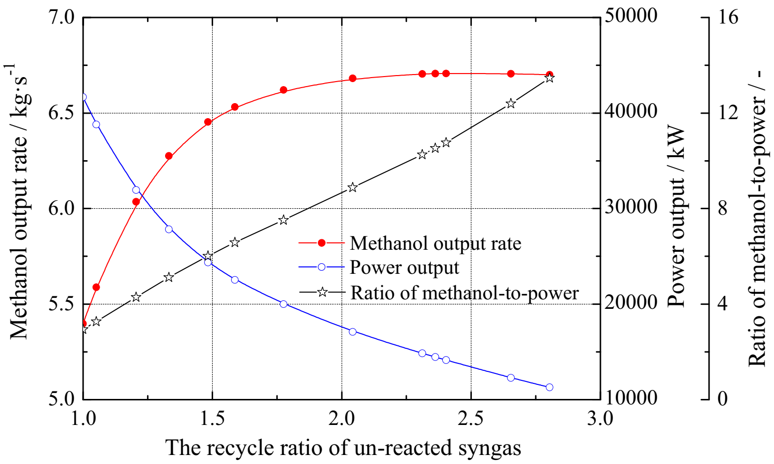

Fig. 9. System product under different recycle ratios.

output power is decreased to 11292.88 kW from 41665.52 kW, which accounts for the reasons that the chemical energy of the gas fuel for the power generation is decreased and the gas flow rate is reduced, and thus more electricity should be supplied for the un-reacted recycle compress.

Although the cost of the improvement of the methanol production will reduce the electricity output, more solar energy can be converted into chemical energy, which will be highly desired for the energy storage and the fuel transportation. However, it is noticeable that the methanol yield achieves a slightly increase when the recycle ratio is higher than 1.48, but the net electricity will be decreased significantly. In fact, increasing the recycle ratio to 2.8 from 1.48, the methanol yield is increased to 0.425 kg/s (i.e. with the heat value of 9641 kJ/s), while the output electricity is reduced by 16534 kW.

According to the performance evaluation, the overall energy efficiency and the exergy efficiency of the system are improved as compared with the scheme of Once-through. As be demonstrated in Fig. 10, when the recycle ratio is 1.48, the highest overall energy efficiency and exergy efficiency approximate 56.09% and 54.86%, which is 1.93 and 1.69 percentage higher than the original scheme. Additionally, under the operation condition of the recycling utilization of the un-reacted syngas for the methanol synthesis, the efficiencies are increased and the production rates of the methanol are also increased to 24.07%. It is should be pointed out that the system efficiencies of the Recycle-utilization will be lower than the scheme of Once-through when the recycle ratio is higher than 2.5.

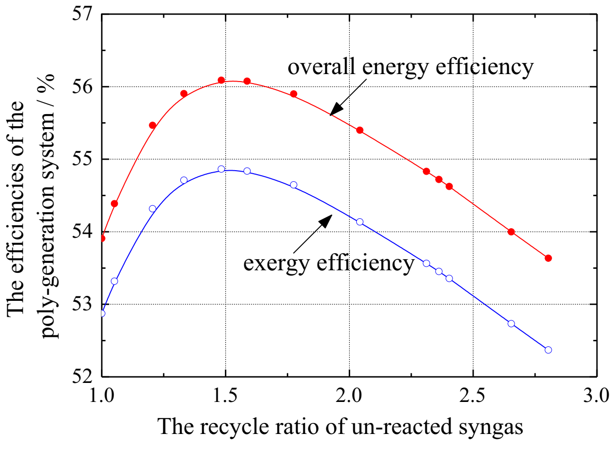

Fig. 10. System efficiencies under different recycle ratios.

4.3. Thermodynamic analysis of the polygeneration system

The differences of the reference system I and the developed polygeneration system depend mainly on the supply approach of the biomass gasification process heat. The proposed polygeneration system can be operated in the schemes of Once-through and Recycle-utilization. The comparisons of the system output under different technical schemes are listed in Table 4. Additionally, CO_2 capture belongs to a power consumption process, and the impact of integrating a CO_2 capture process on the system performances is summarized in Table 4. The gasification temperature in all modes is 1200 K, and the recycle ratio for the scheme of Recycle-utilization is 1.33, and thus all modes can be compared in a fair approach.

Based on the same biomass feed rate, reference system I that is applied to the conventional biomass gasification technologies obtained the lowest methanol production of 5.01 kg/s with CO_2 capture process employed and 4.18 kg/s without CO_2 capture process, owing to the fact that about 1/3 of biomass feedstock was combusted to satisfy the requirement of the gasification process heat. Additionally, it can be found from Table 4 that separating CO_2 from the syngas with a capture ratio of 75% brings a positive effect on the valuable energy output (i.e. methanol and electricity). Though more power is required for CO_2 capture and compression, the synthesis reaction is enhanced, which brings a 3.97–19.86% increase of the output of the methanol.

In particular, for the mode of the Recycle-utilization, in order to analyze the thermodynamic performances of the system under a given operation condition with the gasification temperature of 1200 K and the recycle ratio of 1.33, the distribution of the energy loss and the exergy destruction of the polygeneration system were calculated, which is demonstrated in Table 5.

The total energy loss and the exergy destruction are 119,854 kW and 133,193 kW, respectively. Within the solar energy collection process, the energy loss and the exergy destruction account for 42.79% and 42.2%, which are larger than others. Under the given operation conditions, the solar collection efficiency is 52.05%, which indicates that a portion of 47.95% incident solar radiation does not to be absorbed by the gasifier, and thus the equal amount of the solar energy cannot be utilized. In addition, the second largest energy loss is generated in the steam condenser of the power generation subsystem with the energy loss ratio of 29.08%. For the exergy analysis, the temperature differences

Table 4
Mass and energy balances of different technical modes.

	Reference system I		Once-through		Recycle-utilization	
	With CO_2 capture	Without CO_2 capture	With CO_2 capture	Without CO_2 capture	With CO_2 capture	Without CO_2 capture
Biomass feed rate						
As received (kg/s)	15	15	15	15	15	15
HHV (kJ/s)	196,911	196,911	196,911	196,911	196,911	196,911
LHV (kJ/s)	178,385	178,385	178,385	178,385	178,385	178,385
Oxygen and steam feed rate						
Total oxidant rate (kg/s)	3.66	3.66	0	0	0	0
Pure O_2 (kg/s)	3.49	3.49	0	0	0	0
Steam (kg/s)	0.33	0.33	4.53	4.53	4.53	4.53
Methanol product						
Total product output (kg/s)	5.01	4.18	5.40	5.14	6.28	6.04
HHV (kJ/s)	113,640	94,698	122,537	116,596	142,476	137,182
LHV (kJ/s)	99,871	83,224	107,690	102,469	125,213	120,561
Electricity						
Gas turbine (kW)	12,425	20,986	29,481	32,241	21,126	23,633
Steam turbine (kW)	9609	12,491	18,432	19,495	14,634	15,582
Total gross production (kW)	22,033	33,478	47,913	51,736	35,761	39,215
On-site consumption						
Air-separation (kW)	4211	4218	0	0	0	0
Synthesis compressor (kW)	5885	6994	5127	5468	6814	7745
CO_2 capture and compress (kW)	2756	0	1121	0	1121	0
Total on-site consumption (kW)	12,852	11,205	6248	5468	7935	7745
Total net sale to grid (kW)	9181	22,272	41,666	46,268	27,827	31,470

Table 5
Energy and exergy balances of the polygeneration system.

	Energy loss rate (kW)	Energy loss ratio (%)	Exergy destruction rate (kW)	Exergy destruction ratio (%)
Solar energy collection	51,291	42.8	56,207	42.20
Biomass gasifier	–	–	20,262	15.21
HRSG-I	–	–	4743	3.56
Synthesis compressor	11,912	9.94	5232	3.93
Methanol synthesis	–	–	9043	6.79
Syngas compressor	570	0.48	2081	1.57
Gas turbine	1011	0.84	3188	2.39
Combustor	–	–	13,269	9.96
Steam turbine	298	0.25	1975	1.48
HRSG-II	–	–	2744	2.06
Gas exhaust	3456	2.88	263	0.20
Steam condenser	34,858	29.08	2225	1.67
Sensible heat loss	16,458	13.73	11,961	8.98
Total	119,854	100	133,193	100

between the reactant and the reaction condition in the biomass gasifier and the combustor are relatively large, which may result in more irreversible energy loss, and thus the ration of the amount of the exergy destruction of the devices is about 25.17%.

5. Preliminarily cost estimation and economic analysis of the polygeneration system

An economic comparison for the above-mentioned technical modes is implemented, and the above mass and energy balance analysis of the system is served as a basis for the estimation of the system capital investment and the operating and maintenance costs. Owing to the fact that we cannot find a plant with similar capacity, the capital cost of different technical modes were estimated according to references [28–30] and the reference installing costs of major equipment manufacturers are listed in Table 6.

The basic parameters include 2000 full load hours of completely solar operation per year and the plant life of 30 years. The operation and maintenance cost is assumed to be 4% of the capital cost. According to the baseline parameters assumption and the energy balance analysis, the quantity of the solar thermal energy for driving biomass gasification with the feed rate of 15 kg/s is 107,386 kW, and the heliostat field area is about 175,712 m^2. The capacity of the combined cycle power unit is about 40 MW, the integrated gas turbine refers to the GE product of LM2500RD, with the budget price of $1080/kW in 2013 [31]. The estimations of the capital investment are shown in Table 7.

The investment of the equipment is higher than 160 Million $, and the investment for the modes of the Recycle-utilization with CO_2 capture is the lowest than other technical modes. For all modes, the investments of the gasification and the power generation subsystem account for more than 60% of the total investment. The ratio of the investment of other equipment, like methanol synthesis, syngas compressor and CO_2 capture unit, is relatively small.

Compared with the methanol, the price of electricity often keeps relatively stable, and the methanol has the advantages such as easy storage and various application purposes. According to the economic evaluation, the electricity was regarded as a byproduct in the economic evaluation, and the economic benefits of the generated electricity are transferred into the methanol. The leveled energy cost of the methanol ($LEC_{methanol}$), which is defined as the

Table 6
Reference capital cost for commercially-mature technology.

Reference installed overnight cost	Million $	Reference capacity	Scaling exponent
Syngas compressor	21.3	292.3 t/h	0.67
Methanol synthesis reactor	81.77	10.81 kmol/s syngas feed to synthesis	0.65
Methanol product separation / purification	1.72	4.66 kg/s methanol produced	0.291
CO_2 capture and stripping	43.38	327 t/h CO_2 removed	0.67
CO_2 drying and compression	21.34	292.3 t/h CO_2 removed	0.67
Auxiliary component for power generation unit	57.6	450 gross total MWe	0.67

Table 7
Capital investment cost of the polygeneration system with different modes.

Items	Once-through		Recycle-utilization	
	With CO_2 capture Million $	Without CO_2 capture Million $	With CO_2 capture Million $	Without CO_2 capture Million $
Gasification subsystem				
Equipment for solar collection and gasification	49.55	49.55	49.55	49.55
Auxiliary devices	8.74	8.74	8.74	8.74
Power generation subsystem				
Combined cycle power unit	51.75	55.88	38.62	42.35
Auxiliary devices	10.56	10.56	10.56	11.23
Methanol production subsystem				
Methanol synthesis reactor	14.11	14.79	17.1	18.74
Syngas compressor	5.33	6.17	7.05	8.73
CO_2 capture and compress	6.01	0	6.01	0
Methanol distillation unit	1.94	1.95	2.16	2.2
Auxiliary devices	3.77	4.04	4.64	5.24
Unpredictable investment	16.86	16.85	16.05	16.31
Total	168.62	168.53	160.48	163.09

cost of the methanol production, is estimated and used for the evaluation of the economic performance of the polygeneration system. In this paper, $\mathrm{LEC}_{\mathrm{methanol}}$ is formulated as:

$$\mathrm{LEC}_{\mathrm{methanol}} = \frac{\mathrm{CRF} \cdot C_{\mathrm{investment}} + C_{\mathrm{fuel}} + C_{\mathrm{O\&M}} - R_{\mathrm{electricity}}}{m_{\mathrm{methanol}}} \tag{6}$$

where $C_{\mathrm{investment}}$, C_{fuel}, $C_{\mathrm{O\&M}}$ and $R_{\mathrm{electricity}}$ represent the total investment of the polygeneration system, the annual fuel costs, the annual operation, the maintenance costs, and the revenue of selling electricity, respectively; CRF stands for the capital recovery factor, which can be computed by:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

where i represents the bank rate that is assumed as 8% in this work; n stands for the system life, year.

According to the given price assumption of 40 $/t for the biomass and 0.075 $/(kW h) for the electricity, the $\mathrm{LEC}_{\mathrm{methanol}}$ for different technical modes are illustrated in Fig. 11. It can be seen from Fig. 11 that the $\mathrm{LEC}_{\mathrm{methanol}}$ for the mode of the Recycle-utilization with CO_2 capture is 440.74 $/t and is lower than the others.

The above economic analysis results of the polygeneration system were considered only under the basic market conditions, and the market sensitive of the methanol production cost will be explored. As we known, the biomass is a type of nearly free fuel, but the collection, package and transport of the biomass are costly owing to the low energy density, which may influence the economic performances of the system. Following the above discussions, under the considerations of the biomass price, the electricity price and the technical modes, a market sensitive analysis of the methanol production cost is implemented, and the results are shown in Fig. 12.

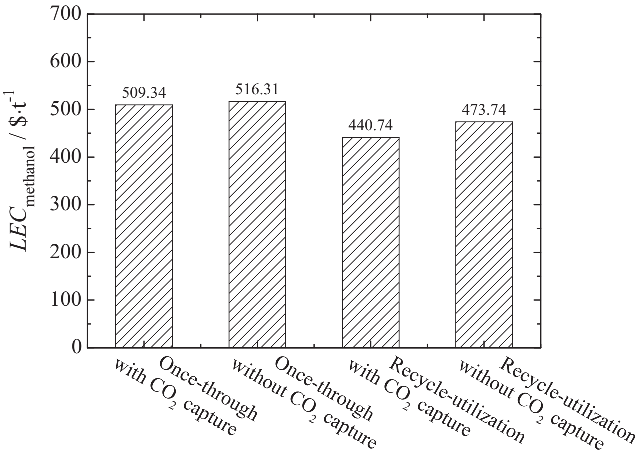

Fig. 11. $\mathrm{LEC}_{\mathrm{methanol}}$ of different technical modes.

The technical scheme of the Recycle-utilization is more favorable than the Once-through scheme, and the CO_2 capture process will reduce the $\mathrm{LEC}_{\mathrm{methanol}}$. In the economic analysis of the polygeneration system, the generated electricity is used to subsidize the system operation cost, and thus the production cost of the methanol would be reduced with the increase of the electricity price. It is found that the $\mathrm{LEC}_{\mathrm{methanol}}$ would be improved with the increase of the biomass price, as the cost of the fuels in a system is about 30% of the cost of the methanol production.

The scheme of Recycle-utilization has a more favorable economic performance than other schemes. But, it is not comparable with the coal-based methanol production technologies presently. However, the benefits from the reduction of the consumption of

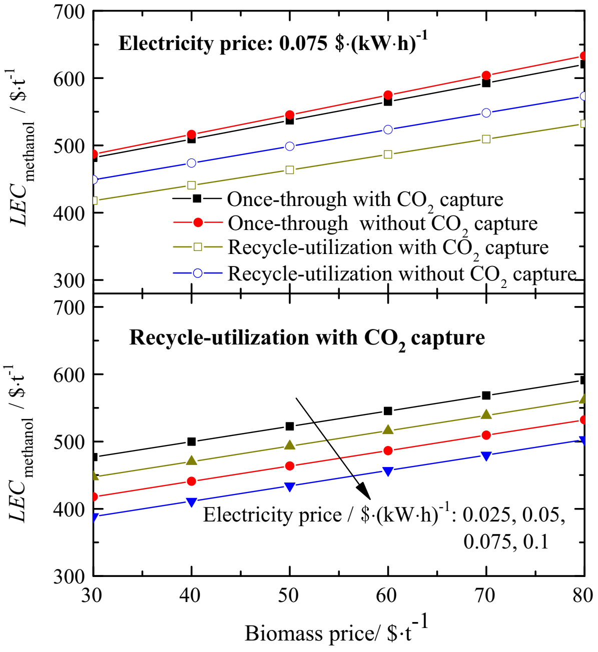

Fig. 12. Market sensitive analysis under different methanol production costs.

the fossil fuels and the mitigation of CO_2 emission should be highlighted. Moreover, the proposed technology provides a promising approach for the efficient utilization of the renewable energies and the production of the alternative fuels.

6. Conclusions

In this work, we propose a solar-driven biomass gasification polygeneration system with the generation of the methanol and the electricity, and the thermodynamic analysis and the economic performances on the system are investigated. The main research findings can be outlined as follows:

(1) The syngas produced by the solar-driven gasification has a higher H_2/CO molar ratio and the chemical energy level of the produced syngas is improved as compared with conventional biomass gasification technologies.
(2) In the proposed polygeneration system, the solar energy is converted into the methanol, which will facilitate the energy storage and transportation. The methanol production rate can be further improved and the system performances can be enhanced by adopting the Recycle-utilization scheme. The highest energy efficiency and the exergy efficiency of the polygeneration system approximately reach to 56.09% and 54.86%, respectively.
(3) All the feedstock of the system are renewable energies including solar energy and biomass, the benefits from the reduction of the consumption of the fossil fuels and the mitigation of CO_2 emission can be highlighted. Moreover, the proposed system can achieve the stable utilization of the solar energy with a higher efficiency.

Although the solar–biomass gasification can only be realized at the laboratory scale at present; however, the conventional biomass gasification and the concentrated solar power will facilitate the practical applications of solar–biomass gasification. With the rapid development of science and technology, the solar–biomass thermal gasification technology will be made a breakthrough, and bridge current fossil-fuel-based technologies and future solar chemical technologies, which will accelerate to achieve the commercial operation in the near future. It is worth mentioning that the integrated method of the biomass and the solar energy provides a promising approach for the effective utilization of the abundant renewable resources of Western China.

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