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Huang, Y., Zhao, Y.-J., Hao, Y.-H. et al. (7 more authors) (2019) A feasibility analysis of distributed power plants from agricultural residues resources gasification in rural China. Biomass and Bioenergy, 121. pp. 1-12. ISSN 0961-9534

https://doi.org/10.1016/j.biombioe.2018.12.007

A feasibility analysis of distributed power plants from agricultural residues resources gasification in rural China

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Abstract：Gasification is one of the most promising technologies for conversion of biomass into power generation due to its tremendous potential in improving efficiency of energy conversion and reducing cost of electricity (COE). In this study, the techno-economic feasibility of distributed power plants via wheat/corn straw gasification in China was investigated, and an economic model was established using a basic discounted cash flow analysis to estimate economic performance of the power plants. The effects of key variables (such as scales, feedstock cost, electricity prices and run time etc.) on economic performance were analyzed, and the results showed that plant scale and straw cost are the most influential parameters on the plant economic performance. It is estimated that a plant with a capacity of 5 MWe can be the optimal option for agricultural straw gasification to distributed power generation, the COE is 0.402 CNY/kWh, and SO_2, NOx and dust emission are 2.5, 2.0 and 0.038 g/kWh, respectively. The net present value (NPV) and the annual average of return on

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investment (ROI) of the plant are 85.9 million CNY and 49.7 %, respectively, with a high discount of 0.12 at a current feed-in tariff (0.75 CNY/kWh) for biomass to power in China, suggesting a good economic feasibility and market competitiveness. The deployment of agricultural residues resources gasification to distributed power generation displacing coal-fired power to supply electricity with rural area shows a significant potential in pollutants emission reduction and coal saves. Biomass gasification to distributed power generation serves as a sustainable technique for utilization of agricultural resources in practice, and would be widely applied in the near future supported by renewable energy strategies of Chinese government.

Keywords: techno-economic; biomass; straw; gasification; distributed power

1. Introduction

Energy shortage and global warming are regarded as two severe issues worldwide [1]. The use of renewable energy sources is becoming increasingly important when it is considered in helping to alleviate global warming and utilising waste agricultural residues as a fuel supply. In the past 10 years, there has been renewed interest worldwide in biomass as an attractive alternative to fossil fuels. Nowadays, renewable energy provided an estimated 19.3% of global final energy consumption and of this total share, traditional biomass accounted for about 9.1% in 2015 [2]. Biomass is also widely recognized as a significant part of sustainable renewable energy. Additionally, the utilization of biomass produces significantly less nitrogen oxide (NOx) and sulphur dioxide (SOx) emissions than fossil fuels [3]. Further and sufficient exploitation of biomass resources is essential for future energy security, global carbon balance and sustainable development of the world.

Gasification, which is one of the promising technologies to exploit energy from renewable biomass, is being used to improve the efficiency of biomass energy conversion and reduce the investment costs of biomass electricity generation. It has advantages for distributed power generation systems that are appropriate for widely distributed biomass resources with low energy density [4, 5]. As the biggest agricultural country, China has abundant agricultural biomass resources, and a total of 889 million tonnes of agricultural biomass residues (about 80% is wheat/corn straw) are produced per annum [6]. Agricultural residues contribute significantly to the biomass energy sector. About 46% of traditional biomass energy is supplied from major crop residues among which corn, wheat and rice account for nearly 80% of the total. Unfortunately, the large part (75%) is discarded, directly burnt in the field, or used by farmers for household energy which not only results in low combustion efficiency (10%), but is a waste of valuable resources and adds to pollution of the environment [1, 3]. If left to rot in the environment, then agricultural residues can lead to uncontrolled release of greenhouse gases, such as methane, adding to the problems of controlling global temperature rise. Therefore, a study on high-efficiency utilization of crop residues in rural China is highly urgent, especially when considering the large scale of the waste agricultural residue problem. In this case, biomass gasification power generation would be a good method to solve such problems in countryside, agriculture and farmers, for it can provide rural energy, improve rural energy mix, subdue environmental pollution, and create more job opportunities, as well as boost the rural economy to some extent by developing the technology widely throughout China [3].

The research on gasification power generation with rice husk as feedstock started in the early 1960s in China, and great progress has been made over the past decade. Even as an emerging biomass power generation technology in China, biomass gasification power generation technology (BGPG) has been extensively studied [7-13], widely applied and well equipped. Sansaniwal et al. [7, 8] comprehensively compared different biomass to power technologies, and proposed a seriers recommendations for policy makers. Pauls et al. [9] developed a model to simulate gasification of pine sawdust in the presence of both air and steam by Aspen Plus. Kaushal et al. [10] proposed a sub-model for tar generation and cracking included in the biomass gaisification process to optimize the gasification parameter. Lopez et al. [11] presented a conical spouted with an enhanced fountain bed for biomass gasification. Some studies focused on the tar removel from the syngas and gasification characteristics during special designed gasification reactor [12] [13]. Hefei Tianyan Green Energy Development Co., Ltd. (Tianyan) and Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (GIEC-CAS) have made a great contribution in the field of biomass gasification power generation. They have established over 30 power plants with a total capacity of more than 50 MWe, in China, Europe and Southeast Asian [3, 14]. Currently, biomass gasification power generation technologies developed in China include the following two types: 1) small- and medium-scale biomass gasification power generation systems, generating power through a simple gas engine system with scale varying from several kWe to 3 MWe with electric efficiency of 15-20% and 2) large-scale biomass gasification power generation system, adopting a subsidiary steam turbine driven by heat recovery steam on the basis of the gas engine power generator to form an integrated gasification combined cycle system with capacity of more than 5 MWe with electric efficiency ranging 26-30% [3]. A 1 MWe BGPG plant was demonstrated in Putian, Fujian Province of China with a rice husk as raw material (150 td^{-1}) [15]. The electric efficiency of the plant is 17% and the available fuels are sawdust, rice husk or straw, etc. This system consists of a circulating fluidized-bed (CFB) gasifier, a combined gas cleaner, five parallel gas engines rated at 200 kWe each and a wastewater treatment system. To promote efficiency, a high-efficient biomass integrated gasification combined cycle (BIGCC) demonstration plant with designed power output of 5.5 MWe was set up at Daiyao town, Xinghua city, Jiangsu Province, China [16]. The plant electrical efficiency can reach to 28-30%. Rice husk, rice stalk and wheat stalk were used as the biomass feed, and air as gasifying agent. This project was developed by Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (GIEC-CAS) and supported by 863 national programs in China. This plant includes a large-scale CFB, ten sets of 450 kWe gas engines, a subsidiary exhaust heat utilization system, a 1.5 MWe steam turbine and a wastewater treatment system, with all the equipment manufactured in China.

However, this technology is still not widely promoted for biomass to distributed power generation in China due to its uncertainty in the terms of techno-economic feasibility. It is of great interest to investigate the impacts of adopting this technology for biomass to distributed power generation and the economic feasibility of the system. In this study, biomass gasification to power generation technology developed by our group (GIEC-CAS) [16] is selected to investigate the feasibility and reliability of distributed power plant from agricultural straw resources gasification in rural China. An economic model and sustainability evaluation model were established to investigate effects of the key variables on the techno-economic performance of the BGPG plant. Uncertainty or sensitivy analysis was performed to determine the most critical impact factors that should be focused on and addressed. The potential of pollutants emissions reduction from BGPG plants was estimated as well. The results from this study will provide valuable information and suggestions for future promotion of biomass gasification to power generation.

2. Biomass gasification power generation plant

2.1. Description of straw gasification power plant

The whole plant mainly comprises of a CFB gasifier, a gas-purifying system, gas engine or gas engine/steam turbine generators (scale ≤4 MWe using the gas engine; scale ≥5 MWe using the gas engine/steam turbine), a wastewater treatment system and etc, as shown in **Fig. 1.** Straws are sent to the gasifier and gasified with air and steam to produce syngas. Most of biomass ash/char and bed materials (quartz sand) are separated at the bottom of the gasifier. The syngas from gasifier contains small amount of fly ash which will be removed by cyclone separator. After removal of particulates, the syngas is sent to wet scrubbing system to remove tar and fine dust [17]. The clean gas then enters internal combustion engine (ICE) for electricity generation (for large scale BGPG plants, a subsidiary steam turbine will be driven by heat recovery steam from the gas engine power generator). Meanwhile, both ash/char and fly ash as a by-product for sale can be recycled to replace a part of fertilizer. Due to the very similar chemical characteristics of wheat and corn straw as shown in **Table S1** [18](shown in the **Support Information**), the feedstock straw properties used in this study are as follows: the ash yield is 14.20 wt.% on a dry basis (db), and the volatile yield and fixed carbon is 69.01 wt.%, and 30.99 %, respectively, on a dry and ash free basis (daf). The moisture of the feedstock is 9.58 wt.% on an air dry basis (ad). The elemental composition of straw sample is C, 40.30; H, 6.53; N, 0.72; S, 0.33; O, 37.92 (by difference), (wt.%, db), and the low heat value (LHV) is 16.50 MJ/kg, on a dry basis. Gas composition and operation conditions of the demonstration atmospheric CFB gasifier are listed in **Table 1,** and **Table 2** shows the main technical parameters of power plant and the other designed technical data of the plant are reported in [15, 16].

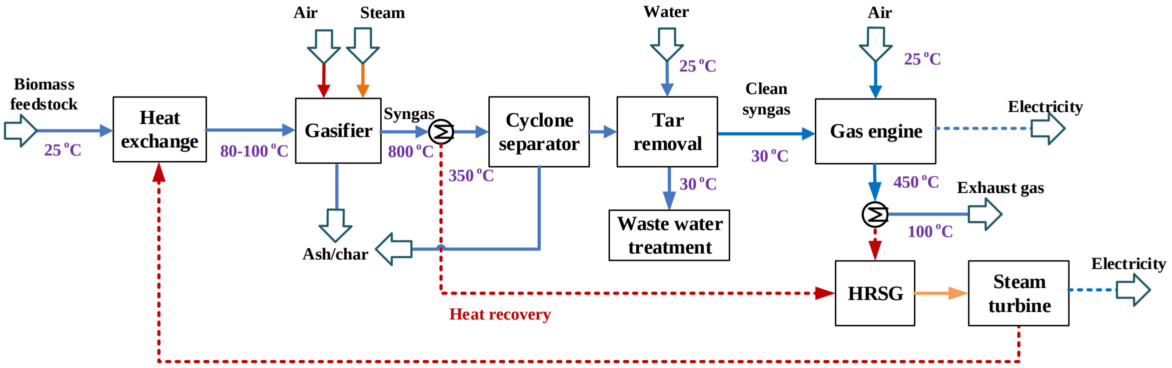


Fig. 1 Flow diagram of biomass gasification power generation plant.

Table 1 Operating conditions and performance parameters of the straw gasification.

Items	value
Operating conditions	
Fuel feeding rate, kg/h (db)	3000-6000
Temperature of gasifier, ^{o}C	700-810
Heat output power of gasifier, MWt	20.0
Gasification efficiency, %	70-75
Gas heating value, kJ/Nm^3	4700-6700
Composition of syngas (vol, %, db)	
N_2	46.8-53.3
CO_2	12.2-18.4
CO	15.2-19.2
H_2	6.1-8.9
CH_4	3.8-5.7
Others (C_nH_m)	0.5-2.3
H_2O	18.2-20.2
Ash/char yield	
Accumulated ash, kg/kg$_{biomass}$	0.13
Unreacted carbon, kg/kg$_{biomass}$	0.045

Table 2 The main technical parameters of power plant.

Key unit	Operation conditions		Introduction
Gasifier	Temperature, °C	800	Circulating fluidized bed gasifier
	Pressure, MPa	0.1	
Cyclone	Separation efficiency, %	90	
Tar removal	Input gas temperature, °C	150	Water scrubber, through the water scrubber, the tar content of the fuel gas is below 100 mg/Nm^3.
	Pressure, MPa	0.1	
	Efficiency of water scrubber, %	95	
Gas engine	Type of gas engines	500GF10	The gas engine (500GF10) is modified from the model 8300 diesel engine, which is manufactured in diesel Engine Corporation in China.
	Model of gas engines	8250/8300	
	Efficiency of gas engines, %	30	
Boiler	Steam temperature, °C	350	Waste heat boiler, the temperature of the discharged gas from gasifier and gas engine sets are 350-500 and 500-550°C, respectively.
	Steam pressure, MPa	1.35	
	Water feeding temperature, °C	60	
Steam turbine	Rate power, MW	1.5	Condensing turbine, the waste heat boiler and steam-turbine-generating system are integrated to from a combined cycle.
	Rated inlet steam pressure, MPa	1.34	
	Rated inlet steam temperature, °C	310	
	Exhaust steam pressure, MPa	0.009	

3. Methodology

3.1. Energy conversion

Net electricity efficiency is defined as the ratio of net generated power to the energy input to the system:

$$\text{Net electricity efficiency} = \frac{\text{net power output (MW)}}{\text{biomass heat input (LHV basis, MW)}} \times 100\% = \frac{\text{gross power (MW)} - \text{consumed power (MW)}}{\text{biomass heat input (LHV basis, MW)}} \times 100\% \qquad (1)$$

The gross power in the equation (1) is the total power generated from the plant, while the consumed electricity refers to either the internally used power or the power used on the site which is calculated as 10% of the gross generated electricity [19].

3.2. Economic evaluation

In this study, an economic model was established using a consistent methodology to allow for the comparison between the different processes and technology options. The model used a basic discounted cash flow (DCF) analysis [20], which consists of capital costs, operating costs (or variable costs) and projected annual revenues. COE is a useful tool for comparing different technologies since it calculates the cost of producing a single unit of electricity. The profits of the power plant is evaluated through the net present value (NPV, i.e. the difference between the present values of all costs and associated revenues) [21], and the annual average of return on investment (ROI, i.e. one of the commonly used economic criterion to evaluate the feasibility of a project)[22]. The higher NPV and ROI are, the more feasible it is to undertake a project [22, 23]. An option is economically attractive if it has the higher ROI and the NPV above zero. The economic assumptions are presented in the **Support Information**.

3.2.1. Economic criteria and capital cost

Eq. (2) shows information about NPV, where i is the discount rate, C_t refers to the net cash flow over years t, and TPC refers to the total plant cost. COE can be obtained through eq. (3-4), where CRF denotes the capital recovery factor, which is a function of the discount rate (i) and the expected plant lifetime (y). TVC is the total variable cost, and S_{bp} is the revenues from the by-products such as ash/char sale. The ROI is calculated using eq. (5), where P is the profit and TR is tax rate.

$$\mathrm{NPV} = \sum_{t=1}^{y} \frac{C_t}{(1+i)^t} \tag{2}$$

$$\mathrm{COE} = \frac{\mathrm{TPC} \times \mathrm{CRF} + \mathrm{TVC} - S_{bp}}{7200 \times \mathrm{Net\ power\ output}} \tag{3}$$

$$\mathrm{CRF} = \frac{i}{1-(1+i)^{-y}} \tag{4}$$

$$\mathrm{ROI} = \frac{P \times (1-\mathrm{TR})}{(\mathrm{TPC} \times \mathrm{CRF} + \mathrm{TVC})} \tag{5}$$

In reality, the increase of capacity is not in proportion with the increase in investment. According to a known investment C_r with the capacity of S_r and the specific factor α derived from historical data for similar plants and usually in the range of 0.7-0.9 [24] (0.8 is used in this study with similar plants and plant scales (1-6 MWe) according to the ref.[19]), the investment required for an estimated plant S can be determined as in eq. (6) [25]:

$$C = Cr \times (\frac{S}{Sr})^{\alpha} \tag{6}$$

The total capital cost of small-scale (1-3 MWe) and medium-scale (5.5 MWe) BGPG demonstration plants [16, 19] are listed in **Table S2**. The capital costs of other BGPG plants with different scale are calculated by the eq. (6).

3.2.2. Biomass cost

The total cost of straw ($C_{delivery}$) refers to the sum of costs for straw production $C_{production}$, straw collecting (including the cost for harvesting and on-farm haulage) $C_{collecting}$, storage $C_{storage}$ and road transport $C_{transport}$. The $C_{production}$, $C_{collecting}$ and $C_{storage}$ are costs of 100-150, 50-100 and 25 CNY/t, respectively, and those costs for different agricultural residues in China can be obtained from the literature[19]. The collection radius of biomass is calculated by the eq. (7), and $C_{transport}$ is calculated by the eq.(8) [19], [26]:

$$r_b = \frac{1}{6}\tau\sqrt{\frac{P\times 330}{(1-\omega)\times 100\times m\times lc}}\times\left(\sqrt{2}+\ln\left(1+\sqrt{2}\right)\right) \tag{7}$$

$$C_{transport} = \begin{cases} 25\ \text{CNY/t} & 0 < L \leq 15\,\text{km} \\ 50\ \text{CNY/t} & 15\,\text{km} < L \leq 25\,\text{km} \\ 70\text{-}100\ \text{CNY/t} & L > 25\,\text{km} \end{cases} \tag{8}$$

Where r_b is the distance for collection (km, one way). τ is the tortuosity factor, and a constant value of 1.5 is used for the rural road system. P refers to the handling capacity of the plant in dry tonnes per day, on the assumption that the plant operates 330 days per year. ω is the straw moisture content (%). lc is the land coverage of straw planting (%), 90% is used in this study for the sake of biomass supply security. m is the straw productivity with typically 10 green tonnes per hectare per year (gt/(ha·year)), and L is the distance covered in the transportation (km). In this study, the $C_{production}$, $C_{collecting}$, and $C_{storage}$ costs are 150, 80 and 25 CNY/t, respectively, and L is below 15 km.

3.3. Sustainability evaluation

The use of sustainability indicators for assessment of process performance aims at providing holistic and integrated evaluation enabling identification of advantages and drawbacks of the analyzed processes. In general, there are four indicators for sustainability assessment: economic, environmental, social and technical sustainability.

- Economic indicators. The economic indicators for BGPG include investment cost, and production cost.

Investment cost: the average capital investment for unit capacity is adopted for the comparison of different alternative processes for making power using biomass or coal, as the production scale of alternatives are always different.

COE: Production costs of coal or biomass to power are represented as the price of electricity (CNY/kWh). This is an important economic index and is easy to compare to the current price of electricity produced by different alternative ways.

- Environmental indicators. The production of power requires consumption of raw material and energy, which leads to resource depletion. Besides, the production of power also releases waste into the environment, which causes environmental degradation. The proposed environmental indicators cover the following aspects: electricity efficiency (or energy conversion), renewability, water consumption, pollution emissions.

Electricity efficiency: the production of power from coal and biomass is to convert them into another energy form so that they could be easily utilized. The calculation of electricity efficiency is expressed as eq.1.

Renewability: the use of renewable resources, aimed at diminishing the consumption of fossil fuels, is a significant factor supporting sustainable development. Renewability is expressed as the mass ratio of feedstock from renewable resources to total main feedstock input.

Water consumption: due to scarcity of water resources and environmental protection, the reduction of water consumption and improvement of its efficient use have become important optimization goals for power plants. Water consumption indicator is expressed as tonnes of fresh water consumed per unit power output (t/kWh).

Pollution emissions: in general, CO_2, SO_2, NOx and dust are the most common emissions of the power plants, and they also can caused severe pollution to environment. The indicators include CO_2, SO_2, NOx and dust emitted from the power plant per unit power output (g/kWh)

- Social indicators. Social area is one of the fundamental elements of sustainability. The social indicators usually include the community development and energy security aspect.

Community development: This indicator is qualitative one, and it comprises many complicated phenomena. Simply, a sub-indicator of employment opportunities offered by the coal/biomass to power process is adopted to indicate community development, i.e., the job opportunities provided by power plants (employee number /MWe).

Energy security: the purpose of making power from coal and biomass is to satisfy the electricity demand of the country, diverse China's electricity supply, and therefore enhance national security. The indicator is expressed as the ratio of expected capacity of power from biomass or coal to the total electricity demand. The higher this indicator is, the more contribution on energy security in power supplies.

- Technical indicators. The technical area has been generally emphasized as a wider aspect of sustainability for energy process. It is usually used to characterize the ability of the process to achieve, maintain, and improve its performance of purposed functions, such as the indicator of system reliability, system operability, etc. The proposed technical indicator in this study is technical maturity. Technical maturity is a qualitative indicator using the categorical scaling method to quantify the concept in the range 0-1, where 1 denotes the best case, i.e., the technology has achieved large-scale industrial operation; 0.75 represents a demonstration project or pilot stage; 0.5 denotes a small test phase; 0.25 indicates a laboratory research stage; and 0 represents the worst case, i.e., the relevant basic research has not yet started [27].

To interpret and compare the overall sustainability of different alternatives more intuitively and clearly, a further processing of these indicators is presented by use of normalization method, according to the eq.(9) [27].

$$X_{ij} = \frac{x_{ij} - \text{worst}\{x_j\}}{\text{best}\{x_j\} - \text{worst}\{x_j\}} \tag{9}$$

where x_{ij} is the indicator j for process i; best$\{x_j\}$ is the assumed best case of indicator j; worst$\{x_j\}$ is the assumed worst case of indicator j; X_{ij} is the normalized indicator j for process i. The indicator varies in the range of 0-1. The greater the index value is, the better its sustainability is.

4. Results and discussion

The results of impacts of key variables on techno-economic feasibility of distributed power plant via agricultural straw gasification are presented in this section. The net electricity efficiencies and COE associated with the plant are calculated. The capital and operating expenditures and the projected revenues generated from electricity and recovered ashes are evaluated as well. Additionally, pollutants (such as CO_2, SO_2, NO_X, and dust) emission reduction in rural region resulting from straw/wheat straw gasification power deployment replacing coal-fired power is analyzed. In order to obtain an accurate and reliable techno-economic evaluation for the biomass power plant, a small to medium plant size with a range of 1 to 10 MWe is selected for this study by both considering the application scope of eq. (6) and the characteristics of straw for distributed use in rural area.

4.1 Sensitivity analysis of economic performance

4.1.1 Impact of plant size

Fig. 2 shows the economic performance of plant on different scales. With the increase of plant scale, the unit capital investment per kW electricity and COE decrease significantly. However, they change slightly when the power capacity exceeds 5 MWe, suggesting that effect of plant scale on economies is no longer significant in a plant with the capacity above 5 MWe. NPV and ROI increase with the plant scale, and ROI increment tends to vary gently with the power plant scale being over 5 MWe. In addition, the scale of the plant exerts influence on the straw transportation. Long-distance road transport of straw may substantially increase the cost of straw delivery according to the eq. (6). The power plant with large-scale usually have a big collection radius due to the low distribution density and availability of straw. Long distance transportation is, clearly, not economically acceptable, and the power plants may be constrained in scale. It can be seen that straw cost (**Fig.2b**) increased significantly from 2.84 to 17.22 million CNY/y with the plant scale increasing (1 to 10 MWe). However, there is big difference at the results obtained at 4MWe and 5MWe. The main reason is that for plants with a capacity ⩽ 4MWe a gas engine is considered while for plants with capacity ⩾ 5MWe a gas engine/steam turbine is used. The latter presented higher capital cost but also higher energy efficiecy. As a result, the toatl investment and straw cost are quite different for them. In fact, the straw price is highly fluid and pliable in response to movements of aggregated supply and demand. Therefore, a proper power generation capacity should be determined under the unfavorable expectations of the current wheat/corn straw cost. Due to the indistinctive economies of scale and increase of the feedstock cost in a larger plant, the COE decreased significantly at the beginning and then declined slightly with the plant scale increasing. Hence, the optimal capacity of a plant has to be determined by transportation cost, plant capital, operating costs, and other factors such as the possible variations of the cost for power grid infrastructure. The BGPG demonstration plants showed that the system within 3-10 MWe is particularly suitable for application in China due to their good cost performance ratio making them more commercially competitive[3, 28]. In this case, the capacity of a power plant is supposed to be 5 MWe taking into consideration both the technique and economic performance. The plant with capacity of 5 MWe as an example will be further discussed in the following sections.

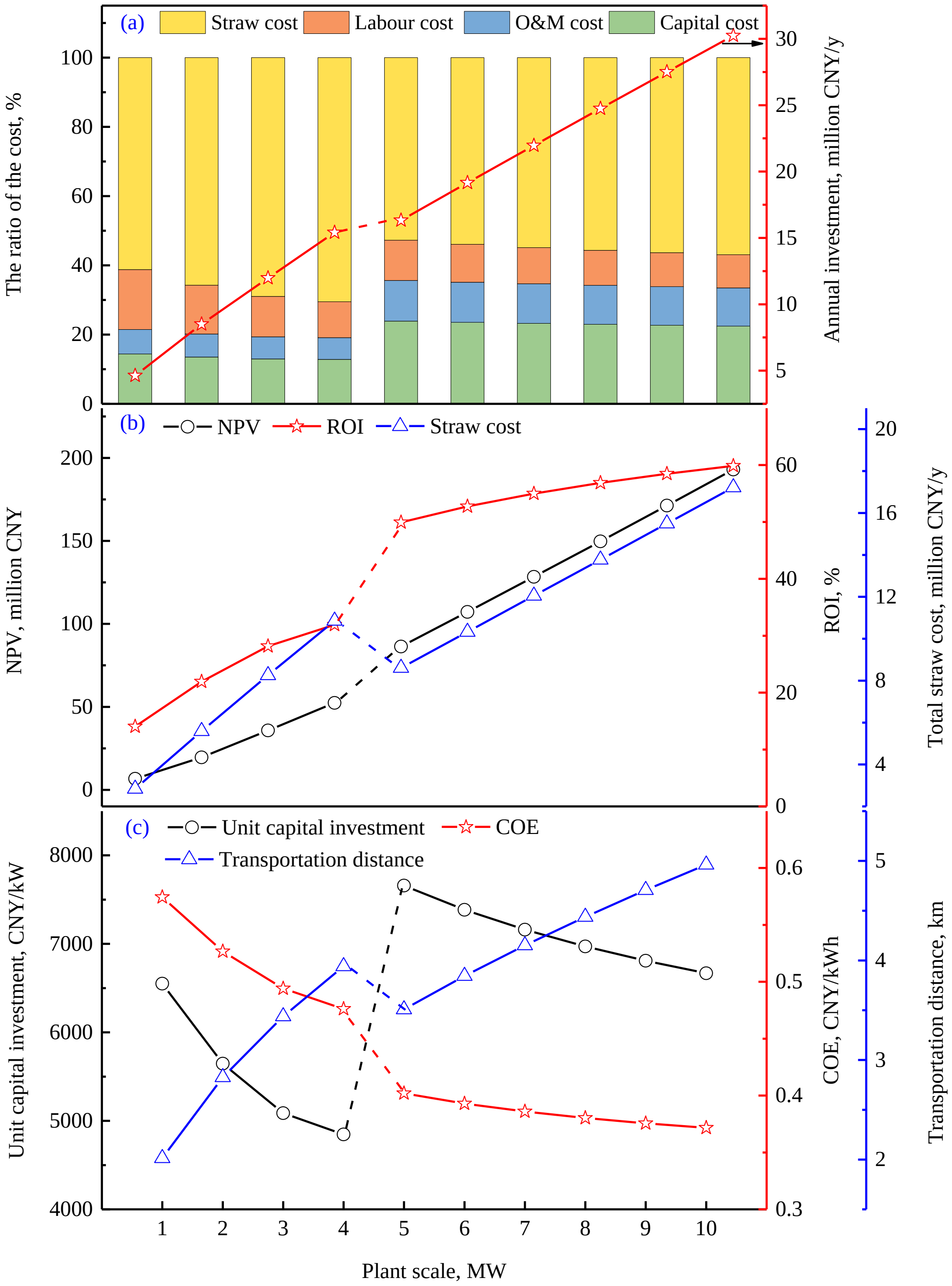


Fig. 2 Economic performance of plant at different scales.

4.1.2 Impact of feedstock cost

Fig. 3 describes the effect of straw cost on ROI, NPV and COE. The relationship between straw cost and the two indicators (NPV and COE) is linear, as would be expected. For every 50 CNY/t increase in biomass cost, NPV and COE decrease by about 1.3×10^{7} CNY and 0.039 CNY/kWh, respectively. ROI decreases sharply with the straw cost rising, though the decrease rate declines gradually. It can be seen that if the straw price is higher than 750 CNY/t, the COE will reach about 0.77 CNY/kWh (higher than biomass to power feed-in tariff 0.75 CNY/kWh in China), and straw BGPG power plant will lose its economic attraction. Nowadays, the wheat/corn straw cost is between 200-300 CNY/t (including transportation cost) in China [19], implying that wheat/corn straw BGPG plants are more competitive in economy.

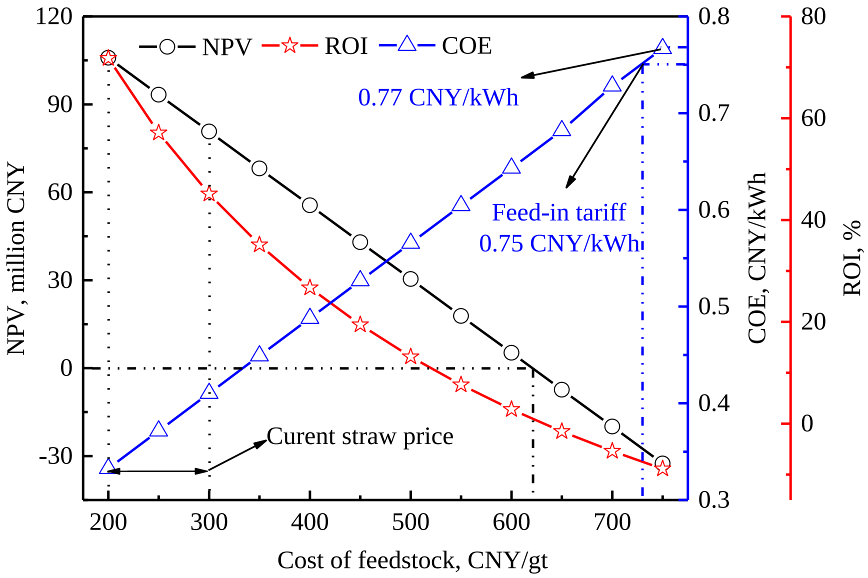


Fig. 3 Impact of straw cost on COE, NPV and ROI.

4.1.3 Impact of run time

Fig. 4 summarizes the COE, ROI and NPV versus annual operational hours. The effect of annual operational hours on COE, ROI and NPV is significant. COE falls sharply, while ROI and NPV rise up remarkably as annual operational hours increase. In general, high operating rate requires high continuity and stability of feedstock supply. However, due to the problems of large straw collection radius, large storage quantity etc., it is very difficult to keep stability of straw supplying and make a high operating rate (above 90%) for the biomass power plant. Nevertheless, for the straw BGPG plant, it can still obtain a relatively low COE of 0.516 CNY/kWh, and high ROI (22.7 %) and NPV (3.0×10^7 CNY) even at a low operating rate of 57% (5000 h), indicating that the straw BGPG power plant has strong ability to resist market risk.

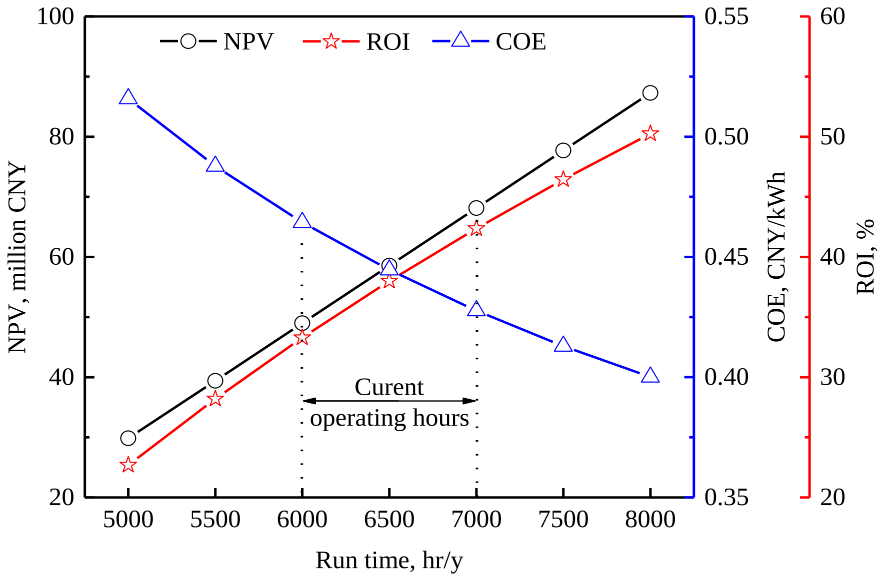


Fig. 4 Impact of run time on COE, NPV and ROI.

4.1.4 Impact of electricity prices

Revenues for electricity sale are significant, especially for the economic viability of the power plant. In general, low feed-in tariff is compatible with a low COE power plant. As shown in **Fig. 5**, ROI and NPV increase dramatically with the increase of electricity price. It is found that when electricity price is higher than 0.50 CNY/kWh, the ROI will exceed 8.9% and the NPV will be above zero at either at a high discount rate (12%) or at a low discount rate (6%), which values are usually used to estimate economic benefits of the biomass power plants[25], [29], suggesting that the straw BGPG plant is economically feasible. What's more, the feed-in tariff rate is 0.75 CNY/kWh (including tax) for biomass energy electricity based on the National Development and Reform Commission in China [3]. Hence, the power plant turns out to be obviously profitable.

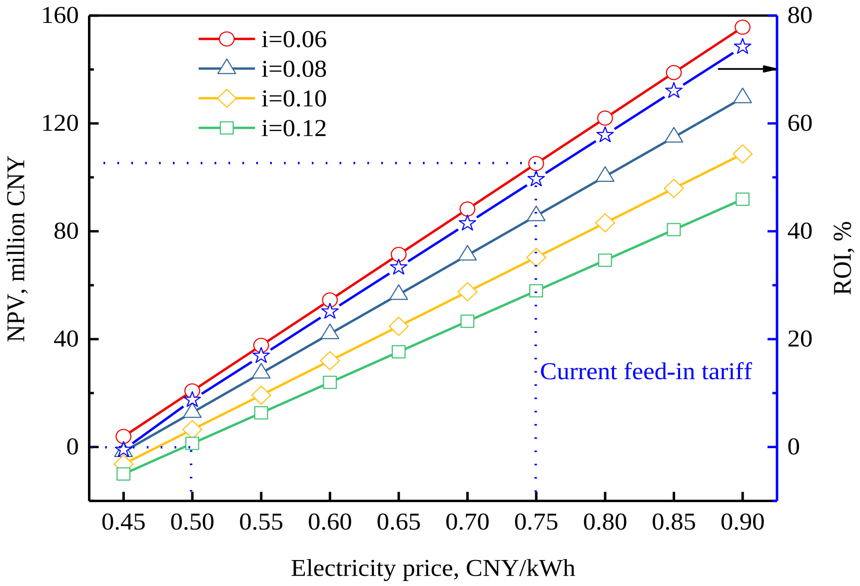


Fig. 5 Impact of electricity price on NPV and ROI.

4.1.5 Impact of by-product ash

The ash formed in the power generation process still remains underutilized, inhibiting further application of BGPG [30]. Making full use of the ash is an important factor to improve the benefit of a BGPG plant. The ash/biochar from straw gasification can be returned to soil to enhance soil quality, realize carbon sequestration and recycle some of the inherent inorganic nutrients (such as Na, K, Mg, Ca and C etc.) in biochar [31]. Otherwise, the use of the fly-ash and chemical fertilizers and organic materials in an integrated way can reduce chemical fertilizer and increase the fertilizer use efficiency (FUE). It was estimated that N, P and K fertilizers can be saved by 45.8%, 33.5% and 69.6% respectively by integrating use of the ash, organic and inorganic fertilizers in a rice–groundnut cropping system[32]. Hence, ash/biochar can be as a by-product for sale to replace a part of fertilizers, which is particularly significant to improve the sustainability and economic performance of biomass to power industry. **Fig. 6** presents the effects of the revenue from the ash/biochar sales on COE, ROI and NPV of the power plant with capacity of 5 MWe. Ash/biochar sales can bring about 2.5-20% reduction of COE on the basis of the power plant with ash recycle or sale when ash/biochar price at 100-800 CNY/t (with i from 0.06 to 0.12). The ROI increased by about 15% and 0.4 to 3.2 million CNY/y profits can be obtained when ash/biochar price increased from 100 to 800 CNY/t. The NPV increased by 3.8-26.8, 3.3-23.1, 2.9-20.3 and 2.6-18.0 million CNY with the increase of ash/biochar price from 100 to 800 CNY/t when the i at 0.06, 0.08, 0.10 and 0.12, respectively.

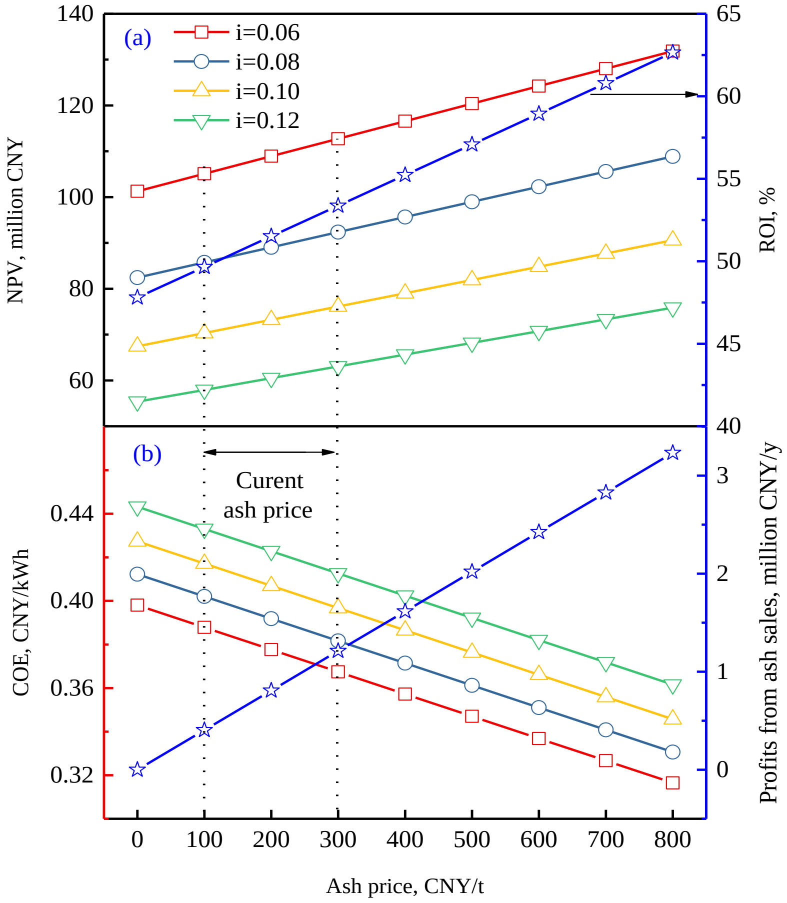


Fig. 6 Impact of by-product ash price on COE, NPV and ROI

4.1.6 Sensitivity analysis to COE

In this section, the sensitive analysis is performed to identify parameters that have a significant impact on COE. Six typical parameters have been selected for the sensitivity analysis over the expected range of parameters variation for different scale plants as shown in **Table S3.** **Fig. 7** presents effects of changes in the most influential parameters on COE for a 5 MWe straw BGPG plant. The straw cost has a considerable impact on COE. It can bring about 12.8% of the variation in COE when the straw price rises up or drops by 20%. These results imply that reducing the biomass resource cost is the most effective way to enhance the economic performance of the straw BGPG power plant. Capital cost data used in this study are from the commercialized power plants, and those data will be probably changed with the techniques development. A sensitivity analysis of impact of capital cost changes on COE was investigated and, although the capital cost of a plant changes with the year of installation, in the **Fig. 7** it is shown that the capital cost barely influences the COE of a BGPG power plant, varying it by 30% leads to COE changing only by 0.03 CNY/kWh. Hence, on the basis of the data in the past, through the economic sensitivity analysis and evaluation, it’s found that the final results show little difference whether the capital cost of 2014 or that of 2015 increase or decrease by 30%.

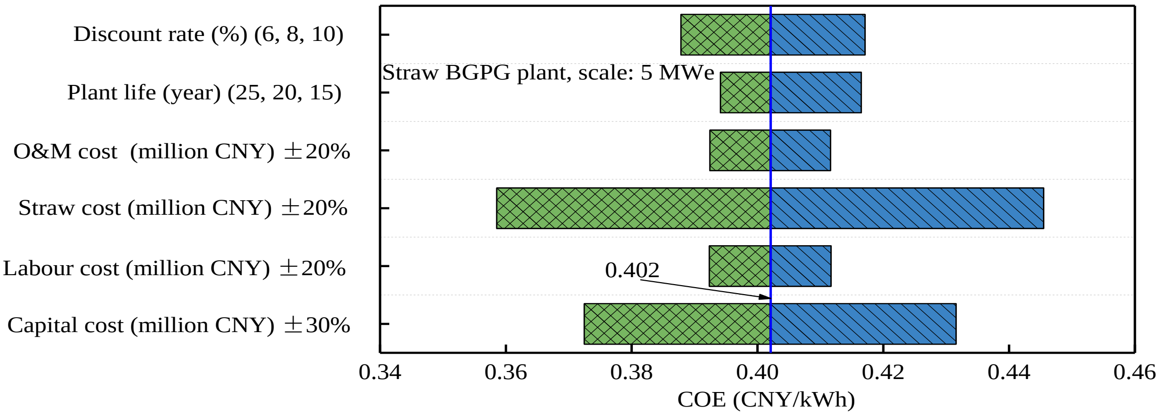


Fig. 7 Effects of changes in the most influential parameters on COE for a 5 MWe straw BGPG plant.

4.2 Technical and economic performance

4.2.1 Economic sustainability

Technical and economic performance of straw BGPG plants with different scale options were summarized in **Table 3**. Small scale BGPG plants (1-4 MWe) show a low capital investment, but display a high COE due to low electrical efficiencies (17-18%). This status will become worse especially at a high price of biomass feedstock. Therefore, small-scale BGPG plant is suitable for the case with low-cost biomass feedstock and difficulty in terms of raising funds. The power plants based on the gasification technology with gas engine /steam turbine combined cycle technology (scale ≥ 5MWe) can offer net electricity efficiencies near to about 28%, resulting in a low COE below 0.4 CNY/kWh, which is comparable to that of a coal fired plant. However, the medium-scale BGPG plant presents a high capital investment due to the complexity of the system compared to a small scale BGPG plant. As a result, the medium scale BGPG plant can be a candidate when investment capital is sufficient. Overall, the medium scale BGPG plant is superior to the small scale BGPG plant in the aspect of economic performance at a reasonable guaranteed price of 0.5 CNY/kWh [19]. Nevertheless, it is noted that the unit capital costs of the plants with the biomass gasification technology is in a range of 6500-7700 CNY/kW with capacity of 1-10 MWe, which is more than that of coal-fired power (about 5000 CNY/kW). In order to be competitive and stand in the market, much efforts should be still focused on technology development of BGPG to further reduce capital investment. The capital costs of straw BGPG plant with the capacity of 5 MWe is about 7650 CNY/kW, which is higher than that of a coal-fired power (CFP) plant (5000 CNY/kW) or a biomass direct combustion power (BDCP) plant (6000 CNY/kW) [6]. However, it should be noted that COE of BGPG plant is 0.402 CNY/kWh, which is comparable to that of a coal-fired power plant (0.40 CNY/kWh) and lower than that of a BDCP plant (0.574 CNY/kWh). Otherwise, straw BGPG plant can still present excellent economic performance at a current feed-in tariff (0.75 CNY/kWh) for biomass to power in China, implying that the power plant has big economic potential and market prospects. If the carbon tax is to be implemented in the future, straw BGPG power plant with low CO_2 emissions will present greater advantages in economy.

Table 3 Technical and economic performance with respect to power plants scale

Scale, MW	1	2	3	4	5	6	7	8	9	10
The total plant capital cost, $\times 10^4$ CNY	655	1129	1526	1939	3829	4431	5012	5577	6128	6667
O&M cost, $\times 10^4$ CNY/y	33	56	76	97	191	222	251	279	306	333
Labour No.	16	24	28	32	38	42	46	50	54	58
Labour cost, $\times 10^4$ CNY/y	80	120	140	160	190	210	230	250	270	290
Straw input, gt/y	10128	19962	29516	38800	30745	36894	43043	49193	55342	61491
Total straw cost, $\times 10^4$ CNY/y	284	559	826	1086	861	1033	1205	1377	1550	1722
The total variable cost, $\times 10^4$ CNY/y	396	735	1043	1343	1242	1465	1686	1906	2126	2345
Ash/char sale profit (200 CNY/t), $\times 10^4$ CNY/y	15.2	29.9	44.3	58.2	46.1	55.3	64.6	73.8	83.0	92.2
Gross electricity, MWe	1	2	3	4	5	6	7	8	9	10
Power consumption (10% of gross power output), MWe	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Net electricity, MWe	0.9	1.8	2.7	3.6	4.5	5.4	6.3	7.2	8.1	9
Net electricity efficiency, %	17.00	17.25	17.50	17.75	28.00	28.00	28.00	28.00	28.00	28.00
CO_2 emission, g/kWh	approximate zero									
SO_2 emission, g/kWh	4.22	4.16	4.10	4.04	2.54	2.54	2.54	2.54	2.54	2.54
NO_X emission, g/kWh	3.20	3.15	3.11	3.06	1.94	1.94	1.94	1.94	1.94	1.94
Dust emission, $\times 10^{-3}$ g/kWh	63.94	63.01	62.11	61.24	38.82	38.82	38.82	38.82	38.82	38.82
COE (i=0.08), CNY/kWh	0.565	0.518	0.486	0.468	0.402	0.392	0.385	0.379	0.374	0.370

4.2.2 Environmental sustainability

As for the straw to power processes, electric efficiency of straw BGPG plant and straw BDCP plant are 28 % and 19.5%, respectively, both of which are lower than that of coal-fired plant (37.5%). BGPG plant requires higher water consumption due to water scrubbing for tar removal. However, the other performance such as renewability and pollutants emission are superior to CFP process. Particularly, the renewability of CFP is 0, while that of straw to power processes are closer to 100%. Renewability is expressed as the mass ratio of feedstock from renewable resources to total main feedstock input [27]. Besides, the CO_2 emission per kWh for CFP is 917 g. In contrast, total-fuel-cycle CO_2 emissions of straw to power are closer to zero. This is due to the fact that all carbon in straw biomass is originally derived from CO_2 in the atmosphere, except for a small amount of conventional fuel consumed in production and transportation.

4.2.3 Social sustainability

The development of biomass to power can facilitate the reuse of agricultural residues. This could have a significant impact on the restructuring of agriculture and development of the local rural economy. Besides, for every investment of 1 MWe output, a straw BGPG plant will create about 9 jobs, and a BDCP plant will provide 8, while CFP plant is about 0.5 at an average level (the jobs is 80-120 for 300 MWe CFP plant, 100-150 for 600 MWe, 200-220 for 1000 MWe in China). The jobs for BGPG and BDCP is set according to the survey on the number of employee of 1-20 MWe biomass power plants, and the jobs of CFP plant is set based on the survey on the number of employee of CFP power plants (which were established in recent years (2015-2017)) with different scale. The purpose of making power from biomass is to partially replace coal-based power, diversifying China's energy supply, and therefore enhancing national security in energy. The indicator, energy security, is expressed as the ratio of expected capacity of biomass power to the total power demand. It is predicted that China's electricity demand will be 8000 billion kWh in 2020 [33], meaning that coal consumption and CO_2 emission will reach 2.8 and 21 billion tonnes, respectively. In order to reduce fossil energy electricity and CO_2 emission, the ratio of coal power to the total power demand will be required to reduce from 70% to 60%, and biomass power ratio will increase to 3% in 2020 according to "The 13th five-year" energy planning [33]. In fact, in China, the total biomass quantity (straw and forest resources) is about 1.8 billion tonnes per year [34]. About 40-60% of them can be used as biomass fuel, which could satisfy about 10% of the total electricity demand. However, the biomass use ratio is currently no more than 5%. The most important reason for the slow development of biomass power is inefficient technology leading to high cost and low energy utilization. BGPG could be an important alternative to coal power and provide a significant contribution in electricity production. However, conventional coal power would still dominate power production for a long period of time to come.

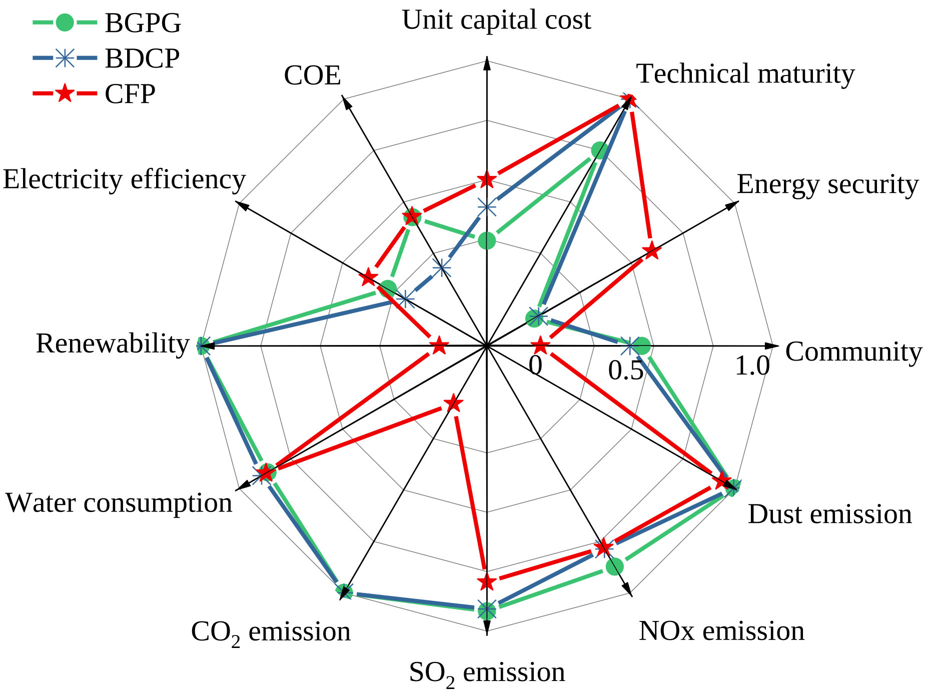
4.2.4 Technical sustainability

The indicator of technical maturity is referred to as the ability of the process to achieve its specific function. Only when the power generation technology from coal and biomass is mature and reliable it can be implemented and promoted on the commercial scale. On the basis of above classification, the technical maturity of straw BGPG plant, BDCP plant and coal power plant is 0.75, 1 and 1, respectively. Currently, the research in BGPG plant mainly focuses on gasifier improvement and a scale-up of the process.

The above mentioned four main indicators (economic, environmental, social and technical indicators) and corresponding sub-indicators for sustainability assessment are presented in **Table 4.** Each sub-indicator for coal-fired power plant is the average level in China nowadays[33]. The reference point for each indicator includes its best-case score and worst-case score. Different reference states are chosen as the worst and best scenarios according to the criteria obtained from literature reviews or definition of indicators. The results are also shown in a graphical manner in **Fig. 8**. Straw BGPG brings more environmental benefits in comparison to coal-fired power processes. However, it has some drawbacks, e.g. high water consumption, low energy efficiency and low energy security. Moreover, this technology is still immature and requires further studies. Finally, the conventional coal-fired process is still cost effective when compared to the straw to power processes due to lower unit capital cost, as well as higher energy efficiency and technical maturity, but it offers fewer jobs.

Table 4 Sustainability performance comparison between straw BGPG, BDCP and CFP.

Indicator (subindicator)	BGPG	BDCP[35, 36]	CFP[33]	Reference value	
				Best	Worst
Economic					
Unit capital cost, CNY/kW	7659	6150	5000	0	10000 [30]
COE, CNY/kWh	0.402	0.574	0.4	0	0.70 [30]
Environmental					
Electricity efficiency, %	28	19.5	37.5	100	0
Renewability, % [27]	100	100	0	100	0
Water consumption, kg/kWh [37, 38]	3.88	3.07	3.68	0	28.4 [39]
CO_2 emission, g/kWh	0	0	917	0	997 [40]
SO_2 emission, g/kWh	2.5	2.8	6.2	0	30.1 [40]
No_x emission, g/kWh	1.9	3.2	3.3	0	15.0 [40]
Dust emission, g/kWh	0.038	0.106	1.7	0	27.2 [40]
Social					
Community development, staff/MWe	9	8	0.5	20 [19]	0
Energy security, %[27]	3%	5%	60%	100%	0
Technical					
Technical maturity	0.75	1	1	1	0



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361 **Fig. 8 Sustainability evaluation of straw BGPG, BDCP and CFP.**

4.3 Potential of pollutants emissions reduction and coal saving from deployment of straw BGPG plant

Half of the crop residues come from east and central south of China, including Shandong province which is a major agricultural province with about 10% (about 88.3 million tonnes per year) of the total agricultural residues in China (shown in **Fig. 9**) [6]. The main agricultural products and agricultural residues in Shandong province are presented in **Table 4S** and **5S**. Although Shandong province is the second biggest agricultural province (Henan province is the biggest one), however, Henan province and Shandong province are adjacent provinces (similar geographic locations), and they have the same crops resources. Therefore, taking Shandong province as a case study can reflect the feasibility of crop resources utilization from an overall point of view. Currently, the total population of Shandong province is 96.9 million, and the rural population and urban population are 40.8 and 56.1 million, respectively [6]. Assuming that the per capita of electricity consumption is 1.2 kWh per day for one rural person, and the total electricity consumption per year for the total rural people is 17.9 billion kWh/y, which requires wheat/corn straw of 14.0 million tonnes per year for 453 BGPG plants with capacity of 5 MW. As can be seen in the **Table S5**, the total corn/wheat straw is 89 million tonnes per year, and only small parts of crop residues (20-40%) are used for forage and household energy, and the large parts (60-80%) are discarded or directly burnt in the field [1]. Therefore, all straw available is 53.0-71.2 million tonnes per year, which can afford the total rural electricity requirement.

Fig.10 shows the effects of straw gasification power replacing coal-fired power on pollutants emission and coal saving. Straw gasification power, replacing CFP, can effectively reduce the pollutants emission and coal consumption. In general, saving electricity of 1 kWh from coal-fired power can save 350 g standard coal, and reduce CO_2, SO_2, NO_x and dust emission by 0.872, 0.026, 0.013 and 0.238 kg [40], respectively. As a result, if the straw gasification power completely supplants local coal-fired power for affordable rural electricity, it will reduce CO_2, SO_2, NO_x and dust emission of 1.6×10^7, 4.6×10^5, 2.3×10^5 and 4.3×10^6 t/y tonnes per year, respectively, and save standard coal 6.2×10^6 tonnes per year in Shandong province. On the basis of this scenario, the deployment of straw BGPG plants in Shandong province according to the distribution of rural population and rural electricity consumption in each region is presented in **Fig. 11.**

The total rural population of the major agricultural residues provinces presented in the **Fig. 9** is 582 million in China [6]. Since the distribution of rural population is not consistent with the distribution of agricultural residues in different regions, not all the places are suitable for the distributed BGPG plant. As a result, a conservative preliminary estimate of the total agriculture residues used for distributed power generation in China can be obtained by the following assumption: (1) agricultural residues requirement for providing with 70% of the rural population electricity, regions with agricultural residues yield ≥ 60 million tonnes/yr; (2) agricultural residues requirement for providing with 50% of the rural population electricity, 30 million tonnes/yr < regions with agricultural residues yield < 60 million tonnes/yr; (3) agricultural residues requirement for providing with 30% of the rural population electricity, regions with agricultural residues yield ≤ 30 million tonnes/yr. Therefore, the total consumption of agricultural residues is estimated about 100 million tonnes per year, which results in emissions reduction of CO_2, SO_2, NO_x and dust at 102.2, 3.0, 1.5 and 27.9 million tonnes per year, respectively, and standard coal saving 4.1×10^7 t/y.

This study provided available models and methods to evaluate the feasibility of agricultural residues resources gasification to power in China. Due to different type biomass leading to different biomass cost (such as biomass production, collection, transportation and storage cost) in different areas or countries, so the optimal scale for biomass gasification power plant and performance may be different from the results of this study, while these results can be a guide or reference to biomass resources utilization of other countries. More importantly, the general models and methods can be extrapolated to evaluate the feasibility of most of biomass resources (such as wood biomass, and agricultural residues biomass etc.) utilization in different countries.

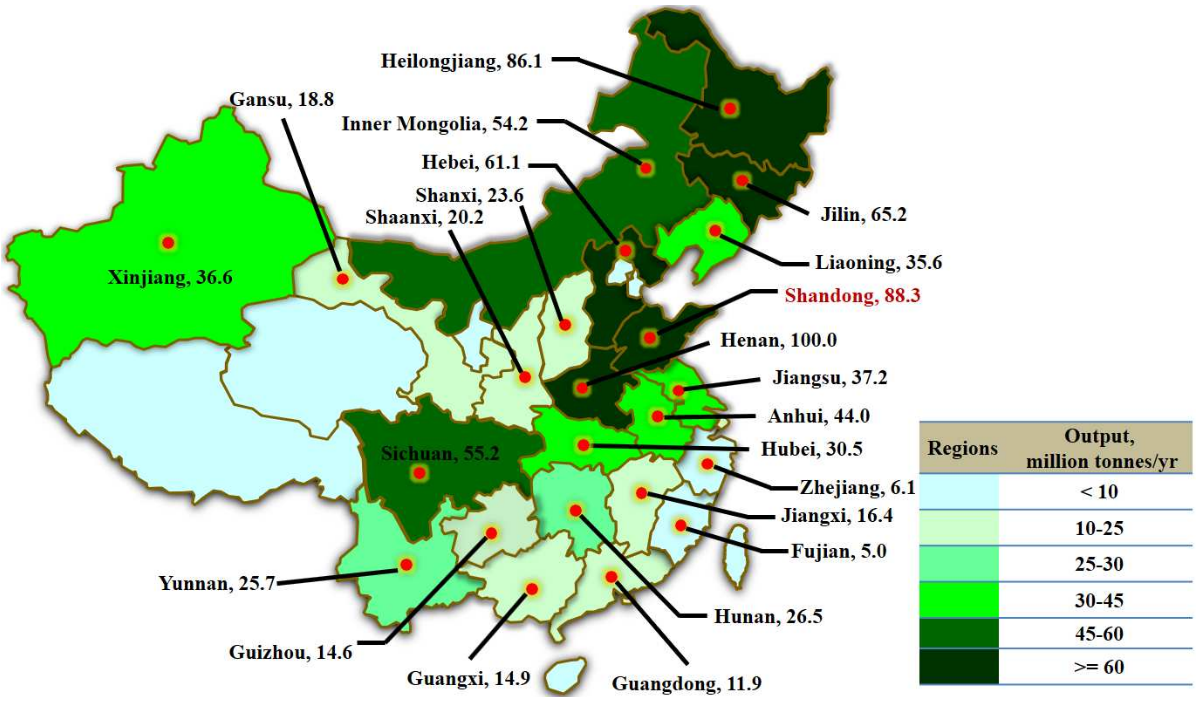


Fig. 9 Distribution of agricultural residues in China

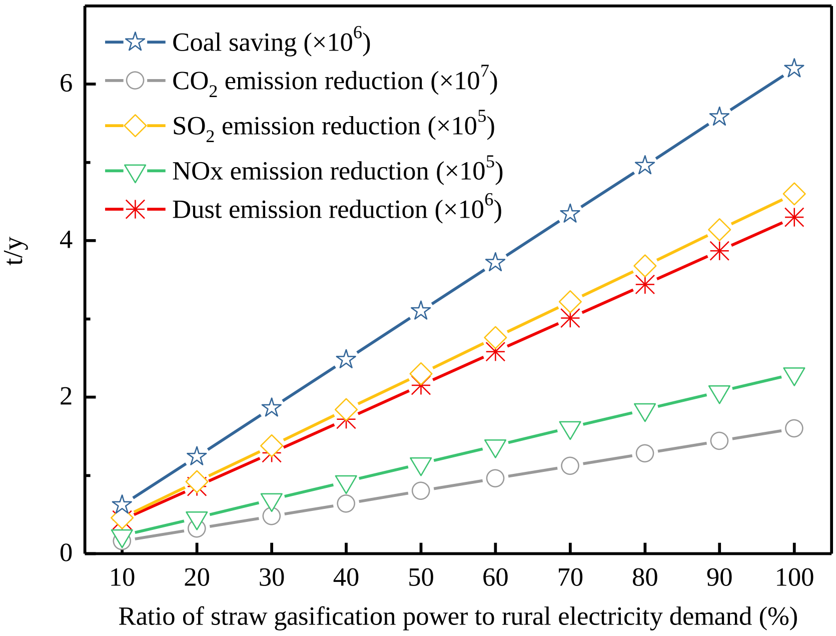
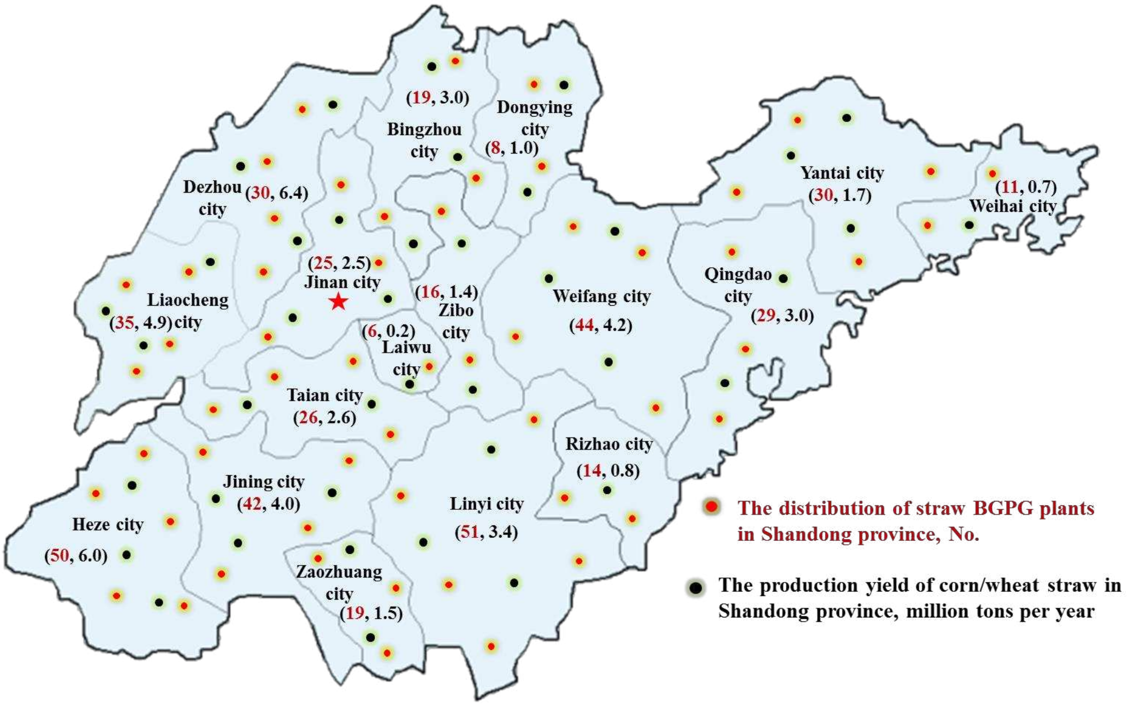


Fig. 10 Impact of straw gasification to power on pollutants emission and coal saving



District	Rural population	Electricity consumption	Wheat/corn straw consumption	Straw BGPG plant	Pollutants emission reduction			
	× 10^4	billion kWh/y	× 10^4 gt/y	NO.	CO_2	SO_2	NOx	dust
						× 10^4 t/y		
Jinan city	220.9	0.97	75.5	25	84.4	2.5	1.3	23.0
Qingdao city	262.0	1.15	89.5	29	100.1	3.0	1.5	27.3
Zibo city	144.8	0.63	49.5	16	55.3	1.6	0.8	15.1
Zaozhuang city	174.4	0.76	59.6	19	66.6	2.0	1.0	18.2
Dongying city	71.1	0.31	24.3	8	27.2	0.8	0.4	7.4
Yantai city	267.7	1.17	91.4	30	102.2	3.0	1.5	27.9
Weifang city	391.6	1.72	133.8	44	149.6	4.5	2.2	40.8
Jining city	373.9	1.64	127.7	42	142.8	4.3	2.1	39.0
Taian city	230.8	1.01	78.8	26	88.2	2.6	1.3	24.1
Weihai city	98.7	0.43	33.7	11	37.7	1.1	0.6	10.3
Rizhao city	125.2	0.55	42.8	14	47.8	1.4	0.7	13.1
Laiwu city	53.5	0.23	18.3	6	20.4	0.6	0.3	5.6
Linyi city	461.2	2.02	157.6	51	176.1	5.3	2.6	48.1
Dezhou city	267.8	1.17	91.5	30	102.3	3.0	1.5	27.9
Liaocheng city	311.0	1.36	106.2	35	118.8	3.5	1.8	32.4
Bingzhou city	168.0	0.74	57.4	19	64.2	1.9	1.0	17.5
Heze city	453.9	1.99	155.1	50	173.4	5.2	2.6	47.3

Fig. 11 The deployment of crop straw BGPG plants in Shandong province[6].

5. Conclusions

The analysis of techno-economic feasibility of the distributed power plant from agricultural straw via biomass gasification power generation technology in China showed that the plant size of 5 MW, with COE of 0.402 CNY/kWh, was an optimal option for distributed generation. The straw BGPG plant can show an excellent market competitiveness at a low operating rate (5000-6000 hrs/y), high feedstock cost (below 300-500 CNY/t) and low electricity price (0.5 CNY/kWh). By the aid of sustainability analysis, the straw BGPG is comparable to the CFP (0.4 CNY/kWh) in the aspect of COE, but also presents strong sustainability. It is estimated that the pollutants emission and renewability of the straw BGPG is obviously superior to CFP.

The case study shows that the straw BGPG deployment displacing coal-fired power to supply electricity with rural area in Shandong province can effectively reduce coal consumption by 6.2×10^6 t/y, and the CO_2, SO_2, NO_x and dust emission by 1.6×10^7, 4.6×10^5, 2.3×10^5 and 4.3×10^6 t/y, respectively. The conservative estimation indicates that agricultural residues gasification to distributed power generation in China will contribute to reduction of CO_2, SO_2, NOx and dust emissions at 102.2, 3.0, 1.5 and 27.9 million tonnes per year, respectively, and save standard coal 4.1×107 t/y. All this suggests that distributed power generation from biomass gasification as a sustainable technique will probably have promising prospects for utilization of agricultural residues in China. Nevertheless, since the capital investment and electric efficiency of BGPG are 7659 CNY/kW and 28%, which can not be comparable to those of CFP (5000 CNY/kW and 37.5%), much efforts still needed to be focused on the technology upgrading of BGPG to reduce capital investment and enhance electric efficiency thus to increase its competitiveness.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (51776133); Shanxi Province Outstanding Youth Natural Science Foundation (201601D201004); program for the Outstanding Innovative Teams of Higher Learning Institutions of Shanxi; and The University of Sheffield for hosting the Fellowship.

Nomenclature

Capital Letters

C = the capital cost of power plant

$C_{collecting}$ = straw collecting cost

$C_{delivery}$ = the total cost of straw

$C_{production}$= straw production cost

C_r = the capital cost of the reference plant

C_t = net cash flows of the year t

C_{tr} = biomass unit transport rate

$C_{transport}$ = straw road transport cost

$C_{storage\ =}$ straw storage cost

L = the transport distance

NOx = nitrogen oxide

P = the processing capacity of the plant in dry tonnes per day

S = the scale of proposed plant

S_{bp} = the revenues from by product

SOx = sulphur dioxide

$S_{r\ =}$ the scale of the reference plant

X_{ij} = the normalized indicator j for process i

Lowercase Letters

ad = air dry basis

daf = dry ash free basis

db = dry basis

gt = green tonne

ha = hectare i = the discount rate

lc = land coverage of straw planting

m= straw productivity

r_b = transport distance (one way)

t = tonne

x_{ij} = the indicator j for process i

x_j = the assumed case of indicator jy = year

τ = the tortuosity factor, 1.5

ω = the straw moisture content (%).

Greek Letters

α = the scale exponent

τ = tortuosity factor

ω = straw moisture content

Acronyms

BGPG = biomass gasification power generation technology

BDCP = biomass direct combustion power

BIGCC = biomass integrated gasification combined cycle

CFP = coal-fired power

CNY = Chinese Yuan, 1 US dollar = 6.5 CNY

COE = cost of electricity

CRF = capital recovery factor

DCF = discounted cash flow

FETI = Fuels and Energy Technology Institute

FUE = fertilizer use efficiency

GIEC-CAS = Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences

HHV = high heat value

HRSG = heat recover steam generator

ICE = internal combustion engine

LHV= low heat value

M = million

MW = million watt

NPV = net present value

O&M = operation & maintenance

ROI = the annual average of return on investment

TPC = the total plant capital cost

TR = tax rate

TVC = the total variable cost

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