https://doi.org/10.1016/j.jclepro.2020.122890

Sustainability assessment of straw direct combustion power generation in China: from the environmental and economic perspectives of straw substitute to coal

Zhanwu Wang[a], Zhenfeng Wang[a], Guangyin Xu[a*], Jingzheng Ren[b*], Heng Wang[a], Jin Li[a]

[a] College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou, Henan Province, China

[b] Department of Industrial and Systems Engineering, Hong Kong Polytechnic University, Hong Kong SAR, China

Corresponding author: College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou, Henan Province, China

Email: xgy4175@henau.edu.cn

Email: renjingzheng123321@163.com; jzhren@polyu.edu.hk (J.Z. Ren)

Abstract: Straw power generation (SPG) can not only reduce dependence on coal, but also can convert agricultural waste into energy and alleviate environmental pollution. In order to address the major challenges such as sustainability of the SPG and to provide scientific ground from environmental and economic perspectives, a sustainability assessment model was established to evaluate the performance of SPG. Life cycle assessment (LCA), life-cycle cost (LCC) and the best-worst method (BWM) were integrated in the model. Four SPG scenarios were studied. The results showed that straw alternative coal-fired power generation had weak economic sustainability, the ratio of benefit to cost of SPG was 0.8752 to 1.1866. While, for the environmental dimension, a strong sustainability was obtained, the greenhouse gas (GHG) abatement potential of -0.8903 t CO_2-eq t^{-1} straw. The findings obtained from the four SPG scenarios suggested that direct combustion SPG had great sustainability potential in China, and several factors such as straw supply chain model, pollutant treatment technology, transport vehicles and straw purchase cost were the main factors which lead to unfavorable economic performance. We suggest that the SPG schemes, transport models and financial subsidies should be carefully designed to improve the sustainability of straw power generation.

Keywords: Direct Combustion Straw Power Generation; Sustainability; Life Cycle Assessment; Best-worst Method; Straw Supply Chain.

1 Introduction

The gap between energy supply and demand is becoming increasingly prominent worldwide. Moreover, environmental and energy security issues are becoming more and more serious. In China, 70% - 80% of the electricity comes from thermal power generation and the main fuel is coal (NSBC, 2018). With the development of renewable energy, the proportion of coal-based power generation has decreased year by year. In 2016, it was decreased by 33.476 million tons of coal compared with 2015 (NSBC, 2018). China is one of the largest agricultural countries with abundant biomass resources. As a renewable and clean resources, biomass can be substituted for traditional fossil fuels. The utilization of crop straw was 720 million tons in 2015, where 390 million tons (43.2%), 170 million tons (18.8%), 20 million tons (2.7%), 40 million tons (4%), and 100 million tons (11.4%) of total straw biomass has been utilized as fertilizer utilization, feedstuff utilization, raw material utilization, straw base stock utilization, and energy utilization, respectively (NDRC, 2015). China's 13th five-year plan for renewable energy development clearly indicates that the proportion of renewable energy consumption in China will be 20% in 2030 (NDRC, 2016). Thus, the utilization of straw for energy production has tremendous development space.

Biomass can replace coal for power generation and alleviate environmental pollution (Wen and Zhang, 2015). The developed countries in Europe, represented by France, Britain and Germany, have set clear targets and road maps for coal-fired power reduction, with plans to phase out all coal-fired power generation by 2022, 2025 and 2050, respectively, and to convert coal-fired power plants into biomass plants (Shi et al., 2017). At present, the UK is implementing the project of transformation coal-fired power stations into biomass power station, in which the installed capacity and power generation capacity of biomass power generation increased by 12% and 27% respectively in 2015; the coal consumption of Denmark decreased by nearly 60% from 2000 to 2015, while the biomass energy consumption of agriculture and forestry increased by 100% in the same period, and the coal-fired power plants in Denmark have been gradually transformed into biomass power plants (Shi et al., 2017). China is also gradually reducing the proportion of coal-fired power generation and encouraging the use of biomass to replace coal-fired power generation. Increasing biomass power generations have been constructed with a total installed capacity of 21.16 million KW by 2019 (NEA, 2019). However, compared with developed countries, biomass power generation started late and developed slowly in China. What's more, there is a lack of clear understanding of biomass to replace coal-fired power generation, which also faces the following problems: Ⅰ Is the environmental and economic benefits of biomass direct combustion power generation better than coal-fired power generation? Ⅱ There are many schemes of biomass direct combustion power generation, but which one is the best? Ⅲ How about the sustainability of biomass direct combustion power generation?

It is widely known that the open burning of agricultural residue emits a large amount of pollutants. Sun et al. (2016) showed that about 2707.34 Tg of CO_2 was emitted by agriculture residue in open burning from 1996 to 2013. Wang et al. (2018) showed that the average annual biomass burning emissions in China from 2000 to 2012 lead to emission of 880.66 Mt for CO_2, 96.59 Mt CO_2-eq for CH_4, and 16.81 Mt CO_2-eq for N_2O. Straw power generation can provide clean energy and solve the pollution problem caused by burning agricultural waste directly in the field (Wen and Zhang, 2015). Straw power generation can not only reduce the use of fossil fuels, but also increases the value of agricultural waste (Wang et al., 2017). There has been a lot of research on biomass power generation. Zhao and Yan (2012) used SWOT analysis method to assess the biomass power generation industry in China. Zhang et al. (2016) developed a real options model for evaluating the biomass power generation investment in China. Wang et al. (2015) studied direct combustion power generation of biomass. Shafie et al. (2013) studied the economic feasibility of rice straw co-firing at coal power plants. Wu et al. (2017) conducted risk assessment on the public-private joint venture project of straw power generation (SPG) in China. Rountree (2019) pointed out that renewable-based electricity was yet to become a competitive alternative to fossil fuel-based electricity. While, the SPG industry is still lack of advanced development in comparison to other types of renewable energy, such as wind and solar energy, mostly due to the high collection cost of biomass (Cao et al., 2016). An efficient supply chain system can reduce transport costs, ensure the sustainable supply of straw, and promote the development of straw power generation enterprises. However, due to the many special characteristics such as small scale and scattered planting in China, it is difficult to implement the straw supply chain system. The transport costs can be reduced by optimizing the supply chain system (Ebadian et al., 2013). Ng and Maravelias (2017) analyzed the impact of straw transportation volume and distance. Golecha and Gan

(2016) studied the relationship between biomass transport costs and fuel productivity. Obviously, reducing the transport cost of straw is an urgent problem to be solved.

Constructing a sustainable straw power generation system is in line with China's development strategy. A set of criteria to assess the sustainability is needed before the construction of the straw power plants. Nishiguchi and Tabata (2016) conducted economic and environmental assessments of wood biomass energy. Kylili et al. (2016) conducted environmental assessment of transportation and processing mechanisms of biomass granulation. Wang et al. (2017) developed an uncertain comprehensive multi-attribute evaluation method to evaluate the biomass poly-generation system. However, reports on detailed assessment methods about straw power generation projects are still missing. To our knowledge, in most of studies about straw utilization, the authors have only considered one indicator. Song et al. (2017) studied the economics of straw pellet fuel. Wang et al. (2017) studied life cycle environmental impacts of straw briquette fuel utilization. Giorio et al. (2019) measured the main emissions from the energy conversion of pruning residues in vineyards and conducted an environmental assessment. Wang et al. (2018) evaluated straw utilization from views of regional energy, environment and socioeconomic benefits. However, there are few studies on SPG.

Sustainability refers to a process or state that can be maintained for a long time, environmental and economic performances are the main factors which affect the sustainability (Sala et al., 2015). In the sustainability study of biomass energy utilization, there have mature evaluation methods for different evaluation indicators. Life cycle assessment (LCA) is the main method for environmental assessment. Giuntoli et al. (2013) adopted the LCA method to study the environmental impacts of power generation from wheat straw bales and pellets. Wang et al. (2017) studied the environmental impact of straw briquette fuel by LCA. Life cycle cost (LCC) is one of the main methods for evaluating economic indicators. Ren et al. (2015) used the LCC method to optimize the cost of the biomass supply chain. Sun et al. (2017) carried out an economic evaluation of straw storage and transportation system. Best-worst method (BWM) is often utilized to determine the weight of indicators. Wang et al. (2019) used BWM to rank the risk factors and studied energy performance contracting system. It can be seen that these methods have been widely applied in different fields.

Given that there is no detailed sustainability study on direct combustion SPG in China. Hence, we integrated the LCA, LCC and BWM methods to develop a sustainability assessment model of straw power generation from environmental and economic perspectives. The objective is to evaluate the sustainability of straw direct combustion power generation in China, and to determine the main factors affecting straw power generation.

2 Methods

In this section, a methodological framework for sustainability assessment of direct combustion SPG systems is presented. It can be summarized to four steps: (1) BWM for determining the weights of the criteria, (2) life cycle environmental assessment, (3) life cycle economic assessment, (4) sustainability assessment model. The methodological framework of this study is presented in Fig. 1.

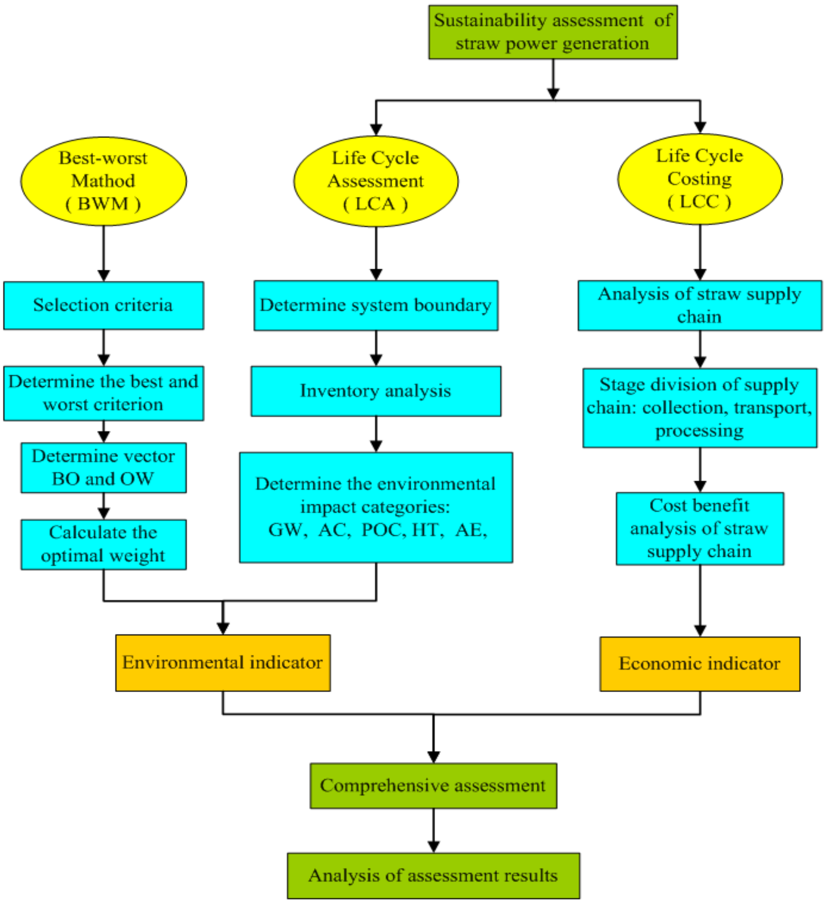

Fig. 1. The methodological framework of this study

2.1 Best-worst method

In decision making problems, the accuracy of the weights of the criteria have significant impacts on the decision result which make determination of weight more crucial. Rezaei (2015) proposed a new method, so-called Best-worst-method (BWM), to determine the weight. Compared with other methods (e.g. Analytic Hierarchy Process), BWM has two main advantages: (1) BWM needs less pairwise comparisons and is easy for operations; (2) BWM can effectively determine the weight of the criteria according to the opinions and preferences of decision makers with higher consistency (Liao et al., 2019). The BWM method had been widely used in various fields, e.g.

supplier selection (Rezaei et al., 2016), sustainable evaluation of gasoline supply chain (Wan Ahmad et al., 2017), selection of biomass energy conversion technology (Van de Kaa et al., 2017). Ren (2018) studied the multi stakeholders system combined best-worst method to select the ballast water treatment technology. The specific steps of BWM as follows (Rezaei, 2015):

Step 1: Build a set of decision criteria.

Decision makers usually make decisions by selecting the main criteria in complex decision-making problems. Suppose the decision makers select n criteria, which can be expressed as $(k_1, k_2, \cdots, k_n)$.

Step 2: Determine the best and worst criteria.

The decision makers determine the best criterion (e.g. the most superior, the most important, or most preferred) and the worst criterion (e.g. the least superior, the least important, or the least preferred), and marks them as k_B and k_W, respectively.

Step 3: Determine vector BO (Best-to-Others).

In this step, selection of number between 1 and 9 represents the preference of the best criterion over all the other criteria. Best-to-Others vector can be obtained: $\mathrm{BO} = (a_{B1}, a_{B2} \cdots, a_{Bn})$, a_{Bj} indicates the preference of the best criterion k_B over criterion k_j. It is clear that $a_{BB} = 1$.

Step 4: Determine vector OW (Others-to-Worst).

Similar to the above step, selection of number between 1 and 9 represents the preference of all the other criteria over the worst criterion. Others-to-Worst vector can be obtained: $\mathrm{OW} = (a_{1W}, a_{2W}, \cdots, a_{nW})^T$, a_{jW} indicates the preference of the criterion k_j over the worst criterion k_W. It is clear that $a_{WW} = 1$.

Step 5: Calculate the optimal weight（$\omega_1^*, \omega_2^*, \dots, \omega_n^*$）

For each pair of ω_B/ω_j and ω_j/ω_W, we set $\omega_B/\omega_j = a_{Bj}$ and $\omega_j/\omega_W = a_{jW}$. To satisfy these conditions for all j, we can find a result ξ that satisfies Eq. (1).

$$\xi = \min \max_{j} \left\{ \left| \frac{\omega_B}{\omega_j} - a_{Bj} \right|, \left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \right\} \quad (1)$$

Considering the nonnegative of the weight, Eq. (1) can be converted into Eq. (2).

$$\begin{gathered} \min \max_{j} \left\{ \left| \frac{\omega_B}{\omega_j} - a_{Bj} \right|, \left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \right\} \\ s.t. \\ \sum_j \omega_j = 1 \\ \omega_j \geq 0, j = 1,2,\cdots,n \end{gathered} \quad (2)$$

Eq. (2) can be converted into the following problem, which is more conducive to solving the weight.

$$\begin{gathered} \min \xi \\ \mathrm{s.t.} \\ \left| \frac{\omega_B}{\omega_j} - a_{Bj} \right| \leq \xi \\ \left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \leq \xi \\ \sum_j \omega_j = 1 \\ \omega_j \geq 0, j = 1,2,\cdots,n \end{gathered} \quad (3)$$

By solving Eq. (3), the optimal weight can be obtained $\omega_1^*, \omega_2^*, \cdots, \omega_n^*$, as well as the value of ξ^*.

Step 6: Consistency check

The consistency ratio (CR) is effective index which reflects the degree of consistency in preference relation. It can be calculated by Eq. (4).

$$\mathrm{CR} = \frac{\xi^*}{\mathrm{CI}} \quad (4)$$

where, CI is consistency index (Rezaei, 2015). The value of CI can be found in Table 1. CR stands for consistency ratio, $\mathrm{CR} \in [0,1]$, $\mathrm{CR} \to 0$ indicates greater consistency, and $\mathrm{CR} \to 1$ indicates less consistency (Rezaei, 2015; Wu et al., 2019).

Table 1. Consistency index (CI) table (Rezaei, 2015)

a_{BW}	1	2	3	4	5	6	7	8	9
CI (max ξ)	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

2.2 Life cycle environmental assessment

Life cycle assessment (LCA) outlined by (ISO, 2006) had been widely employed to evaluate the environmental impact of a product's life from raw material acquisition, production, use and disposal. Ren et al. (2014) studied the life-cycle energy efficiency of biomass fuels. The LCA method has four main steps: (1) target and system boundary, (2) life cycle inventory, (3) impact assessment, (4) life cycle interpretation.

As the SPG system is complex, the following assumptions should be made in the modeling process:

(1) Environmental impact of infrastructure is not considered.

(2) The supply of straw is sufficient and straw supply chain is coordinated.

(3) During the straw collection process, part of the straw has been reserved for returning to the field.

2.2.1 Target and system boundary

In the present study, we have used corn straw for power generation as an example to illustrate the developed model. The goal was to assess the environmental impact of the straw power generation and to carry out sustainability assessment by calculate the environmental indicator. The life cycle of straw can be divided into three parts: planting stage, transportation and burning. However, the differences in pretreatment (baling, briquetting and granulation), storage and transportation modes caused diversity of the straw supply. The boundary division of the straw power generation system is shown in Fig. 2.

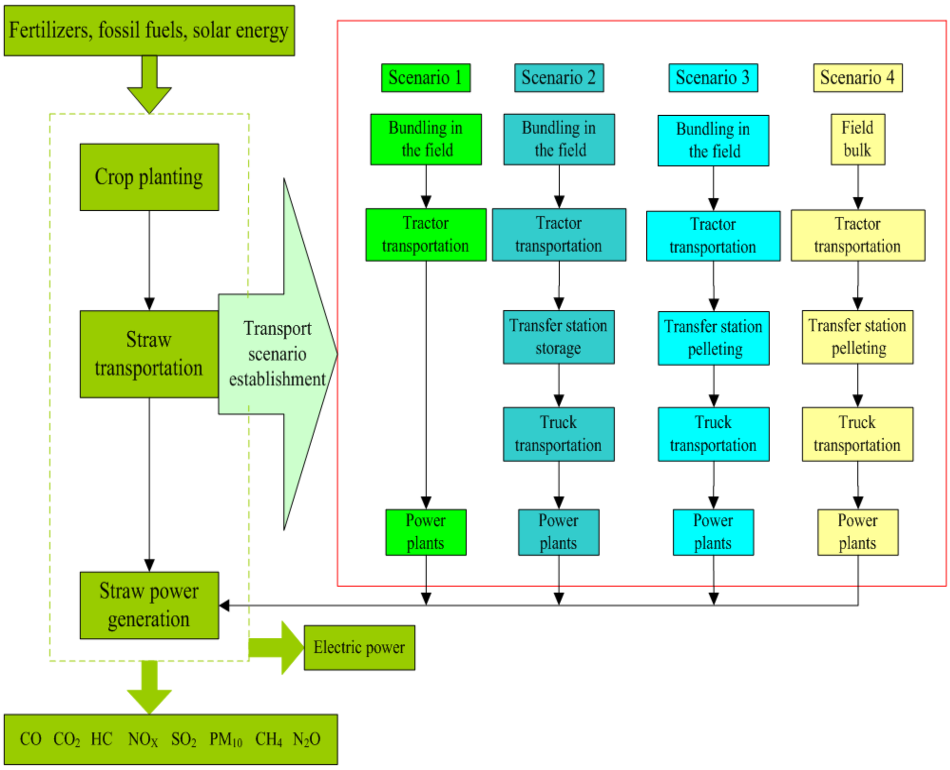

Fig. 2. System boundary of straw power generation system

2.2.2 Life cycle inventory analysis

The second step of the LCA is inventory analysis.

(1) Stage of planting

Straw is the by-product of agricultural cultivation and also called agricultural waste. Xia et al. (2012) provided a calculation of the pollutant emissions during the corn straw planting stage. The pollutant emission coefficient as shown in Table 2.

Table 2. Pollutant emission coefficient of corn straw at planting stage（g/t）

	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O	Reference
Coefficient	84860	46.31	101.35	/	87.43	9.22	186.12	1.44	Xia et al. (2012)

The amount of pollutant emissions during the planting stage can be calculated by using Eq. (5).

$$Q_i^P = Q_{\mathrm{straw}} \times \partial_i \quad (5)$$

where, Q_i^P represents the i-th pollutant emission in the straw planting stage, Q_{straw} represents the amount of straw collected, and ∂_i is the emission coefficient of the i-th pollutant.

(2) Stage of transport

Straw transport consists of the process of baling, transport and granulation. Transport vehicles emit pollutants when burning diesel. Different transport vehicles were used at different times. The emission coefficient of diesel combustion as shown in Table 3.

Table 3. Emission coefficient of diesel combustion (g/L)

	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O	Reference
Baling machine	2616.637	14.995	34.988	4.598	0.588	5.199	0.149	0.068	Wang (2017)
Tractor	2664.456	17.054	44.400	4.440	0.576	1.486	0.151	0.074	Hu et al. (2014)
Truck	2616.637	14.995	34.988	4.598	0.588	0.199	0.149	0.068	Wang (2017)

The pollutant emission in the transport stage can be calculated by using Eq. (6).

$$Q_{ji} = K_j \times \varphi_{ji} \quad (6)$$

where, Q_{ji} represents the emission of the i-th pollutant from the j-th vehicle at the transportation stage, K_j is the amount of diesel used in the j-th vehicle, and φ_{ji} represents the emission coefficient of the i-th pollutant from the j-th vehicle.

(3) Stage of straw burning

Straw is a kind of cleaner energy. The emission of CO_2 from combustion is equal to that from straw planting. Therefore, the emission of CO_2 from straw combustion was not calculated herein. The other pollutant emission coefficients are shown in Table 4.

Table 4. Emission coefficients of pollutants from straw burning

	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O	Reference

Value (g/kg)	/	0.198	0.217	/	0.034	0.197	0.033	0.960	(Hong et al., 2016; Hu et al., 2014; Wang et al., 2017)

The amount of pollutant emission from the power generation stage can be calculated by using Eq. (7).

$$Q_i^b = Q_{\mathrm{straw}} \times \vartheta_i \tag{7}$$

where, Q_i^b represents emissions of pollutants in the straw burning stage, Q_{straw} is the amount of straw burning, and ϑ_i is the emission coefficient of pollutants from straw burning.

2.2.3 Calculation of environmental indicator

The discharge of pollutants can create different environmental problems, e.g. CO_2, CH_4, NO_X and N_2O emissions caused global warming (GW). Present work is focused on well-known existing environmental pollution categories, such as global warming (GW), acidification (AC), photochemical oxidation (POC), human toxicity (HT), and aerosol (AE) (Valente et al., 2017; Ren et al., 2018).

The environmental indicator is the ratio of the environmental impact value of using fossil fuels to the use of biomass fuels (Xia et al., 2012). It can be calculated in five steps as follows.

Step 1: Characterization calculation (Ou et al., 2011)

$$EP(j) = \sum_{i=1}^{n} Q(j)_i \times EF(j)_i \tag{8}$$

where, $EP(j)$ represents the characteristic results of the j-th environmental impact category, $Q(j)_i$ is the emission amount of the i-th pollutant, and $EF(j)_i$ is the equivalent coefficient of the i-th pollutant.

Step 2: Data standardization (Wang et al., 2017).

$$N_j = EP(j)/S(j) \tag{9}$$

where, N_j is the standardized results of the j-th environmental impact category,

$EP(j)$ is the characteristic results, and $S(j)$ is the standardized reference value.

Step 3: Determination of weight.

During the process of environmental impact assessment, weight represents the degree of different impact types on the total target. We chose the Best-worst method to calculate the weight, as described in section 2.1.

Step 4: Calculate the environmental impact potential (Xia et al., 2012).

$$EIP = \omega_j \times N_j \tag{10}$$

where, EIP represents the environmental impact potential, ω_j is the weight of the j-th impact category, and N_j is the standardized results of the j-th environmental impact category.

Step 5: Calculate the environmental indicator (Xia et al., 2012).

By calculating the environmental potential of different fuels, the environmental indicator can be calculated using Eq. (11).

$$E_1 = EIP_{\text{coal}}/EIP_{\text{straw}} \tag{11}$$

where, E_1 is the results of the environmental indicator, EIP_{coal} is the environmental impact potential of coal-fired power generation, and EIP_{straw} is the environmental impact potential of straw-fired power generation.

2.3 Life cycle economic assessment

2.3.1 Collection cost

There are two main pathways to collect straw in China: manual collection and mechanical collection, thus, cost can also be calculated through two different methods.

1. Manual collection cost

It was found that the density of manually collected straw was 40 kg/m^3. The cost of manual collection can be calculated using Eq. (12).

$$C_{\text{collp}} = (P_1/q_{\text{pe}} + p_0) \times Q_{\text{straw}} \quad (12)$$

where, C_{collp} represents the cost of manual collection, P_1 is the daily wage of workers, q_{pe} is the amount of straw that each worker can collect per day, p_0 is the purchase price of straw, and Q_{straw} is the amount of straw collected.

2. Mechanical collection cost

This paper investigates the 9YFK-3043A square baling machine produced by Huaxi-Yutian enterprise, which can shape the straw into square baling with length of 1.2 m, width of 0.3 m, height of 0.43 m and weight of 20 kg. It can collect 32 tons of straw per day with a fuel consumption of 7.5 L/ha. The cost of mechanical collection can be calculated using Eq. (13).

$$C_{\text{collm}} = ((P_2 + C_{\text{de1}} + C_{m1} + C_{f1})/q_{b1} + p_0) \times Q_{\text{straw}} \quad (13)$$

where, C_{collm} represents the cost of mechanical collection, P_2 is the daily salary of the mechanical driver, C_{de1} is the depreciation cost of the baling machine, C_{m1} is the maintenance cost, C_{f1} is the fuel cost, q_{b1} is the baling quantity, p_0 is the purchase price of straw, and Q_{straw} is the amount of straw collected.

2.3.2 Primary transport cost

The straw must be transported to the storage place after balling in the field. Small tractors are the main means of transportation from the field to the transfer station. Transportation cost can be calculated using Eq. (14).

$$C_{\text{tr}} = C_p + C_{f2} + C_{\text{de2}} + C_{m2} + C_u \quad (14)$$

$$C_{f2} = q_s \times Q_{\text{straw}} \times L_1/\rho \times P_3 \quad (15)$$

where, C_{tr} is the transportation cost from field to transfer station, C_p is the labor cost, C_{f2} is the fuel cost, L_1 is the distance between field and transfer station, q_s is the unit fuel consumption of straw transported by the tractor, ρ is the density of diesel, P_3

is the price of diesel, C_{de2} is the depreciation cost of the transport tool, C_{m2} is the maintenance cost and C_u is the handling cost.

2.3.3 Storage cost

Straw cannot be converted in a short time after collection. To ensure the quality of straw, it is necessary to establish a storage center for short-term storage. Storage cost can be calculated using Eq. (16).

$$C_{\mathrm{st}} = \mathrm{A} \times P_4 + P_5 \times Q_{\mathrm{straw}} + C_{\mathrm{s}} \quad (16)$$

$$\mathrm{A} = Q_{\mathrm{straw}}/h_0 \emptyset_0 \rho_1 \times 10^{-4} \quad (17)$$

where, C_{st} is the storage cost, A is the effective storage area, P_4 is the rental price of land, P_5 is the management cost of unit straw, h_0 is the straw storage height, $\emptyset_0$ is the straw occupancy coefficient, ρ_1 is the straw density and C_{s} is the stacking cost of straw.

2.3.4 Processing cost

The processing of straw briquetting mainly includes crushing, drying, transportation, compression, and cooling and quality inspection. The processing cost can be calculated using Eq. (18).

$$C_{\mathrm{pr}} = (C_{\mathrm{pe2}} + C_g + C_{\mathrm{ele}} + C_{\mathrm{de3}} + C_{m3}) \times Q_{\mathrm{straw}} \quad (18)$$

$$C_{\mathrm{ele}} = P_6 \times E \quad (19)$$

where, C_{pr} is the processing cost of straw, C_{pe2} is the labor cost of the unit production, C_g is the operational cost of the feeding machine, C_{de3} is the depreciation cost of production, C_{m3} is the maintenance cost of production, C_{ele} is the electricity cost, E is the power consumption of the unit production and P_6 is the electricity price for agricultural production.

2.3.5 Secondary transport cost

In this stage, straw is transferred from the storage area to the power plant. The method of transport used in this stage is the large logistic truck. The calculation method of transport costs refers to the primary transport in section 2.3.2.

2.3.6 Burning cost

Being end-user of straw, power plants must pay a certain cost for its operational process. The cost of the biomass power plant mainly consists of operation, power generation and pollutant treatment costs. The operation cost mainly includes human resource, management and financial costs. Power generation costs include straw processing, equipment depreciation and maintenance costs. The operating cost of the power plant can be calculated using Eq. (20).

$$C_{\mathrm{op}} = C_1 + C_2 + C_3 + C_4 + C_5 \tag{20}$$

where C_{op} represents the total cost of straw power generation, C_1 is the operation cost, C_2 is the depreciation cost, C_3 is the maintenance cost, C_4 is the straw pretreatment cost and C_5 represents the pollutant treatment cost.

2.3.7 Calculation of economic indicator

The economic indicator refers to the ratio of the benefit of straw power generation to the cost. Benefit mainly derive from the sale of electricity. The price of electricity purchased by the Chinese government is 0.75 Yuan/KWh. The cost of power generation mainly includes the raw material, collection, transport, processing and burning costs. The economic indicator can be calculated using Eq. (21).

$$E_2 = W_1 / C_{\mathrm{straw}} \tag{21}$$

$$W_1 = q \times p \tag{22}$$

$$C_{\mathrm{straw}} = C_{\mathrm{coll}} + C_{\mathrm{tr}} + C_{\mathrm{st}} + C_{\mathrm{pr}} + C_{\mathrm{op}} \tag{23}$$

where, E_2 is the economic indicator of the straw power generation, W_1 is the benefit of straw power generation, C_{straw} is the total cost of power generation, q is the quantity of power generation, and p is the government electricity purchase price.

2.4 Sustainability assessment modeling

By analyzing the environmental and economic data, relevant environmental and economic indicators can be determined. In order to understand intuitive sustainability of SPG, the environmental indicator as the X-axis and the economic indicator as the Y-axis were used to construct the sustainability discriminant graph, as shown in Fig. 3.

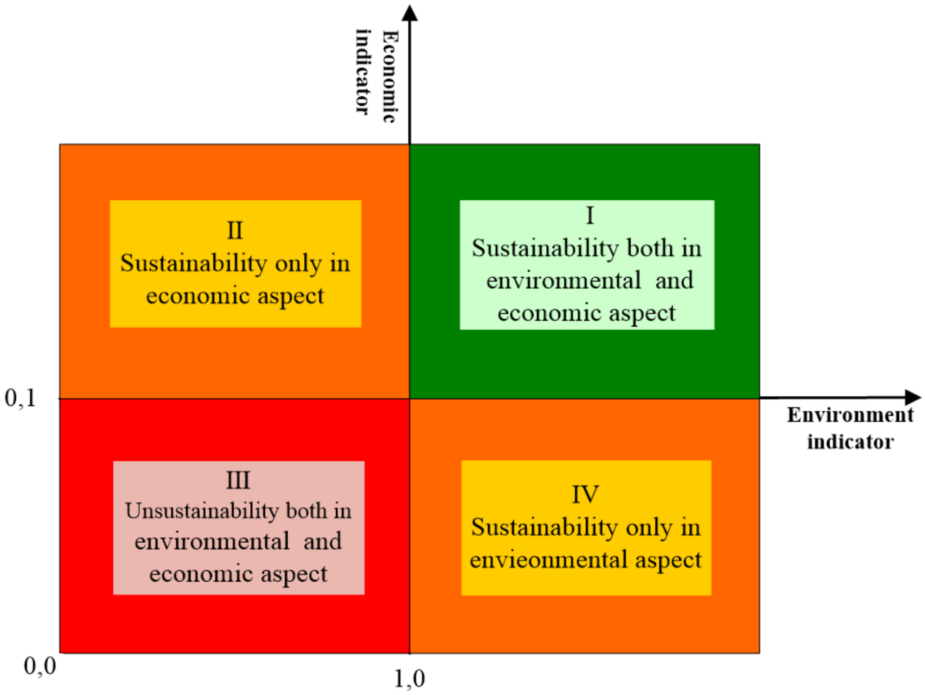

Fig. 3. Sustainability discriminant graph of straw substitute to coal for power generation

There are four regions in the sustainability discriminant graph. Region I represents the sustainability from booth environmental and economic aspects. Region II represents only economic sustainability whereas region III represents unsustainability in both environmental and economic aspects, and region IV shows sustainability only in environmental aspect.

3 Case study

3.1 System parameters

In order to validate the developed model, the Henan Y SPG (power generation scale: 30 MW) was studied. The collection radius of straw was 40 km. The sustainability assessment of straw power generation was studied based on system with production of 10,000 kWh of electricity. The power generation efficiency of Y straw power plant was 1.4 kg/kWh. Because of external environmental and physical changes, the loss rate of straw during storage and processing was assumed to be 5% and 16.67%, respectively. For the production of 10,000 kWh of electricity, approximately 18 tons of straw should be collected. The parameters of agricultural machinery are described in Table 5, whereas parameters of the straw power generation at different stages are summarized in Table 6.

Table 5. Parameters of agricultural machinery

Parameter	Baler	Tractor	Truck	Unit	Data source
price	98000	50000	150000	Yuan	Field research
Fuel consumption in bulk transport	/	0.136	/	L/(tkm)	Field research
Fuel consumption in baling transport	/	0.101	0.078	L/(tkm)	Field research
Straw transportation fuel consumption	/	/	0.053	L/(tkm)	Field research
Depreciation cost	0.839	0.428	1.284	Yuan/t	Field research
The maintenance cost	2.552	0.237	0.710	Yuan/t	Field research

Table 6. Parameters of the straw power generation system

Stage	parameters	Value	unit	Data source
Collection Stage	p_0	25	Yuan/t	Field research
	P_1	100	Yuan	Field research
	q_{pe}	1	t/day	Field research
	q_{b1}	32	t	Field research
	C_{f1}	240	Yuan	Field research
	P_2	400	Yuan /day	Field research

Transport stage	C_p	200	Yuan /day	Field research
	ρ	0.84	kg/L	Field research
	P_3	6.93	Yuan/L	Henan oil price
	L_1	10	km	Field research
	L_2	30	km	Field research
Storage stage	C_u	10	Yuan/t	Field research
	P_4	800	Yuan/mu	Field research
	P_4	1300	Yuan/mu	Field research
	h_0	5	Meter	Field research
	$\emptyset_0$	0.8		Sun et al. (2017)
	P_5	120	Yuan /day	Field research
	C_s	10	Yuan/t	Field research
Processing stage	C_{pe2}	36.63	Yuan/t	Field research
	C_g	1.42	Yuan/t	Field research
	C_{de3}	4.5	Yuan/t	Field research
	C_{m3}	5	Yuan/t	Field research
	E	68	kWh/T	Hu et al. (2014)
	P_6	0.6	Yuan/kWh	Hu et al. (2014)
Burning stage	C_1	0.08331	Yuan/kWh	Field research
	C_2	0.10347	Yuan/kWh	Field research
	C_3	0.04994	Yuan/kWh	Field research
	C_4	0.07	Yuan/kWh	Field research
	C_5	0.044	Yuan/kWh	Field research

3.2 Pollutant emissions from the straw life cycle

The straw supply chain uses different transport vehicles at different stages. Eq. (5)-(7) can be used to calculate pollutant emissions at different stages. The results are summarized in Table 7.

Table 7. Emission amounts of pollutants (g/10,000kWh)

	Stage	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O
Scenario 1	Planting	1527480	833.58	1824.30	/	1573.74	165.96	3350.16	25.92
	Collection	58874.33	337.39	787.23	103.46	13.23	116.98	3.35	1.53
	Transport	193759.20	1240.17	3228.77	322.88	41.89	108.06	10.98	5.38
	Burning	/	2772	3038	/	476	2758	462	/
Scenario 2	Planting	1527480	833.58	1824.30	/	1573.74	165.96	3350.16	25.92
	Collection	58874.33	337.39	787.23	103.46	13.23	116.98	3.35	1.53
	P Transport	48439.81	310.04	807.19	80.72	10.47	27.02	2.75	1.35
	S Transport	104702.10	600.01	1400.01	183.98	23.53	7.96	5.96	2.72
	Burning	/	2772	3038	/	476	2758	462	/

Scenario 3	Planting	1527480	833.58	1824.30	/	1573.74	165.96	3350.16	25.92
	Collection	58874.33	337.39	787.23	103.46	13.23	116.98	3.35	1.53
	P Transport	48439.81	310.04	807.19	80.72	10.47	27.02	2.75	1.35
	S Transport	71143.74	407.70	951.29	125.02	15.99	5.41	4.05	1.85
	Burning	/	2772	3038	/	476	2758	462	/
Scenario 4	Planting	1527480	833.58	1824.30	/	1573.74	165.96	3350.16	25.92
	P Transport	65225.88	417.48	1086.91	108.69	14.10	36.38	3.70	1.81
	S Transport	71143.74	407.70	951.29	125.02	15.99	5.41	4.05	1.85
	Burning	/	2772	3038	/	476	2758	462	/

The results of pollutant emission of the SPG in different scenarios are summarized in Table 8.

Table 8. The total amount of pollutants discharged under different scenarios (g/10,000 kWh)

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CO_2	1780113.53	1739496.24	1705937.88	1647063.55
CO	5183.13	4853.02	4660.71	4323.32
NO_X	8878.30	7856.73	7408.01	6620.78
HC	426.33	368.15	309.19	205.74
SO_2	2104.86	2096.97	2089.43	2076.20
PM_{10}	3148.98	3075.90	3073.35	2956.39
CH_4	3826.49	3824.22	3822.31	3818.96
N_2O	32.83	31.52	30.65	29.12

3.3 Pollutant emissions from coal power generation

The coal power generation system mainly includes three stages of mining, transportation and burning. Pollutants emission from coal burning mainly include SO_2, NO_X, CO_2, CO, HC, N_2O, CH_4 and PM_{10}. The emission coefficients are described in Table 9.

Table 9. Emission coefficients of pollutants from coal burning

	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O	Ref
Mining stage (kg/t)	500	0.330	0.370	0.160	0.021	5	/	/	SEPA (2003)
Transport stage (g/L)	2616.637	14.995	34.988	4.598	0.588	0.199	0.149	0.0680	Wang (2017)
Burning stage (g/MJ)	105.087	0.012	0.270	/	3.249	0.012	/	0.0003	SEPA (2003)

Pollutant emission amounts from different stages of the coal power generation system can be calculated by using Eq. (24).

$$Q_{ji}^{2} = Q_{\mathrm{coal}} \times \varphi_{ji}^{2} \tag{24}$$

where, Q_{ji}^{2} is the pollutant emission amount, Q_{coal} is the quantity of coal burned and φ_{ji}^{2} is the emission coefficient of pollutants.

The pollutant emission amounts in the coal power generation system are summarized in Table 10.

Table 10. Pollutant emissions of coal power generation system (unit: g)

	CO_2	CO	NO_X	HC	SO_2	PM_{10}	CH_4	N_2O
Mining	861500	568.590	637.510	275.680	36.183	8615	0	0
Transport	318549.4	1825.491	4259.439	559.761	71.583	24.226	18.139	8.278
Burning	3786067	1428.851	32443.32	0	390112.3	1440.858	0	36.021
Total	4966116.4	3822.932	37340.27	835.441	390220	10080.08	18.139	44.299

3.4 Calculation of sustainability assessment indicators

Through the calculation of pollutant emissions during different stages of the SPG system, the obtained data can be further processed to calculate environmental impact indicators. The impact categories and equivalent factors of pollutants are described in Table 11.

Table 11. Environmental impact categories and equivalent factors of pollutants

Impact category	Standardized benchmarks	Unit	Weight	Pollutants	Equivalent factor
Global Warming (GW)	8700	kg CO_2-eq	ω_1^*	CO_2	1
				CH_4	21
				NO_X	310
				N_2O	310
Photochemical oxidation (POC)	34.72	kg C_2H_4-eq	ω_2^*	HC	0.416
				CH_4	0.007
Human toxicity (HT)	197.21	kg 1,4-DCB	ω_3^*	CO	0.012
				NO_X	0.780
Aerosol (AE)	18	Kg	ω_4^*	PM10	1
Acidification (AC)	36	kg SO_2-eq	ω_5^*	SO2	1
				NO_X	0.700

The Best-worst method is employed to calculate the weight of environmental pollutant impact categories. Through the guidance of relevant experts, we chose $a_{BW} = 5$ and set $\mathrm{BO} = (1,2,1,5,3)$ and $\mathrm{OW} = (5,3,5,1,2)^T$. According to Eq. (3), the optimal weight can be calculated as $\omega_1^* = 0.34, \omega_2^* = 0.189, \omega_3^* = 0.283$, $\omega_4^* = 0.067, \omega_5^* = 0.121$ and $\xi^* = 0.2$. Using the consistency check by Eq. (4), we obtain CR = 0.087, which is in agreement with the consistency check and the results are authenticated.

The environmental and economic indicators of different scenarios can be calculated using Eq. (11) and Eq. (21). The results are described in Table 12.

Table 12. Assessment indicators for different scenarios of the straw power generation

Scenarios	Environmental indicators	Economic indicators
Scenario 1	9.1101	1.1068
Scenario 2	9.8802	1.1866
Scenario 3	10.2911	1.1632
Scenario 4	10.8306	0.8752

3.5 Assessment results of sustainability

According to the established sustainability discriminant graph, it's easy to get the sustainability assessment results of different straw power generation scenarios, as shown in Fig. 4.

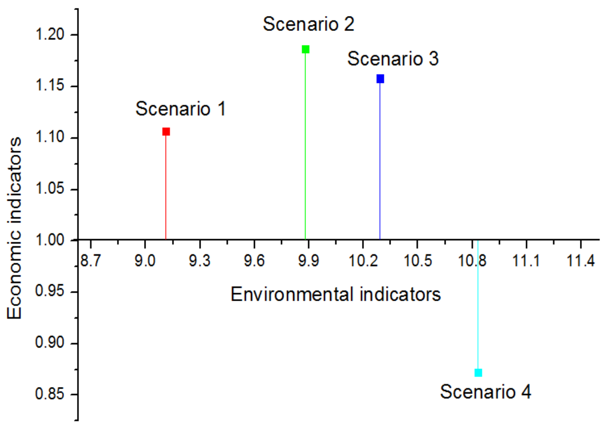

Fig. 4. Sustainability assessment results of different power generation scenarios

It is very clear that the straw power generation has shown better sustainability in scenario 1, scenario 2 and scenario 3, both in economic and environmental aspects. Which Scenario 3 has a better environmental sustainability evaluation indicator and scenario 2 has the best economic indicator. Among these four scenarios, scenario 4 had the best environmental sustainability evaluation indicator, however the economic indicator is less than 1, demonstrating that it can't create profits for enterprises, thus this straw power generation scheme was not considered by enterprise decision makers.

4 Analysis and discussion

4.1 Analysis of research results

Many previous studies used LCA method to assess the environmental impact of biomass utilization. Ji et al. (2018) showed that greenhouse gas (GHG) abatement potential being -0.9 t CO_2-eq t^{-1} straw. In our research the GHG abatement potential was -0.8903 t CO_2-eq t^{-1} straw. Wang (2017) studied different biomass supply models, and pointed that CO_2 emissions from straw bulk transport of 4186.619 10^{-3}g/kg and in baling transport of 5635.834 10^{-3}g/kg. In this study the CO_2 emissions of straw bulk transport and baling transport were 3952.43 10^{-3}g/kg and 5816.7834 10^{-3}g/kg, respectively. It is necessary to understand the emission status of pollutants during different stages of the straw life cycle. The pollutant discharged during different stages can be analyzed, and the proportion of pollutant emissions are shown in Fig. 5 (average value of pollutant emission in four scenarios was used).

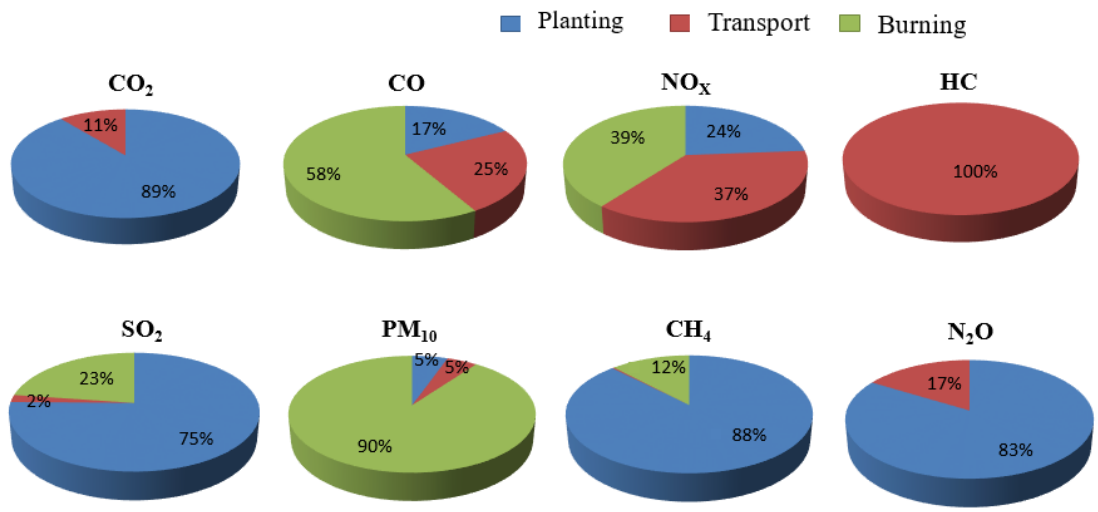

Fig. 5. Emission proportion of different pollutants in different stages

From Fig. 5, it can be observed that CO_2, SO_2, CH_4 and N_2O are mainly derived during the planting and transport stage, accounting for 89%, 75%, 88% and 84%, respectively. The pollutant HC originates during transport stage. The pollutants NO_X, CO and PM_{10} produced mainly during burning stage which accounted 39%, 58% and 90%, respectively.

It has been observed that change in straw transportation mode showed considerable influence on pollutant emission. Liu et al. (2017) studied on different logistics models for SPG and found that the transport model can significantly affect emission reduction goals. Proskurina et al. (2017) pointed out that biomass pretreatment can increase density and exhibits good flow ability in logistics processes. This is conducive to improve transport efficiency and reduce pollutant emissions during transport. Nunes et al. (2014) showed that straw granulation had a significant impact on transport. Accordingly, straw processing technology provides great contribution to reduce pollutant emissions. In this study, the pollutant emissions from the transport stage in different scenarios are shown in Fig. 6.

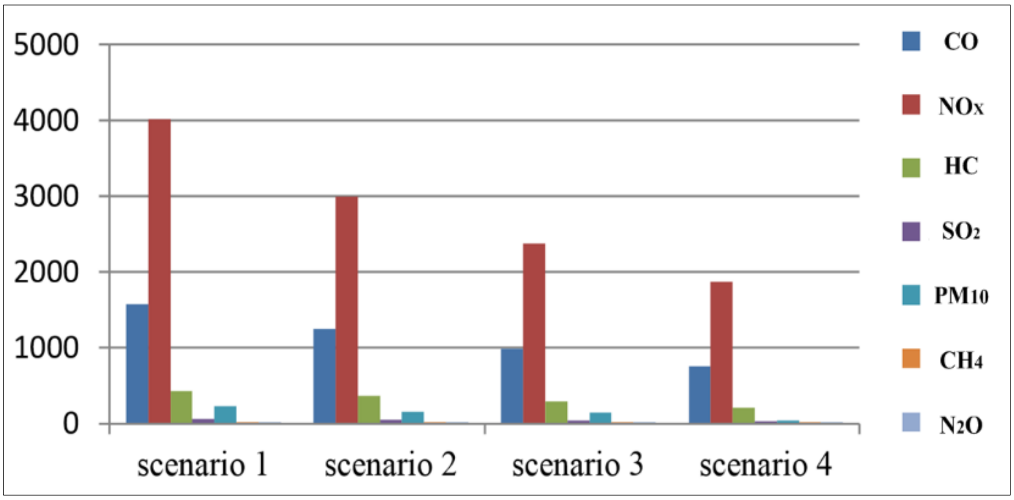

Fig. 6. Pollutant emissions from the transport stage in different scenarios, (unit: g)

From Fig. 6, it is clear that emission of pollutants changed significantly with the change in the transport mode of straw. By comparing the four scenarios, we observed that by reducing the use of machinery without considering economic benefit can effectively reduce pollutant emissions. However, this does not meet the goals of the enterprise. By considering the production efficiency, the pollutant emissions of scenario 3 were the lowest due to the use of straw briquetting technology which confirms that straw briquetting technology has a remarkable impact on pollutant emissions.

A comparison of CO_2 emissions from straw direct combustion power generation and coal power generation is shown in Fig. 7. The CO_2 emissions from straw power generation were far below those from coal power generation which suggests that straw power generation had great potential to reduce pollutant emission.

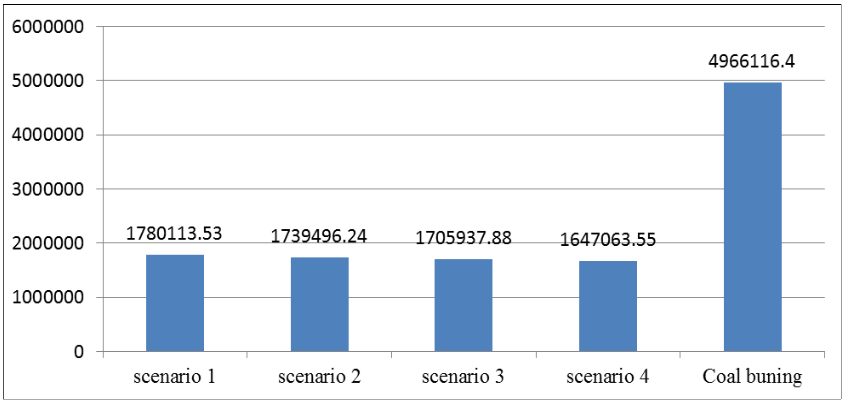

Fig. 7. CO_2 emissions in different scenarios, (unit: g)

4.2 Sensitivity analysis of influencing factors

The straw power generation had good development potential based on sustainability assessment. However, the SPG is a complex system where environmental and economic indicators can be influenced through many factors (e.g. straw purchase price, amount of straw collection, the power plants scale, types of transport vehicles, straw compression rate, operational status and treatment technology of pollutants). In order to understand the influence of these factors on sustainability of straw power generation, sensitivity analysis needs to be carried out.

4.2.1 Impact of the scale of power plants

Power plants need to expand their scale to produce more electricity in order to fulfill the consumption demands. Expansion of the power plant scale leads to the increases in straw collection radius. Assume the straw collection radius increased by 10 km, 20 km and 30 km. The variation trend of the sustainability assessment results shown in Fig. 8.

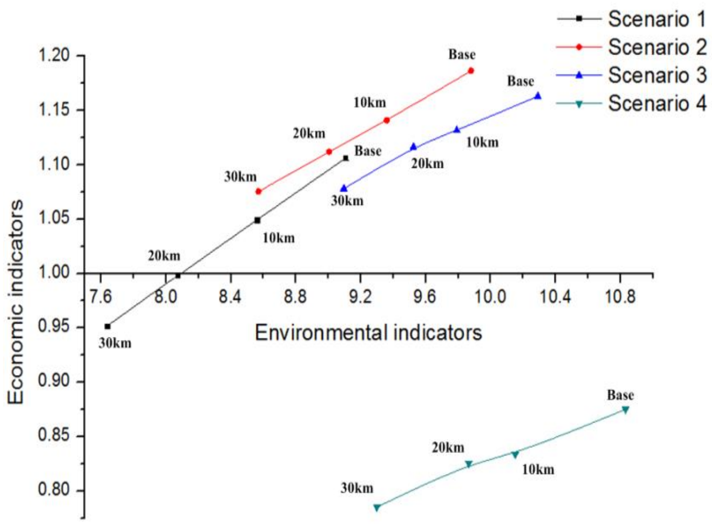

Fig. 8. Impact of the scale of straw power plants on sustainability assessment

Fig. 8 showed that economic and environmental indicators decrease with increase in scale of straw power plants. When the collection radius increased by 20 km, the economic indicators of scenario 1 was 0.998, indicating that enterprises gains no profit. Comparison of scenario 2 and scenario 3 showed a difference between economic indicators of 0.01, while the difference of environmental indicators was 0.503. Power plants should select the scheme of scenario 3 to generate electricity. When the straw collection radius increased by 30 km, the economic indicators of scenario 3 exceed scenario 2, which suggested that scenario 3 was the best choice for power plants.

4.2.2 Impact of the transport vehicles

During the field research process, we figured out that straw is transported mainly by tractors. There are many shortcomings associated with the use of tractors as it consumes more fuel and have a small tonnage. Sun et al. (2017) conducted an economic analysis of straw collection and pointed out that fuel prices affect transportation costs. Tauro et al., (2018) analyzed the impact of trucks with different tonnage on logistics costs. Tsalidis et al. (2014) pointed out that the transportation stage of biomass had the highest contribution for pollutant discharge. El Hanandeh. (2015) showed that longer transportation distances added environmental burdens. To analyze the impact of transportation activities on sustainability, this study assume that straw power plants should adopt a new transport vehicle, which has a large load capacity with lower fuel consumption with reduction by 5%, 10% and 15%. The effects of above assumptions on the sustainability assessment are shown in Fig. 9.

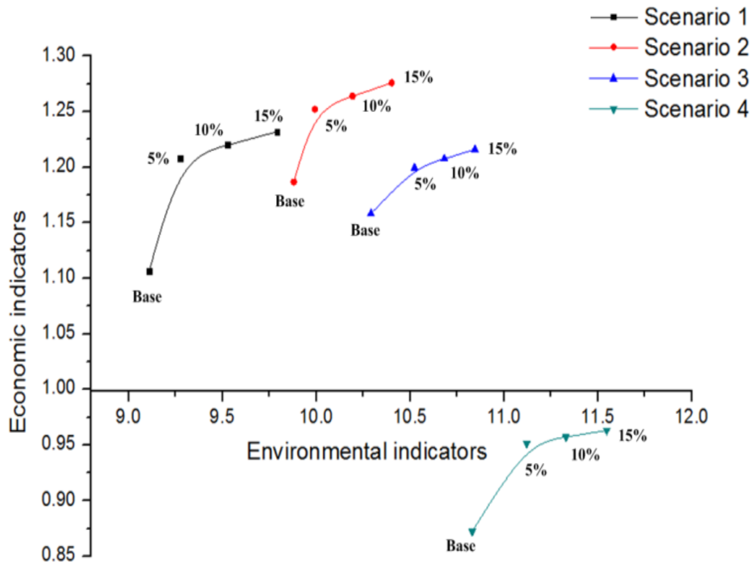

Fig. 9. Impact of transport vehicle changes on sustainability assessment

Fig. 9 shows that the sustainability of the straw power generation can be enhanced by selecting efficient transport vehicles. Selections of low fuel consumption vehicles have shown considerable impact in scenario 1. When fuel consumption is decreased by 5%, the economic indicators is increased by 9.15%. Comparison of scenario 2 and scenario 3 revealed that scenario 2 was more sensitive to changing of transport vehicle and had better economic indicators. Simultaneously, the use of efficient transport vehicle can improve the economic indicators of scenario 4. According to the above analysis, we suggest straw power plants to optimize transport vehicles to improve the sustainability.

4.2.3 Impact of the pollutant treatment technology

China is actively developing renewable energy to reduce its dependence on fossil fuels and to minimize the pollutant emissions. Straw power generation can not only deal with a large number of straw, but also can alleviate greenhouse gas emissions (Ji et al., 2018). Giuntoli et al. (2013) showed that straw-fired power plants can realize high greenhouse gas savings. Karkania et al. (2012) studied agricultural waste utilization and pointed out that the concentration of pollutant was low after combustion treatment. Pollutant emissions from straw power generation are strictly monitored by environmental protection departments. Power plants need to adopt new technology to reduce pollutant emissions. In this manuscript we have assumed that operational cost of the power plants can be to increase 10% if they implement the pollutants reduction technology to bring pollution down by 10%. The variation trend of sustainability assessment results as shown in Fig. 10.

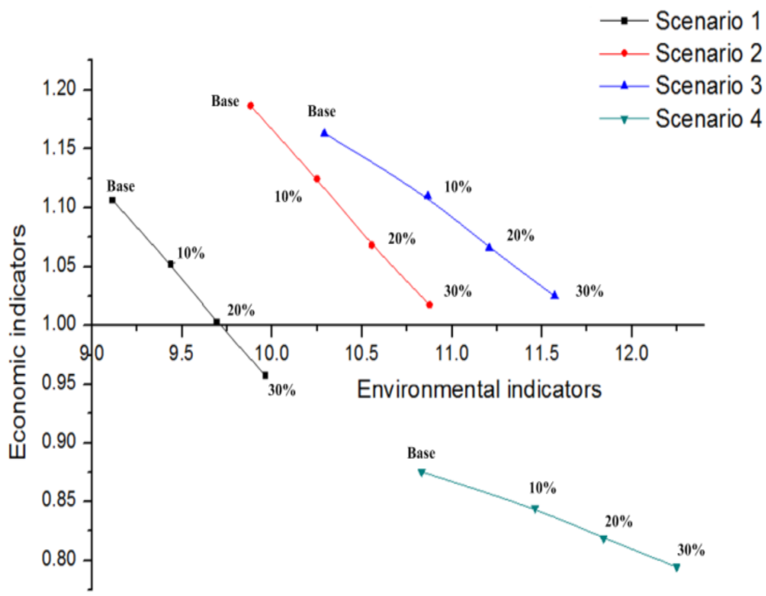

Fig. 10. Impact of pollutant treatment technology on sustainability assessment

Fig. 10 demonstrates that pollutant treatment technology has a great impact on the sustainability. Scenario 1 and Scenario 2 are more sensitive to the treatment technology, the economic indicators rapidly declined with the increase in environmental indicators. Comparison of scenario 2 and scenario 3 showed that when the pollutant reduction is greater than 10%, the economic and environmental indicators in scenario 3 exceed as compare to in scenario 2, demonstrating that scenario 3 can promote the sustainability of the straw power generation system.

4.2.4 Impact of the straw purchase price

The purchase price of straw not only affects the income of enterprises but also the supply of straw. In order to determine the impact of straw price on straw power generation sustainability assessment results, present study also conducted a price sensitivity analysis, can be seen in Fig. 11. As it is clearly shown from Fig. 11 that the economic indicators of straw power generation can be improved when the straw purchase price is low. The increase in straw purchase price will decrease the economic indicators as operational cost of the enterprise increases.

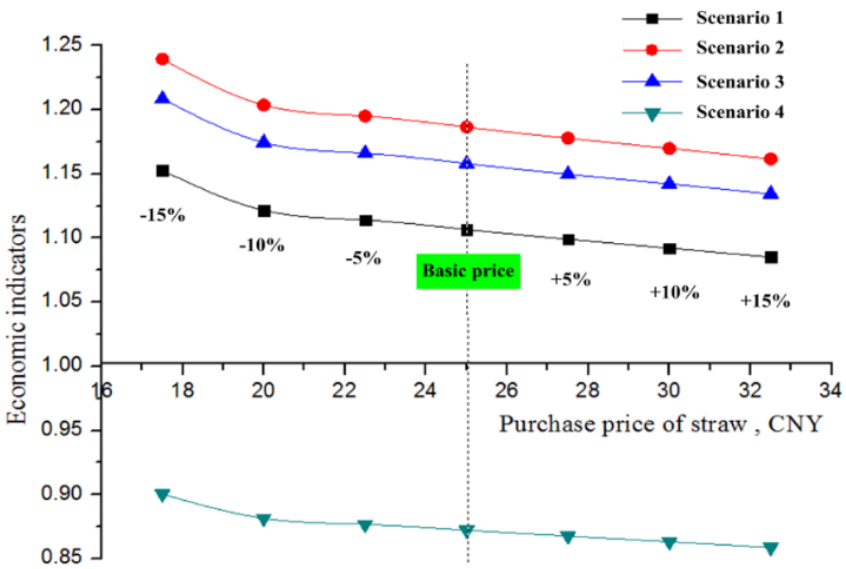

Fig. 11. Impact of straw purchase price on economic indicators

4.3 Emission reduction potential of straw power generation

The emissions from coal-based power generation are major contributors to environmental pollution. Straw can replace coal for power generation and effectively alleviate environmental pollution. Our findings indicated that scenario 3 had the best sustainability, thus the emission data of scenario 3 was selected to study the emission reduction potential of straw power generation. Take CO_2, NO_X, SO_2 and PM_{10} as an example, it can be seen from Fig. 12 that straw power generation has great potential for emission reduction. The emission reduction effect of CO_2 and SO_2 are more obvious with the increase of the substituted coal.

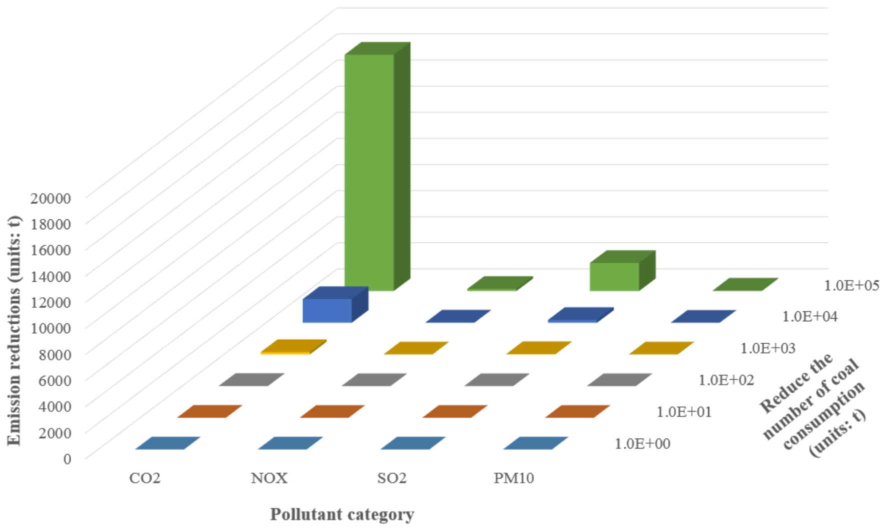

Fig. 12. Emission reduction potential of straw replacing coal-fired power generation

4.4 Discussion

4.4.1 How to select a straw power generation scheme

Our findings showed that straw power generation had great potential to alleviate environmental pollution, whereas sustainability of straw power generation strongly depends on economic indicators. By analysis of four straw power generation scenarios, it can be inferred that the sustainability was different for different straw power generation scheme which supports to decision-makers for selecting an appropriate power generation scheme. The straw power generation scenario 3 presents best sustainability when environment-friendly society with more economic benefits was required. When the goal of enterprise was to achieve maximum benefits while reducing the impact on the environment, the straw power generation scheme of scenario 2 had the best sustainability. Whereas straw power generation scheme of scenario 4 can be good choice when the goal of the enterprise was to get maximize environmental benefits during a special period. Straw power plants can determine their own development goals and select the appropriate power generation scheme based on these assessment results.

4.4.2 How to improve the sustainability of straw power generation

We have analyzed the four main factors that affect the sustainability of the straw power generation. We found that the scale of power plants, pollutant treatment technology and straw purchase price were negatively related to the sustainability, this was consistent with the research of (Wang et al., 2018). The selection of energy-saving transport vehicles can improve the sustainability. In comparison to current situation of straw power generation in China, it is not difficult to discern that the sustainability of straw power generation had not achieved a high level. Mainly due to a lack of systematic planning and management, and the higher operating costs (Wang et al., 2017). Through this study, we found that improving the environmental and economic performance of straw power generation can raise its sustainability. After analyzing the sensitivity of influencing factors, there are some methods to improve the sustainability of straw power generation: establishing an efficient straw supply chain; using transport vehicles with low-energy consumption; developing new technology for pollutant treatment; reducing straw purchase price.

4.4.3 What should government do

By reviewing the research results, we have known that straw power generation industry has lack of economic vitality. The main reasons include higher operating costs, the lower benefit and complex technology of power generation. Through the analysis of emission reduction potential (see Fig. 12), straw power generation had great potential to reduce the emission of pollutants which can help the government to achieve the goal of emission reduction. It's worth popularizing straw power generation technology. While keeping in mind about environmental benefits, Chinese government should promote straw power generation projects along with financial support. Tax, fiscal subsidies and electricity price have an important impact on the economic performance of power plants. And the sustainability of straw power generation can be promoted through policy guidance. Our findings suggest that government can guide farmers to plant on a large scale to reduce the cost of straw collection; make policies for automobile industry to develop low-carbon and efficient vehicles for transport; lead straw power plants to develop innovative straw-processing and pollutant treatment technologies.

5 Conclusion

In this study, from the environmental and economic perspectives of straw substitute to coal, a sustainability assessment model was built by integrating life cycle assessment, life cycle cost and best-worst method. The environmental and economic indicators were calculated and the sustainability of four different SPG scenarios were assessed. Findings showed that straw direct combustion power generation had great sustainability potential in China. In terms of environment, the results showed that straw power generation had great potential to reduce emissions and alleviate environmental pollution in comparison to coal-based power generation. However, from economic aspect, the sustainability had not up to the advanced level in the current situation. It had weak economic sustainability potential, there can be losses (e.g. scenario 4) when scheme of straw power generation was not appropriate. Finally, sensitivity analysis of different factors affecting the sustainability of SPG was carried out. The sensitivity analysis results showed that straw supply chain model, pollutant treatment technology, transport vehicles and straw purchase cost were the main factors which lead to unfavorable economic performance. The research findings can provide support to the government in popularizing straw power generation technology, and also can help to develop direct combustion SPG system with more environmental friendly and economic sustainability.

Based on the research results, here are some suggestions which may help enterprises to improve the sustainability of straw direct combustion power generation system: (1) Power plants should design the appropriate straw power generation scheme. The scale of straw power plants affects the choice of power generation scheme, and different power generation schemes should be selected for different power plant scales. (2) Power plants should choose energy-saving vehicles. The transportation cost of straw is about 60% of the total cost, and a lot of pollutants are emitted during the transportation stage. The use of energy-saving transportation is conducive to improving the sustainability of straw power generation projects. (3) Enterprises should innovate in pollutant treatment technology. In the straw burning power generation stage, the treatment technology of pollutants directly affects the discharge and operating costs of pollutants. The efficient treatment technology can save costs and reduce the discharge of pollutants. (4) The government can provide subsidies to balance power generation enterprises and farmers. Through the results of this study, it can be found that the economic performance affects the sustainability of straw power generation. Government subsidies can reduce the production cost of enterprises and encourage farmers to supply more straw resources. This can improve the economic indicators and promote the sustainability of straw power generation.

Acknowledgment

This study was supported by Henan province science and technology research project (Grant No: 192102110205).

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