Cost Analysis of straw-based power generation in Jiangsu Province, China

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HIGHLIGHTS

► We estimate the straw-fired power generation costs in Jiangsu Province, China.
► The causes for the deficit of straw-fired power generation plants are identified.
► Poor management is the primary factor for explaining the deficit of the plants.

ABSTRACT

As one of the most developed provinces in China, Jiangsu Province has been actively developing bio-energy in order to deal with its electricity supply shortage. By the end of 2010, there are 12 grid-connected straw-based power plants, but only two of them are profitable in this province. This paper presents a simple and detailed method for estimating the cost of straw-based power generation with life cycle analysis, and identifies the main causes for the financial deficit of these plants through a sensitivity analysis and survey. It concludes that: (i) compared with coal-fired power generation, the cost of straw-based power generation is indeed high. (ii) The fuel cost takes the largest share in the operation cost. (iii) The basic causes of the high cost are from straw characteristics, mismatch between demand and supply, immature technology, inappropriate project planning and low motivation of farmer selling straw. Based on the basic causes, we propose the countermeasures.

1. Introduction

Crop residues are very rich in China and the annual output is roughly equal to 728 million tons [1]. The Chinese Government realized the importance of straw-based power generation and proposed four programmes about it in 2006–2010. Under these programmes, the NDRC and other governmental agencies developed a series of auxiliary policies, such as mandatory grid connection, cost-sharing, feed-in tariff and tax credits.

JSP is a large province in both economic size and energy consumption, which locates in the Yangtze River Delta region of China. However, JSP is lack of energy resources. It has been estimated that the electricity supply shortage accounts for 10% of total electricity consumption [2]. Meanwhile, it has abundant crop residues and the annual output is about 40 million tons [3]. In view of these facts, JSP has been actively exploring and utilizing straw-based power generation. In early November 2003, JSP started to implement the CRESP project that aimed to promote the development and utilization of its renewable energy resources. In September 2004, the NDRC for the first time approved three straw-based power generation projects in China, which included the project in Rudong County, JSP. By September 2010, JSP had 12 grid-connected SPPs with the total 273 MW; Meanwhile China had 85 SPPs with the total 1669 MW.1 Despite these policy supports, only two SPPs in JSP are profitable [4,5]. Straw-based power generation has been implemented successfully in some of the European countries, such as Denmark as a pioneer user of wheat straw, UK and Spain [6]. This has led us to examine why the SPPs in JSP are under deficit. Additionally, because the number and scale of the SPPs in JSP rank first in China, we take JSP as an example to investigate the reasons for their financial deficit. The findings could also be useful to help us identify the root of economic losses of the SPPs elsewhere in China.

Several authors examined the profitability or cost of SPPs in China. Gu [7] pointed out that the price of the feedstock in different regions and the vapor parameters of boiler in addition to policy

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would have effects on whether a straw-based power generation project is profitable or not. Jiang and Zhu [8] showed that the straw-based power generation in Yancheng City of JSP is economically feasible. Jiang et al. [9] developed an integrated model for assessing the benefits of SPPs from economic, ecological and social points of view. The empirical analysis on the Sheyang SPP in JSP showed that a 25 MW SPP requires more than six years to become profitable. Li and Hu [10] analyzed the cost compositions about construction and electricity generation in SPPs in JSP, and concluded that the actual grid-connected electricity tariff is lower than that estimated from a breakeven analysis. Liu et al. [11] evaluated the environmental externality, i.e. the greenhouse gases emissions, of Shiliquan SPP in Shandong Province, China by Life Cycle Analysis. Sun et al. [12] aimed to shed light on the interaction mechanism of cost risks for biomass material supply in power generation, especially for biomass-coal dual-fuel systems by simulation. Wu et al. [13] analyzed the economic characteristics of biomass gasification and power generation in China from investment, electricity cost, and cost for waste treatment. Liu et al. [14] systematically analyzed the temporal and spatial patterns of crop stalk resources, evaluated the bioenergy potential of crop stalk resources, and explored possible pathways of developing stalk-based energy strategies in Inner Mongolia, China. Perлack and Turbhillow [15] evaluated the costs for collecting, handling, and hauling corn stover to an ethanol conversion facility. Kumar et al. [16,17] investigated the relationships between the costs and the issues such as payment, profitability, and optimum size of SPP. Cameron et al. [18] studied the relationship between distance variable cost and distance fixed cost. Delivand et al. [19] investigated the logistics cost consisting of machinery cost, operating cost, fuel cost and labor cost in three regions of Thailand. Delivand et al. [20] assessed economic feasibility of rice straw utilization for electricity generating through combustion in Thailand. Dassanayake and Kumar [21] focused on the techno-economic assessment of triticale straw based power generation and the GHG abatement cost in Canada, by field cost, construction cost of power generation project, operating costs. Mobini et al. [22] investigated the logistics of supplying forest biomass to a potential power plant, put forward a simulation model based on the framework of Integrated Biomass Supply Analysis and Logistics to evaluate the cost of delivered forest biomass, the equilibrium moisture content, and carbon emissions from the logistics operations.

Although several earlier studies described above also mentioned the costs of some SPPs in JSP or elsewhere, this paper is different from them in estimation method and data acquisition. Specifically, we present a simple but more detailed method for calculating the cost of straw-based power generation by life cycle analysis. A method for finding out the causes of the costs is also given. Using these methods, we can easily derive the unit cost of power generation and find the main causes. In the next section, we briefly introduce the status of straw-based power generation in JSP. Section 3 gives the cost breakdown and calculation method. Section 4 discusses the causes of the high cost and proposes the countermeasures. Section 5 obtains the conclusions.

2. Status of straw-based power generation in JSP

2.1. Straw production and distribution

JSP has different kinds of straw resource. However, the rice, wheat, rape and corn straw accounts for more than 80% of the total straw resource. Other crops mainly include barley, highland barley, cotton, soybean, peanut, potato, vegetables and melons. The wheat,
rape and other summer crops account for 32.8%, and the rice, corn, cotton and other autumn crops is about 55.9% of the total. Geographically, the Northern, Central and Southern Areas respectively produce 23, 11 and 6 million tons of straw resource. Northern Area in JSP involves Xuzhou, Lianyungang, Suqian, Huia’an and Yancheng; Central Area has Yangzhou, Taizhou and Nantong; South Area covers the rest.

The straw can be divided into two categories, namely soft straw and hard straw. Soft straw, also called yellow straw, mainly consists of rice straw and wheat straw, which is produced in Suqian, Huai’an, Yangzhou, Lianyungang and Nantong. Hard straw, i.e. gray straw, involves cotton straw, branches and bean straw, which the major portion of production is in Yancheng.

2.2. General status of straw-based power generation

In the above-mentioned 12 grid-connected SPPs, as shown in Fig. 1, the total investment was 2.658 billion RMB yuan, the total demand for straw about 2.13 million tons/year. Among them, ten are direct-fired, one is gasified and the other is mix-fired upgraded from coal-fired by technical improvement with an investment of 80 million RMB yuan.

The equipments and systems of SPP are the same nominally. The differences come from their brands, suppliers, price and capacity, as Table 1 shows the cost and composition of the investment.

In Table 1, a 25 MW turbotes is driven by a boiler that the nominal capacity is 130 t/h, superheated steam pressure 9.2 MPa, superheated steam temperature 540 °C and feed-water temperature 210 °C. And the driving force of a 2 × 15 MW or 2 × 12 MW turbotes is from a 2 × 75 t/h boiler.

2.3. Production of straw-based power generation

The life cycle of straw-based power generation begins with plant construction and finish till grid-connection of electricity. Roughly, it can be divided into two stages, i.e. project implementation and power production. The production stage includes off-site straw acquisition, processing and shipping and in-plant power generation, as shown in Fig. 2.

2.3.1. Straw acquisition

Straw is collected from farmland, flows to temporary stack points and then collection stations. After proper processing and shipping, it reaches the power plant. Prime brokers purchase the straw from the farmers, and ship it to the temporary stacking points, which are usually the wasteland or near open field. The village management committee is responsible for the coordination of the use of the field. Different straws have different calorific values, one kilogram straw is roughly equivalent to 0.386–0.657 kg standard coal. Among them, rice straw is the lowest, and corncob is the highest. According to Ding [23], the parameters in Table 1 and the water enthalpy, a 25 MW, 2 × 15 MW or 2 × 12 MW SPP running 24 × 300 h will respectively require around 0.92 × 10^5, 1.13 × 10^5 and 1.21 × 10^5 tons standard coal that they equivalent to 1.40 × 10^5–2.38 × 10^5, 1.72 × 10^5–2.93 × 10^5 and 1.84 × 10^5–3.13 × 10^5 tons straws.

The share of straw used to energy production, including electricity generation, was only 3.5% in 2008, and is expected to be increased to 26% by 2012 [3]. The typical grain yield of JSP in 2010 is

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3 1 RMB yuan = 0.1538 USD.

6.125 t/ha and the highest yield is 11.165 t/ha [24]. In accordance with 1:1 of the residue to product ratio [1], if the straw yield of JSP is 7.0–7.5 t/ha and one quarter of that is available for power generation, the catchment arable land from which straw is to be collected should be averagely 1.1 × 10^5 ha in order to satisfy the demand for 2.0 × 10^7 tons straw, the straw-collection radius is about 20 km. But, the actual radius was 50–80 km [25], mostly greater than 100 km, and maximum radius even was 200 km [26,27] because the farm output quotas are fixed by household in the 1980s, and divided into scattered, irregular form of bars or ingots [26,27] because the farm output quotas are fixed by household in the 1980s, and divided into scattered, irregular form of bars or ingots. In China, the collection area of JSP is 7.0–7.5 t/ha and one quarter of that is available for power generation. The daily labor wage in these areas is 40–400 RMB yuan/d [32,33] and the short rural manpower. It was estimated that the proportions of residue burnt on the field in JSP were about 30–40% in 2003 [34] and 39% in 2009 [35].

2.3.2. Straw shipping, processing and storing

The rural roads in JSP are usually 3.5 m wide, which are only 5 m wide plus the subgrades. These paths are only suitable for three/four-wheeled tractors and the roads may be fit for 5/6-ton trucks. Some parameters of vehicle are shown in Table 2. Diesel prices increased from 4.65 RMB yuan/L in early 2007 to 6.85 RMB yuan/L in late 2010. The vehicles and related expenses are born by farmers or brokers. The distance of shipping straw is generally less than 10 km by tractor [36].

When primary broker sends straw to collection stations, the secondary broker will process and store them. The process can contain quality detecting, weighing, crushing, baling, carrying, stacking, storing, unstacking and entrucking. Shipping straw to the power plant is contracted by the secondary broker or third-party.

A collection station, which covers 1–4 ha and has storage capacity of 8000–10,000 t/year, installs the equipments including crusher, packer, straw special machine, rainproof, fire fighting, 5–7 workers and necessary office sites. The installation and its inside equipments, which may be freely used by the secondary broker in certain period, are built and invested by power plants. The daily operation fee, except for depreciation cost, of course, is undertaken by the secondary broker.

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3.1.2. Processing and storage cost in collection station

The processing and storage cost, \( c_p \) (RMB yuan/t), is calculated as follows:

\[
C_p = \left[ C_{\text{crw}} + c_e + C_{\text{sm}} + h \right] (1 + \theta)
\]

where

\[
C_{\text{crw}} = \frac{(360m_w + m_i)}{Q}
\]

\[
C_{\text{sm}} = 0.025c_e/Q
\]

\[
h = rc
\]

The processing cost, \( c_p \) (RMB yuan/t), is the sum of unit cost of energy consumption about crushing, packing, carrying, stacking, unstacking, entrucking, as shown in Table 4.

Table 3

On-grid quantity of electricity of the SPPs (Unit: MWh).

<table>
<thead>
<tr>
<th>Year</th>
<th>( P_{3,1} ) (1 × 12 MW)</th>
<th>( P_{3,2} ) (2 × 12 MW)</th>
<th>( P_{3,3} ) (1 × 25 MW)</th>
<th>( P_{3,4} ) (2 × 15 MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>88,220</td>
<td>141,270</td>
<td>103,850</td>
<td>140,090</td>
</tr>
<tr>
<td>2010</td>
<td>103,137*</td>
<td>153,863</td>
<td>197,161</td>
<td>153,356</td>
</tr>
</tbody>
</table>

Runtime (d)

- \( \leq 315.1^1 \)
- \( \leq 293.8 \)
- \( \leq 123.3 \)
- \( \leq 257.2 \)
- \( \leq 236.3 \)
- \( \leq 361.5 \)
- \( \leq 295.8 \)
- \( \leq 223.9 \)
- \( \leq 203.7 \)
- \( \leq 264.7 \)
- \( \leq 256.5 \)

2.3.3. Operation in power plant

The operational procedure of the power plant is: (i) straw unloading, handling, storage and feeding, etc. (ii) boiler combustion, (iii) hot-swap, (iv) steam, and (v) power transmission.

A SPP may use about 50 species biomass as substitute due to supply shortage [26,37]. In 2007–2008, the power consumption rate in production, at a very high level, was 10.31–39.24% [37]. The on-grid quantity of electricity is as shown in Table 3.

3. Cost breakdown and calculation

3.1. Cost of straw arriving at plant

3.1.1. Collection cost

The total cost for collecting the straw, \( c_c \), can be calculated from:

\[
c_c = \left[ c_p + c_w + (c_d + c_i) + c_{\text{ad}} + c_m \right] (1 + \theta)
\]

where

\[
c_{\text{crw}} = (Q_i + q_s)dp_d/w_t
\]

\[
c_w = n_sW/W_t
\]

Based on above Section 2, the assumptions are obviously reasonable here and hereunder, i.e. \( d = 10 \text{ km}, q_s = 0.11 \text{ L/km}, q_e = 0.08 \text{ L/km}, w_t = 1.5t, c_i = 0.15c_e \) [38], \( p_w = 6.0 \text{ RMB yuan/L}, p_i = 15,000 \text{ RMB yuan/y}, y = 6, x = 5\% , n_s = 2, q_i = 3 \text{ t/d}, w_t = 60 \text{ RMB yuan/d}, p_i = 150 \text{ RMB yuan/t}, \theta = 10\% , c_m = 0.5c_{\text{crw}}, c_i = 0.10c_d, \theta = 10\% , \) thus \( c_c = 222.24 \text{ RMB yuan/t}. \)

If farmers themselves send the straw to the collection station, the purchasing price of straw is equal to the field collecting cost.

3.1.2. Processing and storage cost in collection station

The processing and storage cost, \( c_p \) (RMB yuan/t), is calculated as follows:

\[
C_p = \left[ C_{\text{crw}} + c_e + C_{\text{sm}} + h \right] (1 + \theta)
\]

where

\[
C_{\text{crw}} = \frac{(360m_w + m_i)}{Q}
\]

\[
C_{\text{sm}} = 0.025c_e/Q
\]

\[
h = rc
\]

If \( Q = 10,000 \text{ t}, m_j = 12,000 \text{ RMB yuan/year}, n = 6, w_w = 60 \text{ RMB yuan/d}, p_i = 780,000 \text{ RMB yuan}, r = 8\% , \theta = 10\% , \) thus \( c_{\text{crw}} = 14.16 \text{ RMB yuan/t}, c_e = 324.569/Q = 32.46 \text{ RMB yuan/t}, c_m = 1.95 \text{ RMB yuan/t}, h = 17.78 \text{ RMB yuan/t}, c_p = 72.99 \text{ RMB yuan/t}. \)

3.1.3. Shipping cost

The cost of the shipping straw is \( c_p \) (RMB yuan/t):

\[
c_p = \left[ c_w + (c_d + c_i) + c_{\text{ad}} + c_m \right] (1 + \theta)
\]

If \( p_s = 100,000 \text{ RMB yuan}, q_s = 0.25 \text{ L/km}, q_e = 0.15 \text{ L/km}, y = 12, x = 5\% , d = 70 \text{ km}, q_i = 12 \text{ t/d}, n_s = 1, w_w = 70 \text{ RMB yuan/d}, c_m = 0.5c_{\text{crw}}, c_i = 0.10c_d, \theta = 10\% , \) thus \( c_p = 43.32 \text{ RMB yuan/t}. \)

Under the same assumption in the above, \( p_p = 338.55 \text{ RMB yuan/t}. \) In practice, the price at plant was form 310 RMB yuan/t [28] to 400 RMB yuan/t [26], the price at the SPP is:

\[
p_p = c_p + c_e
\]

3.2. Project investment and operation cost

According to account subject, the investment and operating cost type of a SPP is operating costs, sales taxes and addition, and financial cost, as shown in leftmost of Table 6.

Fuel cost: the total cost of feedstock in SPP per year, i.e. \( p_D D \).

Material expense: the cost of raw materials, auxiliary materials, components, parts in facilities and equipments maintenance.

Water rate: \( p_w W G / (1 - \beta) C \).

Salary and welfare expense: The total salary and welfare of people who work in SPP.

Depreciation cost: By the financial rule of Chinese enterprise, service life of the facilities is 20 years, depreciable life 15 years, fixed assets formation 100\%, residual value 5\%, integrated rate of depreciation 6.40\%.

Maintenance cost: The cost of manpower in facilities and equipments maintenance. In general, it is 2.5% of the value of fixed assets.

Sales taxes and addition: In accordance with the relevant provisions of Chinese tax policies, output tax rate of the project is 17\%, input tax rate is deducted according to raw and auxiliary materials and fuel, including straw for fuel 13\% and the rest 17\%.

\[ ^1 \text{ Data source: calculate according to our survey and NDRC, State Electricity Regulatory Commission. On notifications of renewable electricity price subsidies and quota trading scheme in 2009 and from Jan. to September, 2010.} \]

\[ ^2 \text{ Here and hereunder, the assumptions including method of repayment capital with interest are from "Research Report on Project Feasibility of Sheyang Biomass Power Plant of China National Energy Co., Ltd. (2006)".} \]
Financial cost: The cost of SPP repaying bank interest. The enterprise pays off the debt by means of average capital plus interest, which formulation is following:

\[
L_p = \frac{(1 + \lambda)^{N_b}}{(1 + \lambda)^{N_b-1}}
\]  

(11)

Other expenses: miscellaneous, maybe including some purchasing items.

Table 6 shows that the cost and composition about power generation (unit: million RMB yuan).

4. Discussions

4.1 Sensitivity analysis

Because the input and output in Section 3 are only for one scenario, we shall conduct a simple sensitivity analysis. When some parameters change, the unit power generation cost would change. i.e. fuel cost and water expense shown in Table 6. Besides, power generating hours, total investment and rate of power consumption in production can also affect unit cost of power generation. Most of the total investment is used for fixed assets, so its change will also lead to the change in the depreciation cost.

Assume that “Other expenses” can be deducted by only 50%, so the tax is 2.50 × 50% × 17% = 0.21 million RMB yuan/year. Enterprise’s tax liability is 11.67 – (8.80 + 0.18 + 0.09 + 0.92 + 0.21) = 1.47 million RMB yuan/year.

There are the following basic conditions about uses of funds. The proportion for the first years is 60%, and for the second year is 40%. Capital source: the registered capital occupies 30% of the capital, and the rest is from the bank loans. Project construction cycle is 2 years. So “Financial cost” is 28.19 million RMB yuan/year.

At last, we obtain the unit cost of the electricity production, 0.780 RMB yuan/kW h that higher than 0.745 RMB yuan/kW h of coal-based on-grid tariff in 2010.
We think that the power generation cost of 25 MW can represent the cost of other capacities. Although the cost structure of 25 MW is different from that of other capacities, e.g. according to Fig. 1, the average unit investment of the 25 MW projects is $1.12 \times 10^7$ RMB yuan/MW, the rest are $1.00 \times 10^7$ RMB yuan/MW and $0.93 \times 10^7$ RMB yuan/MW, its on-grid quantity of electricity is highest (see data in 2010 of Table 3) because the efficiency of 25 MW equipments is highest as the above mentioned, and then the investment of unit on-grid quantity of electricity is almost the same ($1.7$ RMB yuan/kW h). In fact, the generating power cost of the SPP in Rudong [30] and Chuzhou of Huai’nan [39] both was $0.90$ RMB yuan/kW h.

4.2. Cause of the high power generating cost

From Table 6 and the sensitivity analysis results, we can conclude that the high power generating cost is associated with five problems (see Fig. 3), namely, price at plant, use ratio of the equipment, maintenance cost of the equipment, power consumption in production and total investment cost. The light green boxes indicate that they are the basic causes, which are expressed as C1–C5, and are further explained below.

C1: Straw Characteristics. Chemical constitutions of straw are including Na, Si, S, K, Cr, Fe and Cl what make boiler corrode and incrust when straws burn [40,41]. The density (weight volume ratio) of straw is small, and soft straws are fluffy, flexible, bad floating so that they twist each other to feed difficulty and jam easily in conveying [42].

C2: Mismatch between demand and supply. The continuous demand for straw in the power generating does not match crop harvesting twice a year. Hence, the enterprises need a lot of inventories and storage space or land area.

C3: Immature technology. The boiler was initially designed only suitable for one kind of biomass. The boiler fired many kinds of fuels in production, which not only increased boiler corrosion and incrustation, but also had boiler insufficiently burn [43]. The feeding system had the problems, too [42]. The equipments often went wrong and needed to be repaired or improved [5,41], no matter whether they was imported or manufactured domestically. Immature technology leads to the high price of equipment what cannot be made in lot. The price of some import equipments was 4–10 times the prices of the domestic equipment [5,44].

C4: Inappropriate project planning. Inappropriate project planning consisted in: (i) project location. There are three SPPs in Suqian, at a distance of 30–50 km away from each other [4,5]. The straw knitting in Rudong, Nantong had been developed several decades and became a mature industry [45]. (ii) Equipment choice. High temperature and high pressure technology of boiler is the most advanced one in the world [10], but it was only applied in decade and became a mature industry [45]. (iii) Equipment choice. High temperature and high pressure technology of boiler is the most advanced one in the world [10], but it was only applied in

C5: Low motivation of farmer selling straw. C5 is explained in Section 2.3, and C5 & C4 are combined causes for insufficient straw supply that it is the main obstacle of biomass CHP. Heat supply needs continuous production and more fuel, especially in winter

10 A few of application for the high temperature and high pressure technology is due to “Demonstration catalogue of national advanced pollution abatement technology” by the Chinese Government issued in 2006, which it encouraged enterprise to use the medium temperature and medium pressure technology.
while purchasing straw is the most difficult task. In JSP, 7 SPPs
planned on CHP when the projects feasibility argumentation, and
3 SPPs supplied heat in practice.

4.3. Countermeasures

We have no good measure to cope with C1 & C2 because they
are natural and impersonal factors, but can give following sugges-
tions for C3–C5.

About C3. The Chinese Government funded the 52 national-le-
vel R&D projects with the total about 32 million RMB yuan from
2007 to 2010. The 120 invention & utility model patents had been
approved from 2007 to 2011. However, there are more or less the
similar in these subjects or achievements, such as, there were 22 for
combustion mechanism and effect, 5 for feeding system, 17 for flu-
idized bed and boiler, 2 for packer in the research projects, and there
were 42 for feeding system, 8 for crusher, 4 for boiler in the patents.
Apparently, it should integrate the existing science and technology
resources to solve key and difficult problems. For example, the
state-level R&D center should be established and the achievements
are able to be shared by the proper benefit distributing measures.

About C4. A SPP can obtain straw from a farmer, broker and
cooperative. Since 2009, many cooperatives were suddenly set up
for straw collection and utilization in JSP, such as there were 23
cooperatives with the total registered capital 73.39 mil-

![Fig. 3. Causes of high power generating cost.]

High price at plant
Low use ratio of equipment
High maintenance cost of equipment
High power consumption
High project investment

A little combined heat and power
More fault of equipment
Difficult feeding
Corrosion & incrustation
Incomplete combustion

Chemical constitution
Bad floating
Low density

Large volume
More inventories
High equipment price

C1: Straw characteristics
C2: Demand no match supply
C3: Less mature technology
C4: Inappropriate project planning
C5: Low motivation of farmer selling straw

Insufficient straw supply
More straw demand of relative plants

Large collecting radius
High shipping cost
High purchasing price
Large volume
More inventories
High equipment price

Fig. 3. Causes of high power generating cost.

12 Data source: http://www.sipo.gov.cn/zljs/