Applied Energy 114 (2014) 717–723

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Potential usage, vertical value chain and challenge of biomass resource: Evidence from China's crop residues

Jun Yang [a,c], Xiaobing Wang [a,*], Hengyun Ma [b], Junfei Bai [d], Ye Jiang [e], Hai Yu [f]

[a] Center for Chinese Agricultural Policy, Institute for Geographical Sciences and Natural Resource Research, Chinese Academy of Sciences, Jia 11, Datun Road, Beijing 100101, China
[b] College of Economics and Management, Henan Agricultural University, 95 Wenhua Road, Zhengzhou 450002, China
[c] School of International Trade and Economics, University of International Business and Economics, 10 East Huixin Street, Chiaoyang, Beijing 100029, China
[d] College of Economics and Management, China Agricultural University, 17 Qinghua East Road, Haidian District, Beijing 100083, China
[e] College of Economics and Management, North China Electric Power University, 689 Huadian Road, Baoding 071000, China
[f] Policy Research Center for Environment and Economy, Ministry of Environmental Protection, 1 South Yuhui Road, Beijing 100029, China

HIGHLIGHTS

- China owns large quantity of crop residues to develop the renewable energy.
- Priority of using crop residues should be different across provinces.
- Policy supports are critical for the existence of power generation plant.
- Important to increase power generation efficiency and lower the cost of feedstock.

ARTICLE INFO

Article history:
Received 24 September 2012
Received in revised form 22 February 2013
Accepted 10 October 2013
Available online 7 November 2013

Keywords:
Renewable energy
Crop residue
Vertical value chain
Cost-benefit analysis

ABSTRACT

China's energy needs and its environment are facing great challenges because of the country's rapid urbanization and industrialization. It is China's strategic choice to exploit renewable energy to guarantee its energy security and reduce CO_2 emissions. Crop residue has been identified and targeted by the Chinese government as a promising renewable energy resource. The purposes of this study are to investigate the potential supply of crop residue nationally and regionally, the vertical value chain from the field to final usage of these crop residues, as well as to conduct cost-benefit analysis on power plant-based crop residue. Our results show that the large amount of crop residue in China has great potential to meet the country's demand for renewable energy. Crop residues, however, are distributed unequally across regions. Therefore the use of crop residues to produce energy should be different across provinces, especially with respect to large power generation plants. Government supports right now are critical for power plants based on crop residue to survive. Based on our findings, it is suggested that China should attach more importance to technology innovation and creative policy reforms to improve the overall efficiency of the industry and reduce the cost of feedstock.

1. Introduction

China is confronting severe challenges to meet its rapidly increasing demand for energy. It is well known that over the past several decades China has experienced remarkable economic growth. The annual growth rate of gross domestic product (GDP) reached 10.4% between 1979 and 2010 [1]. Along with the rapid economic growth, China's energy consumption rose significantly, increasing annually by 9.1% during 1992–2010, which was much faster than the world average of 2.6% [2]. Although great efforts have been made to improve China's domestic energy supply by carrying out market-oriented reforms and promoting production efficiency, China became a net energy importer in 1992 and even then its energy deficit continued to rise rapidly [1]. The dependence on foreign trade of petroleum and natural gas has exceeded 55% and 24% respectively in 2011 [3]. Exploiting new energy sources has become a strategic choice for China in order to secure a reliable energy supply and maintain its high economic growth [4–7].

Meanwhile, China must deal with a deteriorating environment and face the rising pressure to reduce its carbon dioxide (CO_2) emission. China's energy consumption is dominated by coal, accounting for 70.5% of total primary energy consumed in 2010 [2]. The use of coal has dropped continuously in recent years [3]. Despite that, because the combustion of coal is the main source of pollution and CO_2 emission, China surpassed the USA in 2005

* Corresponding author.
E-mail address: xbwang.ccap@igsnrr.ac.cn (X. Wang).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.10.019

and now contributes more CO_2 emissions than any other country in the world [8]. The severe and worsening environmental problems in China and increasing pressure worldwide to reduce CO_2 emissions precludes China from following previous conventional development patterns and suggests that China should make it a priority to develop and use clean energies [9,10].

Crop residues have proved to be one of the most promising clean energy resources for energy supply in China [11,12]. A large amount of crop residues are available in China [13,14] and the supply is expected to keep rising in the future as agricultural production increases [15,16]. Moreover, the significance of power generation from crop residues is not just as an energy supplement. It has great potential to increase farmers' incomes and resolve the serious air pollution caused by burning crop residues in the open field [17,18]. The development of biomass energy has attracted attention both by energy industrialists and policymakers in China. The bio-energy from crop residues has been targeted in the Twelfth Five-Year Plan for national economic and social development.

Researchers have become interested in analyzing the potential use of crop residues and other biomaterials in China because of the country's energy shortage and widespread concerns about environmental issues. While the estimates vary among studies, it is agreed that large amounts of crop residues are available for energy production in China [13,14,19–21]. For example, Shi estimated that in 2007 about 704 million tons of crop residues were available based on 9 crops[1] [13]. The estimate would increase to 840 million tons when herbs and vegetables were further considered [14]. Furthermore, the use of bio-energy in China could lead to a more efficient use of marginal lands to expand agricultural production [13]. However, the development of bio-energy based on crop or crop residue should be region specific because the supply of agricultural residues is spatially heterogeneous [12,21,22].

Despite the large volume of crop residue in China, the outlook for bio-energy is far from optimistic because of high production costs [18,23,24]. For example, Yu and Tao conducted several case studies by using the 3E Life Cycle Assessment (LCA) approach to evaluate the efficiencies of several biomass-based fuel ethanol projects in China. They concluded the ethanol production based on wheat and corn is not economically viable and second-generation biofuel is even less so [18]. Even with high subsidies, the power plants based on crop residues could not compete with their conventional counterparts [23,24].

Given the importance, potential future prospects and many controversial issues, the development of bio-energy based on crop residue in China needs deeper and more systematic study to address development problems, efficient strategies and needed policy supports. Current literature mainly focuses on the availability of crop residues in China. Few studies analyze key factors undermining development. A number of questions remain unanswered. For example, how will the spatial heterogeneity of resources among provinces influence the capacity of power generation? How will it be affected by storage and transportation costs? What are the benefit and cost comparisons of biomass power plants? What are the main constraints and challenges of the development of biomass power plants? Answering these questions has important policy implications for sustainable agricultural and renewable energy economies in China.

The study seeks to determine what key elements affect the development of power generation from crop residues and what technologies and policies would be most effective. To meet our objectives, the paper is organized as follows: Section 2 estimates the potential availability of crops residues nationally and regionally; Section 3 describes the value chains of supplying crop-derived biomass from the crop field to power generation plants; Section 4 uses cost-benefit analysis and sensitivity analysis to highlight key points related to the development of power generation plants from crop residues; and Section 5 provides research conclusions and suggests policy implications.

2. The potential of crop residues used for biomass energy

The availability of substantial crop residues provides important opportunities for China to develop biomass energy. Since no official statistics exist on the crop residues and their coal equivalent, China's biomass potential can be estimated from the crop output in two steps. First, the amount of crop residue is estimated by transforming the crop output weighted by residue ratio for each of crops [11,12]. Second, there is evidence that crop residue is discounted depending on the crop because of different collection costs, which are measured by the collection ratio of residue and which vary by 10% across crops from 0.80 for yam to 0.90 for cotton (Table 1). This suggests that the previous estimation of Chinese biomass resources without taking the collection residue ratio into consideration will overestimate the biomass potential [28].

Using the above procedures, the calculated potential of crop residue in China is shown in Table 1. This approach shows 729 million tons of crop residues produced in China in 2010, an estimate that is similar to those produced by Shi [13], Wang and Zhang [19] and Zhang et al. [21]. This amount of crop residue is equivalent in terms of energy content to 364.39 mmt standard coal (Table 1).

The energy stored within agricultural residue is potentially an important resource to increase the energy supply in China. Fig. 1 presents the potential biomass of coal equivalent and coal consumption in the past three decades. Chinese biomass potential is substantial given that the coal equivalent of biomass increased at the annual growth rate of 2.7% from 1978 to 2010 [1]. As discussed previously, this growth rate is expected to be stable and may even increase in the future [29]. While the ratio of potential energy from crop residues to total energy consumption dropped a little bit as the higher growth of energy consumption in 1978–2010, the biomass in China could still supply a large amount of energy, accounting for 11.3% of total energy consumption in 2010 (Fig. 1).

The output and distribution of crop residues, which is highly correlated with crop production structure and cropping intensity, is geographically heterogeneous both across and within provinces [26,30]. As shown in Panel A of Fig. 2, crop residues are mainly concentrated in regions of Northeast (Heilongjiang, Jilin, Inner Mongolia), Central (Hebei, Henan, Shandong, Jiangsu, Anhui and Hubei) and Southwest (Sichuan) China. Interestingly, it is found that many severe energy-deficit regions overlap with regions which have a rich supply of crop residues. As shown in Panel B of Fig. 2, there is an energy shortage in the Eastern and Southern coastal areas (i.e., Hebei, Shandong, Zhejiang, Jiangsu, Fujian and Guangdong) as well as in the Central area (Hubei and Hunan) and in Southwest area (Sichuan) [1,31]. There are obvious overlaps in regions of Hebei, Shandong, Jiangsu, Hubei and Sichuan. No doubt, the bio-energy development provides opportunities both to alleviate the energy deficit and increase farmers' incomes in those regions. Regions in Northeast China with plenty of crop residue and a balanced supply and demand for energy still could increase their energy production to mitigate the overall energy-deficit situation for the entire country.

3. The vertical value chain from field to power generation

This section will analyze the vertical value chain of crop residues from field to power generation plants. The entire chain

[1] It includes rice, wheat, maize, other grains, beans, tuber crops, oilseeds, cotton and sugar cane.

consists of a number of consecutive stages and one or more independent agents at any stage. As shown in Fig. 3, the power generation plants are defined as down-stream. The middle-stream includes agents or firms responsible for crop residue collection, transportation, storage and solidifying them into an energy resource. The up-stream consists of rural households with tiny plots of land of about 0.14 hectare per household scattered on the fragmented plots. The small size makes the crop straw collection, storage and transportation very expensive in China [27,32–34]. Therefore, the power generation industry from crop residues can be characterized as an inverted-pyramidal-hierarchic strategic network. Such networks have a local firm that is expected to manage the system in order to realize its targeted output.

3.1. The modes of collection

Three parallel modes emerged in the collection of crop residues from households or farms (Fig. 3). One is an agent or firm which specializes in collecting crop residues either directly from the field or supplied by households or farms. These residues are then delivered to the middle-stream firms or directly to power generation plants. It is noted that very few of the agents and firms have warehouses suitable for storing crop residues in China [35]. A second mode includes power generation plants that are set up as collection branches, normally in a circle of 30–50 km around the plants [36,37] where households or farmers deliver their crop residues. The third includes power generation plants that contract with households or farms to harvest crops like rice, wheat and corn, then send the useable output to the households or farms and the crop residues to power generation warehouses. However, this mode is not found in the major crop producing regions where mechanization is possible.

3.2. The storage

One of the major constraints that limit the effective use of crop residues is the storage cost due to the seasonal and spatial distribution of crops residues [33,35]. Crop residues that are characterized as loose and low density need a certain size of open area or warehouse to store. Generally, only power generation plants have the storage condition to meet the demand of biomass resources for at least 5–7 days. In China, the building and maintenance of these warehouses by Chinese smallholders are constrained by credit and land [34,35].

3.3. Solidifying crops residues into energy resource

The conversion of crop residues into biomass for power generation has developed rapidly in China and is defined as the biomass solidification technology, which is one of the universal and effective technologies for bio-energy utilization [38,39]. Under the right temperature and pressure, the pieces of crop residues are solidified into solid biomass fuel with certain shape and density through a process of drying and grinding. Biomass solidification technologies applied in China include screw extrusion, the piston stamping, molding, rolling and fiber grinding technologies. Crop residues will be compressed into lignin pellet fuel or briquettes in about 1/6–1/8 of its original volume and the density of 1.1–1.4 t/m^3, which is equal to mid-quality coal and suitable for use both by power generation plants and households. Within the Medium- and Long-term Program of Developing Renewable Energy (MLPDR) implemented by National Development and Reform Commission (NDRC) in 2007, the industry of solidifying crops residues into energy resource is highly recommended. By 2020, the annual supply of solid biomass fuel will increase 50 times to 50 mmt from the level of 1 mmt in 2010 and zero in 2005 [40].

3.4. Power generation from solidified crop residues

Power generated from solidified crop residues is achieved through three technologies: direct combustion, mixed fuel and gasification, of which the first two are commercialized in China. The energy conversion process could be simplified as:

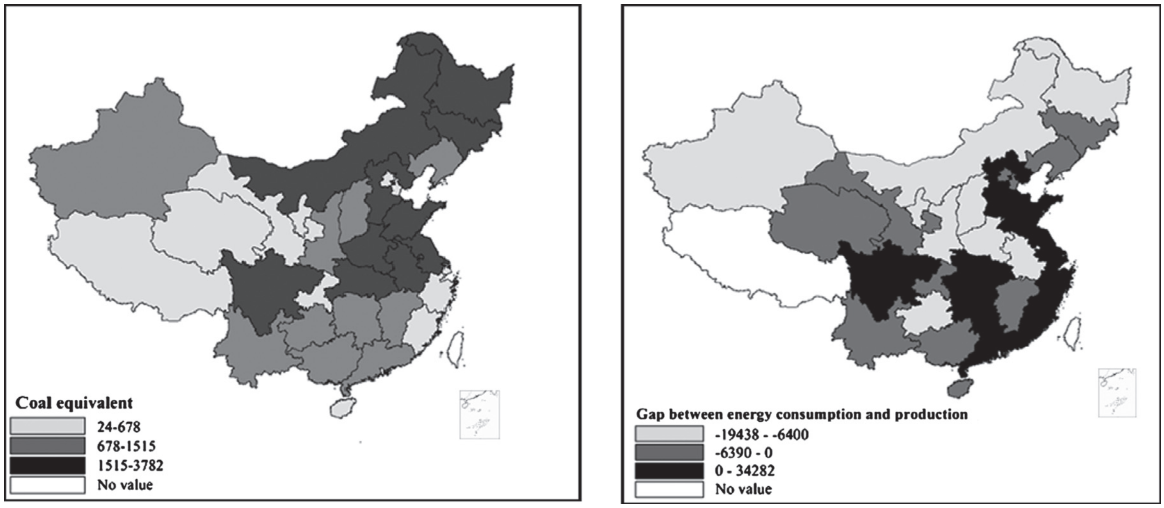
$$\text{Chemical energy} \rightarrow \text{Heat} \rightarrow \text{Mechanical energy} \rightarrow \text{Power}$$

Stage one combusts the lignin pellet fuel or briquettes solidified from crop residues in the boiler to convert chemical energy into heat energy. In stage two of converting heat to mechanical energy, through a process of high temperature and pressure, the saturated steam is pressed into a steam turbine to drive the rotation of turbine-generator unit. Finally, the power generator converts mechanical energy into power. Several specific technologies are involved in the energy conversion process. Any innovation related

Table 1
Crop production, potential residues and biomass fuel potential at coal equivalent in China in 2010.

Crops	Production[a] (mmt) (1)	Residue/crop ratio[b] (2)	Output residues (mmt) (3)[e]	Collection residue ratio[c] (4)	Potential collection of residues (mmt) (5)[f]	Ratio of coal equivalent (6)	Coal efficiency [d] (7)[g]	Energy from crop residue (mmt) (8)[h]
Rice	195.76	1.1	215.34	0.83	178.73	0.43	0.39	76.68
Wheat	115.18	1.1	126.70	0.83	105.16	0.50	0.46	52.58
Maize	177.25	2.0	354.49	0.83	294.23	0.53	0.88	155.65
Beans	18.97	2.0	37.93	0.88	33.38	0.54	0.95	18.13
Yam	31.14	1.2	37.37	0.80	29.90	0.49	0.47	14.53
Cotton	5.96	3.0	17.88	0.90	16.10	0.54	1.46	8.74
Oilseeds crops	32.30	3.0	17.88	0.85	61.45	0.53	1.35	32.51
Sugar crops	120.09	0.1	12.01	0.88	10.57	0.53	0.05	5.59
Total	696.64	–	819.60	–	729.50	–	–	364.39

[a] Calculated based on [25].
[b] Residue/crop ratio (column 3) is obtained from [26].
[c] Collection residue ratio (column 4) is obtained from [12].
[d] Ratio of coal equivalent (column 7) is obtained from [27].
[e] Column (3) = (1)*(2).
[f] Column (5) = (3)*(4).
[g] Column (7) = (2)*(4)*(6).
[h] Column (8) = (5)*(6).



Panel A: Coal equivalent [a] (10 thousand tons) of crop residues in China

Panel B: The gap between energy consumption and production (10 thousand tons)

Fig. 1. Spatial distribution of coal equivalent of crop residue, the gap between energy demand and supply, coal production by province in 2010. [a]– Crop residues at coal equivalent are calculated by the potential collection of crop residues multiply ratio of its coal equivalent. The crops included and calculated procedures are exactly same to Table 1. *Source:* China agricultural Statistics Yearbook [25], China Energy Statistics Yearbook [27].

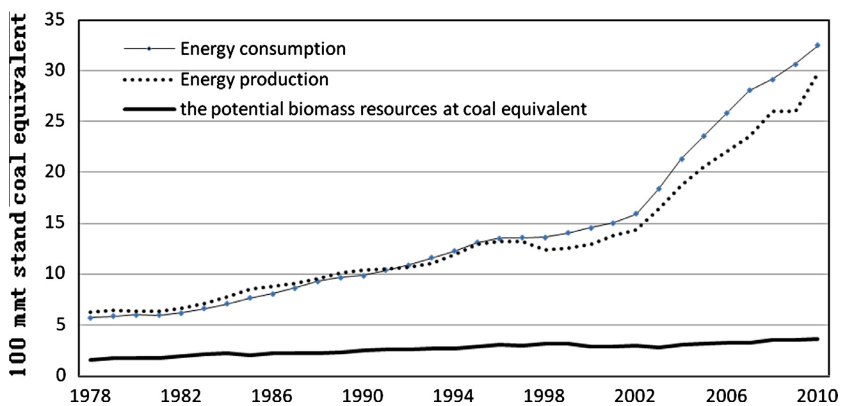


Fig. 2. The trend of potential biomass resources at coal equivalent, energy demand and supply from 1978 to 2010. *Source:* China agricultural Statistics Yearbook [25], China Energy Statistics Yearbooks [27]

to these technologies will improve the overall efficiency and affect the development of power generation from crop residues in China.

Although China has launched three pilot projects of crop straw biomass power generation since 2003, much later than in most of the developed countries, this industry has developed rapidly with preferential policy support on investment, subsidy and tax reduction [31,36]. The first power generation plant where power was generated completely from crop residues was officially approved by NDRC in Jinzhou country of Hebei province. The total investment was 260 million RMB (41.2 million US$) and electricity of 130 mm kW h supplied annually after construction [40]. According to the MLPDR, 200 billion RMB (or about 31.67 billion US$) were appropriated to improve the capacity of biomass power generation by China's local governments. Meanwhile, the subsidy was tied to the price of electricity on the grid for 15 years from the commercialization of biomass power generation plant at 0.25 RMB/kW h (0.04 US$/kW h). The price of electricity including tax generated from crop residues is 0.75 RMB/kW h (0.12 US$/kW h), much higher than that from traditional coal (0.35–0.45 RMB/kW h) [41].

Table 2 tabulates the capacity installment of power generation plants by 2009 by province. It is noted that the numbers reported in the table only include those which were in operation in 2009 and obtained subsidies on the electricity price from the government [31]. By 2009, less than half of China's provinces had built biomass power generation plants based on feedstock of crop residues. The total installed capacity is 1193 MW. As shown in Fig. 4, more than half of the enterprises have capacity of over 20 MW. Four major agricultural producing provinces (Jiangsu, Shandong, Henan and Heilongjiang) are leading in both the number of the plants and the installed capacity.

4. Cost-benefit analysis of biomass power generation

Many studies have shown that the suitable scale of biomass power plant in China should be between 20 MW and 60 MW [42]. As shown in Table 2, the average capacity of power plants installed in provinces is about 24 MW or smaller. Therefore, this study uses the 24 MW power plant as representative to carry out a cost-benefit analysis and emphasize the key factors influencing the profitability.

According to the China Electricity Industry Annual Report 2010, about 65 million RMB (or about 10.3 million US$) is required to construct a steam power generation plant on the scale of 24 MW. As shown in Table 3, excluding the 13% internal utilization, it could provide 114.8 TW h power for sale [42]. Many similar studies have

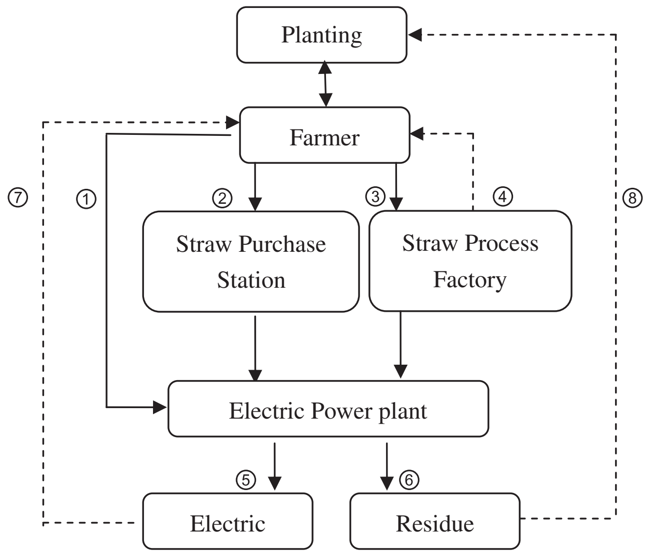


Fig. 3. Illustrating the vertical chain of crop residues from the field to power generation plants. ① Farmers directly sell the straws to power generation industries; ② Power generation plants collect crop straws from farmers through straw collection stations they set up in different regions; ③ Straw processing corporations collect crop straws from farmers, processed them and then sell to power generation industries; ④ The straw processing corporation sell the processed energy resource to famers; ⑤ Power generation industries use solidified crop residues to generate electricity; ⑥ The by-product from electricity generated from crop residues in the process of electric generation; ⑦ Electricity is sent to farmers; ⑧ The residues from the process of electricity generation can be used as fertilizer by farmers.

indicated the power generation efficiency of power plant scaled at 24 MW is about 18%, equivalent to the conversion ratio of dry crop residue to electricity of 1.35 kg/kW h [42,43]. Therefore, it is estimated 178.2 thousand tons of dry crop residue are needed, which costs about 53.5 million RMB (or 8.5 million US$) for feedstock at a price of 300 RMB/ton (47.5 US$/ton) [34,42], and 15.2 million (2.4 million US$) for consolidation cost at a price of 85 RMB/ton (13.5 US$/ton) [44]. When other expenditures (labor cost, capital depreciation, management and operating cost) are considered, the total cost per year is about 84.4 million RMB (13.4 million US$). As shown in column 1 of Table 3, even excluding tax and the distribution cost, the break-even electricity price is about 0.74 RMB/kW h (0.12 US$/kW h), which is too high to be competitive with the present electricity price of 0.45 RMB/kW h (0.07 US$/kW h). The power generation plant only has a marginal profit of 2.0% even under the high supported price of 0.75 RMB/kW h (0.12 US$/kW h). No doubt, it was impossible for power plant to survive without government subsidies.

It is critical to improve the power generation efficiency and reduce the cost of biomass feedstock in order to enhance the sustainable development of power generation plants from crop residue. According to the above calculation, the production cost is dominated by the cost of crop residue and consolidation, which accounts for 63.4% and 18% respectively (Table 4). Consequently, the competitiveness would increase remarkably if the cost of feedstock was effectively reduced. In order to capture the impacts of technology improvement and cost reduction, a sensitivity analysis, composed of four alternative scenarios, is developed. As shown in Table 3, the first is the alternative scenario of higher power generation efficiency, under which the power generation efficiency increases to 28% [42]. The reduction of feedstock cost and consolidation costs are considered separately in the second and third alternative scenarios. The price of crop residue and consolidation drops to 200 yuan/ton and 40 yuan/ton respectively. The combined effects of the three alternative scenarios are evaluated in the fourth scenario.

As expected, the profitability of power plants based on crop residues would improve significantly if the new technology was adopted and the cost of feedstock was reduced. As shown in Table 4, the break-even electricity price will drop to 0.62 RMB/kW h (0.10 US$/kW h) under the scenario of high power generation efficiency. The profit ratio will rise to 20.0% under the high supported price of 0.75 RMB/kW h, much higher than 2.0% in the current situation. Meanwhile, any crop residue price and consolidation reduction will lower the cost of power production significantly because of their overwhelming cost shares. With other costs held constant, the break-even electricity price would drop to 0.58 RMB/kW h (0.09 US$/kW h) under the scenario of lower crop residue cost (column 3 of Table 3), to 0.67 RMB/kW h (0.11 US$/kW h) under scenario of lower consolidation cost (column 4 of Table 3). The profit ratios in the two alternative scenarios will also increase dramatically to 29.2% and 12.7% respectively with the high supported price of 0.75 RMB/kW h.

Furthermore, if the joint effects of improving power generation efficiency and lowering cost of feedstock mentioned above are taken into consideration together, the break-even electricity price can be reduced to 0.44 RMB/kW h (0.07 US$/kW h), which is even lower than the present electricity price (0.45 RMB/kW h). In this case, the profit ratio will rise to 69.8% with the high supported price of 0.75 RMB/kW h (column 5 of Table 3). It is likely that such

Table 2
Tabulating the number of power generation industries by the categories of installed capacity and province in 2009. *Sources:* China price yearbook (NSBC, 2010).

Province	Installed capacity (MW)					
	⩾30	20–30	10–20	⩽10	Total	Total capacity
Jiangsu	5	5	3	0	13	317
Shandong	3	3	1	1	8	177
Henan	1	3	3	1	8	155
Heilongjiang	1	1	5	1	8	118
Hubei	0	4	0	0	4	97
Hebei	0	3	0	0	3	72
Jilin	1	1	1	0	3	67
Inner Mongolia	0	1	2	0	3	48
Hunan	0	0	2	0	2	27
Anhui	1	1	0	0	2	55
Xinjiang	0	0	1	0	1	24
Liaoning	0	0	1	0	1	12
Zhejiang	0	0	1	0	1	12
Shanxi	0	0	1	0	1	12
Total number[a]	12	22	21	3	58	–
Total installed capacity (MW)	366	533	276	18	–	1193

[a] The numbers of power generation industries from crop residues are those commercialized and obtained subsidy on the electricity price from government in 2009.

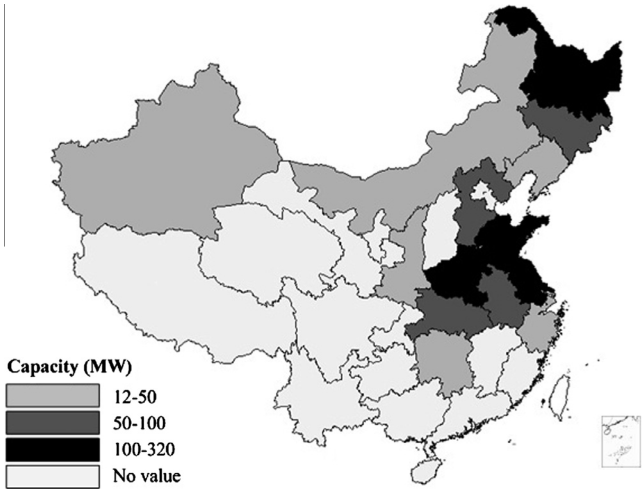


Fig. 4. Capacity (MW) of power generation industries based on crop residues installed by provinces in 2009. *Sources:* China price yearbook (NSBC, 2010).

a high profitability would lead to increased investment in and quick development of power plants based on crop residues in China.

5. Conclusions and policy implications

A larger share of the expected growth in energy demand could be supplied through utilizing agricultural residues to develop biomass energy in China. China's energy and environment are facing great challenges because of urbanization and industrialization. With its rapid economic growth, China's primary energy consumption has increased dramatically on average by 8.9% per year in the past decade. It is the top priority for Chinese government to find alternative energy to maintain its energy supply. According to our and previous studies, crop residues could be a promising energy resource. Even if one accounts for the loss of collection and excludes the moisture and ash contents, about 729 million tons of crop straw are available annually, which is equivalent to 364 million tons of standard coal. This accounted for about 11.3% of total primary energy consumption in 2010. While it is not fully discussed in the paper, the renewable energy generated from crop residues will definitely contribute to China's CO_2 reduction and also eliminate serious environmental issues caused by residue directly burned in open fields [17,18,45].

Although crop residues are one of the promising renewable resources, several critical issues need to be addressed according to our findings. First, as the spatial distribution of crops residue varies remarkably, the priority of using agricultural residues as energy resources should be different across provinces, especially for the large power generation plants. Second, government support is currently important and is needed for power generation plants to survive and develop. Our results illustrated that without the subsidy from government, the power plant cannot guarantee the normal operation due to the high cost of the biomass materials, lower price of electricity, and higher investment needed for capacity building.

China should attach more importance to the technology innovation and creative policy reforms related to efficient usage of crop residue. As analyzed, the production cost is dominated by feed-

Table 3
Key parameters to affect the production cost of power generation plants based on crop residues (Yuan/ton).

	Current situation	Sensitive analysis			
		Higher efficiency	Lower crop residues cost	Lower consolidation cost	Combined effects
Power generation efficiency (%)	18[a]	28[b]	-s-	-s-	28
Feedstock demand (kg/kW h)	1.35[a]	1.1[b]	s	s	1.1
Price of crop residue	300[b]	-s-	200	-s-	200
Price of consolidation	85[c]	-s-	-s-	50	50

Note: -S- means the value same to the correspondence of current situation.
[a] Estimated by [42,43].
[b] Estimated by [42].
[c] Estimated by [44].

Table 4
Cost-benefit analysis of biomass power generation with scale of 24 MW, and sensitive analysis with changes of key parameters (10 thousand Yuan).

	Current situation	Sensitive analysis			
		Higher efficiency	Lower crop residues cost	Lower consolidation cost	Combined effects
Installed capacity (10^4 kW)	2.4	2.4	2.4	2.4	2.4
Equipment investment	6500	6500	6500	6500	6500
Utilized hours per year (h)	5500	5500	5500	5500	5500
Electric energy generated (10^4 kW h)	13,200	13,200	13,200	13,200	13,200
In-plant power consumption rate (%)	0.13	0.13	0.13	0.13	0.13
On-grid electricity (10^4 kW h)	11,484	11,484	11,484	11,484	11,484
Crop straw consumption (10^4 ton)	17.82	14.52	17.82	17.82	14.52
Operation costs					
Crop residues (freight included)	5346	4356	3564	5346	2904
Crop residues curing costs	1515	1234	1515	713	581
Depreciation of fixed assets [a]	412	412	412	412	412
Management costs [b]	360	360	360	360	360
Financial costs [b]	228	228	228	228	228
Operational costs-repairs [b]	130	130	130	130	130
Other costs [b]	457	457	457	457	457
Total costs	8448	7177	6666	7646	5072
Break-even price (RMB/kW h)	0.74	0.62	0.58	0.67	0.44
Profit rate (%)	2.0	20.0	29.2	12.7	69.8

[a] Estimation based on the assumption that the salvage value is 5% of the total investment, and the rest investment will be deprecated over 15 years.
[b] Values based on the estimated by [42,43].

stock. However, China's agricultural production is comprised of millions of small households, which make the collection, delivery and storage of crop residue not only difficult, but high risk to guarantee a stable supply [31,41]. Moreover, no closely coordinated mechanism is found between farmers and power plants in China. Therefore, it is critical for China to creatively design new policy to integrate the interests of all agents to efficiently lower the cost and uncertainty. Meanwhile, the development of profitable power plants based crop residue depends on breakthroughs in technology. Support policies should be diverted to research and engineering to create new technologies and more efficient supply chains, instead of maintaining the existence of current uncompetitive power plants. Policies should highlight the need for improved technology and systematic policy reform. Just as in the combined scenario, such improvements and reforms could make the power plant competitive and more profitable as both the efficiency improves and feedstock costs are reduced.

According to our studies, it is worth noting that several key issues need more intensive study in the future. First, the potential to improve the efficiency of power plants based on crop residues in China should be examined systematically with respect to technological innovation and operational optimization. Second, the interests of small households and power plants should be analyzed theoretically and empirically in order to closely integrate them through policy reforms. Finally, the optimal utilization of the unevenly distributed biomass should be addressed nationally and regionally. Those issues are critical for China to design the proper policies to support the development of renewable energies industries, and ultimately realize its strategic goals of maintaining high energy sufficiency and reducing CO_2 emission.

Acknowledgements

We would like to thank the financial support of Chinese Academy of Sciences (KZZD-EW-08-04) and China's Foundation of Soft Sciences (2009GXS5B084).

References

[1] NSBC [National Bureau of Statistics of China]. China's statistics yearbook. Beijing: China Statistical Press; 2005–2011.

[2] Tong X. Global demand and supply situation of petroleum and natural gas, as well as the China's development strategy. Beijing: Presented in seminar in economic and management forum; 2012.

[3] Economic and Technology Research Institute of China Petroleum Company. Global development of petroleum and natural gas sectors; 2011. <http://ishare.iask.sina.com.cn/f/25618166.html?from=dl>.

[4] Ma H, Oxley L, Gibson J. Gradual reforms and the emergence of energy market in China: evidence from tests for convergence of energy prices. Energy Policy 2009;37:4834–50.

[5] Liu W, Hu W, Lund H, Chen Z. Electric vehicles and large-scale integration of wind power – the case of Inner Mongolia in China. Appl Energy 2013;104:445–56.

[6] Jansson C, Westerbergh A, Zhang J, Hu X, Sun C. Cassava, a potential biofuel crop in (the) People's Republic of China. Appl Energy 2009;86(s1):95–9.

[7] Li S, Halbrendt C. Ethanol production in (the) People's Republic of China: potential and technologies. Appl Energy 2009;86(s1):162–9.

[8] EIA. International Energy Outlook. Washington, DC: Energy Information Administration; 2007.

[9] Liu T. Strategic thinking on China's energy development under the new era. Truth Seeking 2012;13:33–4 [in Chinese].

[10] Li JF, Wan YH, Ohi JM. Renewable energy development in China: resource assessment, technology status, and greenhouse gas mitigation potential. Appl Energy 1997;56:381–94.

[11] Tian Y, Zhao L, Meng H, Sun L, Yan J. Estimation of un-used land potential for biofuels development in (the) People's Republic of China. Appl Energy 2009;86(s1):77–85.

[12] Liu J, Wu JG, Liu FQ, Han XG. Quantitative assessment of bioenergy from crop stalk resources in Inner Mongolia, China. Appl Energy 2012;93:305–18.

[13] Shi Y. China's resource of biomass feedstock. Eng Sci 2011;2:16–23 [in Chinese].

[14] Bi Y, Wang D, Gao C, et al. Straw resources evaluation and utilization in China. Beijing: China Agricultural Science and Technology Press; 2008 [in Chinese].

[15] Huang J, Yang J, Rozelle S. China's agriculture: drivers of change and implications for China and the rest of world. Agric Econ 2010;41:47–55.

[16] Yang J, Qiu H, Huang J, Rozelle S. Fighting global food price rises in the developing world: the response of China and its effect on domestic and world markets. Agric Econ 2008;39:453–64.

[17] Matsumura Y, Minowa T, Yamamoto H. Amount, availability, and potential use of rice straw (agricultural residue) biomass as an energy resource in Japan. Biomass Bioenergy 2005;29:347–54.

[18] Yu S, Tao J. Economic, energy and environmental evaluations of biomass-based fuel ethanol projects based on life cycle assessment and simulation. Appl Energy 2009;86(s1):178–88 [in Chinese].

[19] Wang H, Zhang R. Utilization, distribution and exploitation tactics of crop stalk resources in China. J Shandong Agric Admin 2007;23(2):164–5 (in Chinese].

[20] Liu W, Lund H, Mathiesen BV, Zhang XL. Potential of renewable energy systems in China. Appl Energy 2011;88:518–25.

[21] Zhang P, Yang Y, Li G, et al. Energy potentiality of crop straw resources in China. Renew Energy Resour 2007;25(6):80–3 [in Chinese].

[22] Cai Y, Qiu H, Xu Z. Evaluation on potentials of energy utilization of crop residual resources in different regions of China. J Nat Resour 2011;26(10):1637–46 [in Chinese].

[23] Zhang Q, Zhou DQ, Zhou P, Ding H. Cost analysis of straw-based power generation in Jiangsu Province, China. Appl Energy 2013;102:785–93.

[24] Zhao X, Ma Y, Wang T, Song Z. The pretreatment technology of straw and economic analysis. Power Syst Eng 2008;3:30–3 [in Chinese].

[25] NSBC. Chinese agricultural statistical yearbook. Beijing: China Statistical Press; 2011.

[26] Liu G, Shen L. Quantitative appraisal of biomass energy and its geographical distribution in China. J Nat Resour 2007;22(1):9–19 [in Chinese].

[27] NSBC. China Energy Statistics Yearbook. Beijing: China Statistical Press [Various years from 2009 to 2011].

[28] Hallam A, Anderson I, Buxton D. Comparative economic analysis of perennial, annual, and intercrops for biomass production. Biomass Bioenergy 2001;21(6):407–24.

[29] Huang J, Yang J, Msagi S, Rozelle S, Weersink A. Global biofuel production and poverty in China. Appl Energy 2012;98:246–55.

[30] Rovere E, Pereira A, Simões A. Biofuels and sustainable energy development in Brazil. World Dev 2011;39(6):1026–36.

[31] Ma H, Oxley L, Gibson J, Li W. A survey of China's renewable energy economy. Renew Sustain Energy Rev 2009;14(1):438–45.

[32] Liu G, Hao D. Research on collection cost of crops residue and empirical analysis. Technol Econom 2006;2:85–8 [in Chinese].

[33] Liu H, Yin X, Wu C. Cost analysis of crop residue supplies. J Agric Mach 2011;42(1):105–12 [in Chinese].

[34] Cao Y, Shen H. A research on collection cost in the process of straw power generation. Power Energy 2012;5:463–6 [in Chinese].

[35] Han X, Wei Y, Qin D. How to establish strategic reserves of raw materials and scientific straw storage and transport model received. Energy Conserv Technol 2012;4:382–4 [in Chinese].

[36] Fan L, Zhang Y. Problem and implication for development of China's power generation plants from biomass. J North China Electric Power Univ 2010;2(1):10–3 [in Chinese].

[37] Zhang Y, Wang F, Zhao L, Sun L. The operating model, existing problems and development strategies for China straw storage and transportation system. Renew Energy Resour 2009;27(1):1–5 [in Chinese].

[38] Zhang B, Fan F, Li B, Zhang J. Analysis of industrialization prospect of biomass briquette technologies. J Henan Agric Univ 2005;39(1):109–14 [in Chinese].

[39] Han S. Research on straw curing technology and energy utilization. Res Agric Mach 2012;12:201–5 [in Chinese].

[40] National Development and Reform Commission. Medium- and Long-term Program of Developing Renewable Energy in China; 2007. <http://www.sdpc.gov.cn/zcfb/zcfbtz/2007tongzhi/t20070904_157352.htm> [in Chinese].

[41] China's New Energy Website. China's first power plant based on crop residues launched in JinZhou County; 2006. <http://www.newenergy.org.cn/html/0064/2006418_9739.html>.

[42] Wu C, Zhou Z, et al. Economic analysis of biomass gasification and power generation projects. Trans Polar Energy 2009;30(3):368–73 [in Chinese].

[43] ChangJiang Securities. Pilot and leader of development of power plants based on biomass; 2010. <http://www.gtja.com/bolanfile/attachments/201006/201006011642026816.pdf> [in Chinese].

[44] Li G, Wang G. Economical and policy analysis in the industrialization of biomass briquette fuel. Trans Chinese Soc Agric Eng 2006;22(s1):142–6 [in Chinese].

[45] Nguyen TJE, Hermansen JE, Mogensen L. Environmental performance of crop residues as an energy source for electricity production: the case of wheat straw in Denmark. Appl Energy 2013;104:633–41.