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Regionalized Techno-Economic Assessment and Policy Analysis for Biomass Molded Fuel in China

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Abstract: As a relatively mature technology, biomass molded fuel (BMF) is widely used in distributed and centralized heating in China and has received considerable government attention. Although many BFM incentive policies have been developed, decreased domestic traditional fuel prices in China have caused BMF to lose its economic viability and new policy recommendations are needed to stimulate this industry. The present study built a regionalized net present value (NPV) model based on real production process simulation to test the impacts of each policy factor. The calculations showed that BMF production costs vary remarkably between regions, with the cost of agricultural briquette fuel (ABF) ranging from 86 US dollar per metric ton (USD/t) to 110 (USD/t), while that of woody pellet fuel (WPF) varies from 122 USD/t to 154 USD/t. The largest part of BMF's cost composition is feedstock, which accounts for up 50%–60% of the total; accordingly a feedstock subsidy is the most effective policy factor, but in consideration of policy implementation, it would be better to use a production subsidy. For ABF, the optimal product subsidy varies from 26 USD/t to 57 USD/t among different regions of China, while for WPF, the range is 36 USD/t to 75 USD/t. Based on the data, a regional BMF development strategy is also proposed in this study.

Keywords: biomass molded fuel (BMF); pellet; briquette; techno-economic assessment; policy analysis

1. Introduction

Since it is responsible for more than half of all global energy demand, the heating and cooling sector is a cornerstone of any energy or anti-climate change strategy [1]. As 92% of all renewable heat is produced from biomass, bioenergy will play a key role in reducing the greenhouse gas footprint of this sector [2]. Biomass molded fuel (BMF) is a type of solid fuel made from biomass materials such as agricultural or forestry residues, *i.e.*, straws, cornstalks, peanut shells, wood branches, sawdust, shavings, *etc.*, [3] densified by molding machines. Densification of biomass has demonstrated numerous merits in improving the properties of biomass and possesses great potential for heating applications. One of the leading advantages of BMF is the highly increased specific weight. Typical unit densities of biomass pellets can be as high as 1000–1400 kg/m^3, and bulk densities are about 700 kg/m^3, while the density for grass type biomass ranges from 40 kg/m^3 to 150 kg/m^3, 150 kg/m^3 to 200 kg/m^3 for commercial wood chips, and 320–720 kg/m^3 for most types of dried hard- and softwoods [4]. This characteristic reduces logistical costs and gives BMF wider application. BMF offers many other advantages such as greater efficiency (less fuel required), lower emissions due to cleaner burning (less health and environmental impacts), easier operation, easier storage of fuel and eliminates the need for further drying of the fuel [5]. An emission savings of 77% can be realized by co-firing torrified pellets with fossil coal [6].

The global BMF industry has experienced tremendous growth in recent years. In 2006, worldwide wood pellet production (excluding Asia, Latin America and Australia) was between 6 million metric tons and 7 million metric tons, while in 2010 production in the same countries had increased to 14.3 million metric tons [7]. Europe ranks first worldwide in terms of wood pellet production and this advantage is expected to increase further; consumption of pellets in the EU steadily increased from 3.8 million tons in 2005 to 9.8 million tons in 2010 and is expected to reach 24 million tons by 2020, of which 11 million tons will be imported [8]. Similarly, in China, BMF is given great importance as a promising alternative source of renewable energy. In its 12th-five-year plan [9], China set a target of utilizing 10 million tons of BMF every year; and in the "Medium and Long-Term Development Plan for Renewable Energy in China", a target was set that by 2020, the annual use of BMF will reach 50 million tons [10]. With the support of a series of incentive policies such as feedstock subsidies and tax credits, the annual BMF output in China has increased rapidly to 6.3 million tons in 2014, 20 times that in 2008.

The techno-economic characteristics of BMF have been studied in many papers. Case studies have been carried out to make economic, environmental and social assessments of BMF in different countries and regions [11–16]; biomass briquette fuel systems have been optimized using gain and loss method [17], grey relational analysis [18], or mixed integer linear programming [19]. Policy analyses have also been carried out in this field: Doumax *et al.* [20] using a computable general equilibrium (CGE) model examined the efficiency of an alternative incentive scheme for biodiesel consumption and found that the 10% biodiesel mandate set by the European Parliament and Council 2009 Renewable Energy Directive (called RED) would not be achieved even if the fixed taxes on diesel reach the same level as those on gasoline; Bernard and Prieur [21] used a partial equilibrium model based on linear programming to evaluate the marginal revenues of liquid biofuels and calculate the minimum tax exemption; Zhang *et al.* [22] evaluated policies for current biomass power generation by calculating net present value (NPV) based on Monte-Carlo simulations. From the literature review we found that most policy analyses have focused on liquid biofuels and biomass power generation, whereas minimal study of BFM has taken place, moreover, most economic assessments of BMF in China have been based on one particular plant or conducted at the national level, with little research occurring at the regional level.

The study aims to address this gap, by evaluating the regional techno-economy for BMF in China and providing suitable policy recommendations for each region. The paper is organized as follows: the current situation is introduced first to provide relevant background; methodologies and data are then presented for understanding our results; regional BFM economic performance and suitable subsidies are calculated and analyzed; and finally, conclusions are drawn.

2. The Current Development Situation of Biomass Molded Fuel in China

2.1. Technologies

In most developed countries, BMF is composed of wood produced from sawdust obtained at sawmills, using a machine with a die block in the shape of a ring [23]. In China, the most commonly used BMF products are from agricultural and forestry residues, and mostly take the form of briquettes, pellets, and sometimes of rods. The technologies and products of BMF used in China are shown in Table 1 and Figure 1. Due to China's current status as an agricultural country, compared to developed countries, the technologies in China are still immature and vulnerable to various disadvantages: low mechanization level in feedstock collection; friction in the die blocks and rollers; short service life of key components; high energy consumption in the molding process; imperfect matching system; and high content of alkali and chlorine in BMF products, resulting in the slagging and corrosion of biomass boilers.

Table 1. Common biomass molded fuel (BMF) technologies in China.

Products	Machines types	Diameter	Raw material	Applications
Pellet	Ring/flat die pellet mills	<10 mm	Agricultural/ forestry residues	Small- and medium-scale distributed heating/exporting
Briquette	Ring/flat die briquette machine	10–25 mm	Agricultural/ forestry residues	Small- and medium-scale distributed heating
Rod	Piston presses machine/ screw extruder	>30 mm	Forestry residues	Large scale biomass boilers/ exporting

(**a**) (**b**) (**c**) (**d**)

Figure 1. Forms of BMF product in China: (**a**) pellet; (**b**) briquette; (**c**) rod; (**d**) hollow rod.

2.2. Industries

Although there is still a big gap between the BMF industry in China and that in developed countries, the industry has developed rapidly in China and shown marked progress in its technology R & D, machine manufacturing, formulation and implementation of standards, and service systems. By 2014, there were more than 1000 BMF production plants in China, with an annual output of 6.3 million tons, of which about two-thirds came from agriculture and the remainder from forestry. Figure 2 shows the annual BMF output from 2008 to 2014.

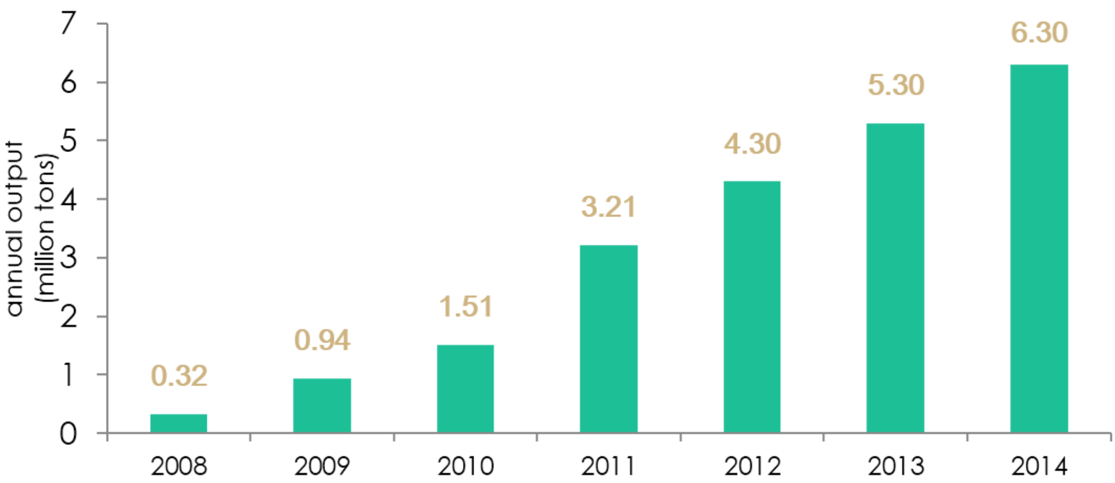


Figure 2. Annual BMF outputs (2008–2014) (source: the Energy Research Institute of the National Development and Reform Commission of China).

The BMF industry in China has a strong regional character. As a result of China's agricultural structure, most provinces in central, northern and eastern China, like Henan, Hebei, Shandong, and Anhui, have abundant agricultural residues, so agricultural briquettes fuel (ABF) dominates the BMF market in these areas. However, because of the relatively low economic level, environmental issues are not the primary concern in these areas, and there are no bans on coal in most of these jurisdictions. Since coal is the main fossil fuel being replaced by BMF, the market price of BMF is relatively low in these areas. Meanwhile, in northeastern provinces like Jilin, forestry residues are abundant and cheap; BMF in these regions consists mainly of woody pellet fuels (WPF). Figure 3 gives the regional BMF productions and consumptions.

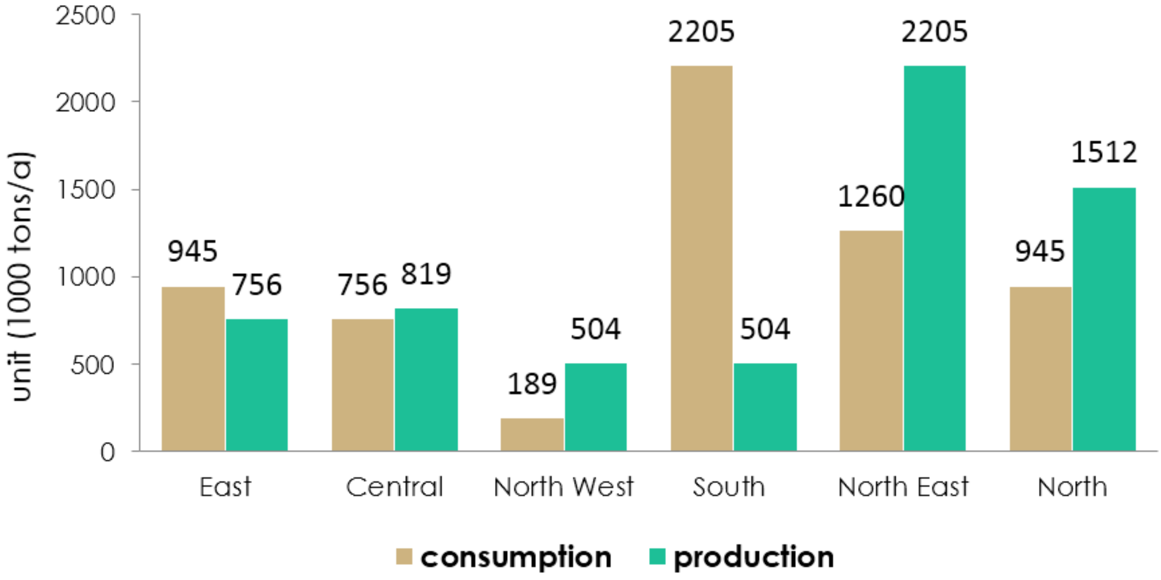


Figure 3. BMF production and consumption in China by region (2014) data source: field investigation.

2.3. Policies

BMF has attracted worldwide attention as a promising alternative fuel, and many countries have formulated policies to stimulate the development of this industry. In China, the main incentive measures have included the following:

- Target planning

As noted above, in its 12th-five-year plan, China set a target of utilizing ten million BFM every year; and in the "Medium and Long-Term Development Plan for Renewable Energy in China", an annual BMF use target of 50 million tons was set for 2020.

- Direct subsidies

The "Interim Measures for the Application of Agricultural Briquette as Energy Subsidy" specify that for enterprises with registered capital of more than ten million CNY, with an annual consumption of agricultural straw of more than 10,000 tons (including 10,000 tons), a subsidy of 140 CNY/t (22.58 USD/t) for each ton of agricultural straw would be granted [24].

- Subsidized loans

The "Interim Management Measures on Renewable Energy Development Special Fund" stipulated that for the projects listed in the directory of the national renewable energy industry development guidance, a subsidized loan would be provided. The subsidized loan period is 1–3 years, with a maximum annual interest rate of 3% (the average loan rate in China during 2014 was 6.55%) [25].

- Value-added tax (VAT) return or refund

The taxpayers who produce items comprehensive products using "the three kinds of residue (forestry logging residue, rough-hew residues and wood industry processing residues) , and the secondary or small fuelwood, agricultural straw, sugar cane bagasse as feedstock" could enjoy an 80% VAT return [26].

- Income tax reduction

Chinese income tax law provides that for enterprises who follow to "Preferential Catalogue of Enterprise. Income Tax on Resource Comprehensive Utilization" (2008 Edition), income tax could be levied based on 90% of its total income [25].

- Equipment subsidies [27].

3. Methodology

In this study we built a regionalized NPV model based on real production process simulation. The model's framework is as follows: first build a universal production system module, initiating it with equipment parameters; then build a regionalized plant module, which are embedded with the production system module; after inputting the regional operating data and price reference, use NPV method to calculate the price when NPV is zero; use sensitivity analysis to search for the most effective policy; after that, make the regional BMF selling price equal to that of coal and through linear programming method to calculate to what degree the incentive compensation should be in each region. Figure 4 gives the flowchart of the regionalized NPV model.

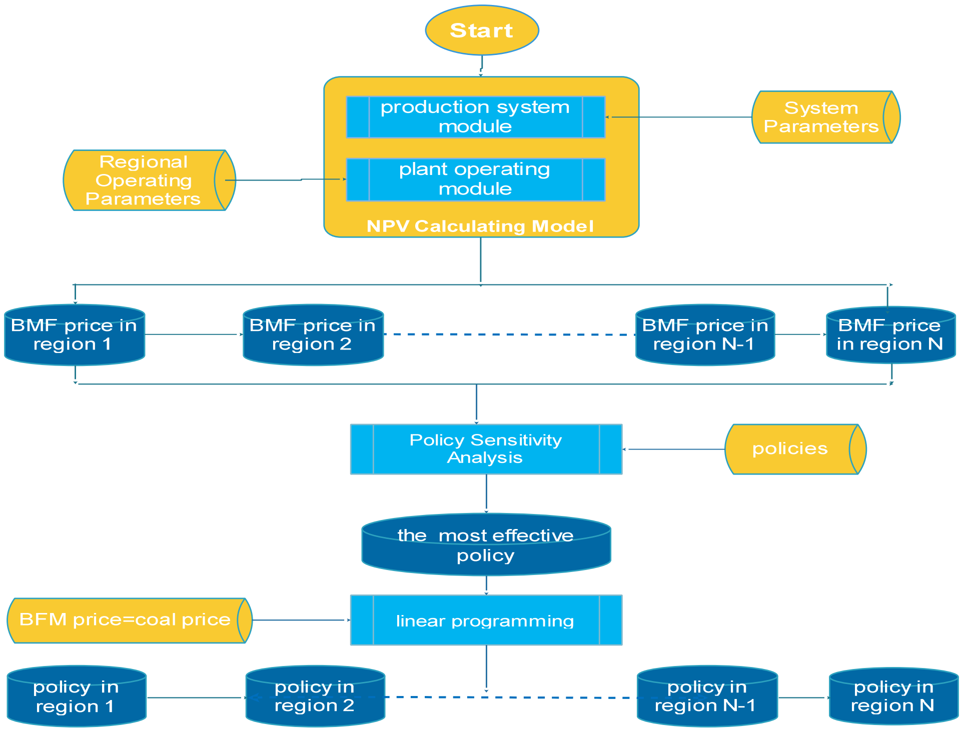


Figure 4. Flowchart of the regionalized net present value (NPV) model.

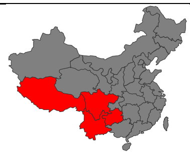
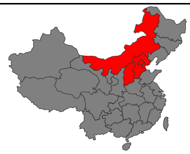
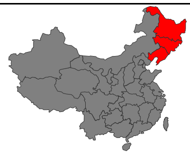
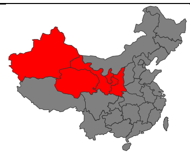
3.1. Regionalization

In order to get the first hand information about BMF in China, we have investigated 117 BMF production companies (78 ABF, 39 WPF) in 31 provinces in China, about their feedstocks, the parameters of their production plants, and how the current incentive policies worked by the means of questionnaires and interviews. In most economic analyses regarding biomass energy in China, a uniform set of data is always used. However, in our nationwide investigation, we have found a major regional imbalance: Although the plant scales, production process and process parameter differences like machine type and power consumption vary little between regions, the operating parameters, such as feedstock price, human labor cost, electricity price, *etc.* vary greatly, and these operating parameters have resulted in great differences in BMF price. In this study we divided the whole of China into seven regions, *i.e.*, Central, North, South, East, Northeast, Northwest and Southwest, according to the comparability of their geographic and climatic, economic and societal features, as well as the similarity of their biomass resources, market and end-users. Table 2 gives the details of each region and their resource, technological, market characteristics.

3.2. Net Present Value Production Model

An NPV method was employed to study the relationship between production costs and incentive policies such as tax breaks, subsidies and loans, *etc.*, so as to identify the best policy portfolio to promote this industry.

Table 2. The seven regions and its characteristics.

Region	Map	Provinces	Characteristics
Central China		Henan; Hubei; Hunan	Rich straw resources, few forestry residues, briquettes/pellets are straw-oriented; Land rent and labor cost are low; low coal price.
East China		Shanghai; Anhui; Fujian; Jiangsu; Jiangxi; Shandong; Zhejiang	Rich in agricultural straw and forestry residues; land rent and labor cost are high; high coal price; environmental issues are highly concerned, so BMF can be economically competitive.
South China		Guangdong; Hainan; Guangxi; Hong Kong; Macau	Rich in wooden residues, limited in straw; typical scale 20,000 t/a or more; land rent and labor cost are high; coal is in short supply and the price is high, and environmental issues are highly concerned, so BMF can be highly competitive.
Southwest China		Chongqing; Guizhou; Sichuan; Yunnan; Tibet	Sufficient raw material and broad sources; land rent and labor cost are low; low coal price.
North China		Beijing; Tianjin; Hebei; Shanxi; Inner Mongolia	Sufficient of both straw and wooden material, relatively low price; land rent and labor cost are medium; The price of traditional energy like coal and electricity are low.
Northeast China		Heilongjiang; Jilin; Liaoning	Sufficient straw material, relatively low price and broad sources; land rent and labor cost are low; low coal price.
Northwest China		Gansu; Qinghai; Shaanxi; Ningxia; Xinjiang	Sparsely populated, rich in straws, while the transportation cost is high; land rent and labor cost are low; low coal price.

3.2.1. Cost

The cost of operation and management is calculated as follows:

$$O\&M = VO\&M + FO\&M \tag{1}$$

where O & M represents operation and management costs, VO & M represents variable operation and management costs and FO & M represents fixed operation and management costs.

The formula for calculating variable operation and management costs is as follows:

$$VO\&M = F + C + T + S \tag{2}$$

where F represents feedstock costs, C represents electricity costs, T represents transportation costs and S represents the cost of sales. Fixed operation and management costs are calculated as follows:

$$FO\&M = LR + M + L + O \tag{3}$$

where LR represents land rent, M represents maintenance costs, L represents labor costs and O represents operation cost.

3.2.2. Cash Flow

The annual net cash flow is calculated as follows:

$$CF = R - O\&M - I - VAT - VATA - LPP - LI \tag{4}$$

where CF is the cash flow; R represents product sales revenue, I represents the income tax, VAT represents the value-added tax, $VATA$ represents the surcharge on the VAT, LPP represents loan principal repayment and LI represents interest on the loan.

Similarly:

$$I = \left(R - O\&M - D - LI - VAT - VATA\right) \times IR \tag{5}$$

$$D = D_C + D_M \tag{6}$$

$$VAT = VAT\_O - VAT\_I = \frac{R}{1 + VAT\_OR} \times VAT\_OR - \frac{F}{1 + VAT\_IR} \times VAT\_IR \tag{7}$$

$$VATA = VAT \times VATAR \tag{8}$$

where D represents depreciation charge, D_C represents depreciation of land and construction investment, D_M represents depreciation off machinery, VAT_O represents the output tax of VAT, VAT_IR represents the input tax of VAT, VAT_OR represents the output tax rate, VAT_IR represents input tax rate and $VATAR$ represents the VAT additional tax rate.

3.2.3. Net Present Value and Internal Rate of Return

$$NPV = \sum_{n=0}^{N} \frac{CF_n}{\left(1+d\right)^n} = CF_0 + \frac{CF_1}{\left(1+d\right)^1} + \frac{CF_2}{\left(1+d\right)^2} + \cdots + \frac{CF_N}{\left(1+d\right)^N} \tag{9}$$

where NPV represents net present value, N represents the period and D represents discount rate.

Similarly:

$$NPV = \sum_{n=0}^{N} \left(CF_n \times \left(1 + IRR\right)^{-n} \right) = 0 \tag{10}$$

where IRR represents the internal rate of return.

3.3. Sensitivity Analysis Method

The method used here is single factor sensitivity analysis, which sets variation range for one given policy factor and keeps other factors unchanged:

$$\beta_i = \frac{\Delta C_i}{\Delta P_i} \quad (11)$$

where β_i represents the sensitivity coefficient of the *i*th policy, ΔC_i represents the variation of the BMF cost impacted by the change of the *i*th policy and ΔP_i represents the variation of the *i*th policy.

4. Assumptions, Data and Calculation

4.1. General Assumptions

All prices involved are reported real value and normalized to US dollar in 2015, offsetting inflation. Expected Life span of the production plant is 20 years. For economy of scale the per unit cost of larger BMF plants are usually less than that of smaller ones; this is called the "economy of scale" and the corresponding basic equation is as follows:

$$\frac{c_2}{c_1} = (\frac{S_1}{S_2})^a \quad (1)$$

where c_2 and c_1 represent the fixed cost of plants 1 and 2, respectively, S_1 and S_2 represent their respective scales, *a* is the proportionality factor; according to former studies, *a* value of 0.7 is recommended.

4.2. Plant Scale

In the nationwide field investigation, we found that the most popular scales of BMF plants are 10,000–30,000 metric tons per annum (t/a), as 67 out of 117 investigated plants are of this scale, representing a 57% share. Only 33 plants have a production scale beyond 30,000 t/a, and 17 plants are below 10,000 t/a. The average BMF plant scale in the east region is the largest, at about 50,000 t/a, followed by the northeast region, at about 30,000 t/a, the remaining regions have similar average scales, at about 20,000 t/a. The model calculation will be based on regional average scales. Figure 5 and Table 3 lists the details.

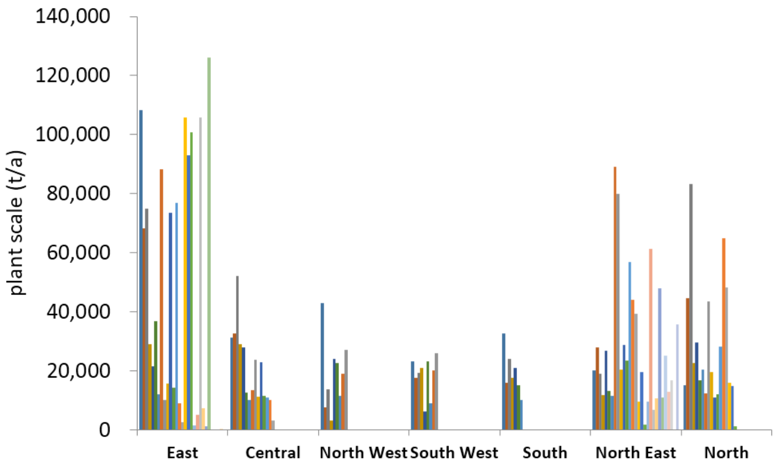


Figure 5. Regional plant scale distribution.

Table 3. Plant scale distribution and regional average scales.

Region	Plant numbers				Average scale
	<10,000 t/a	10,000–30,000 t/a	>30,000 t/a	Total	
East	6	6	12	24	49,436
Central	1	11	3	15	20,101
North West	2	6	1	9	19,023
South West	2	7	0	9	18,349
South	0	6	1	7	19,444
North East	5	19	11	35	32,955
North	1	12	5	18	27,954
Total	17	67	33	28	30,680

4.3. Feedstock Price

The feedstock prices used in this model are also based on our investigation. They include four parts: in-field cost, collection cost, transport cost and storage cost. The regional feedstock prices are shown in Figure 6.

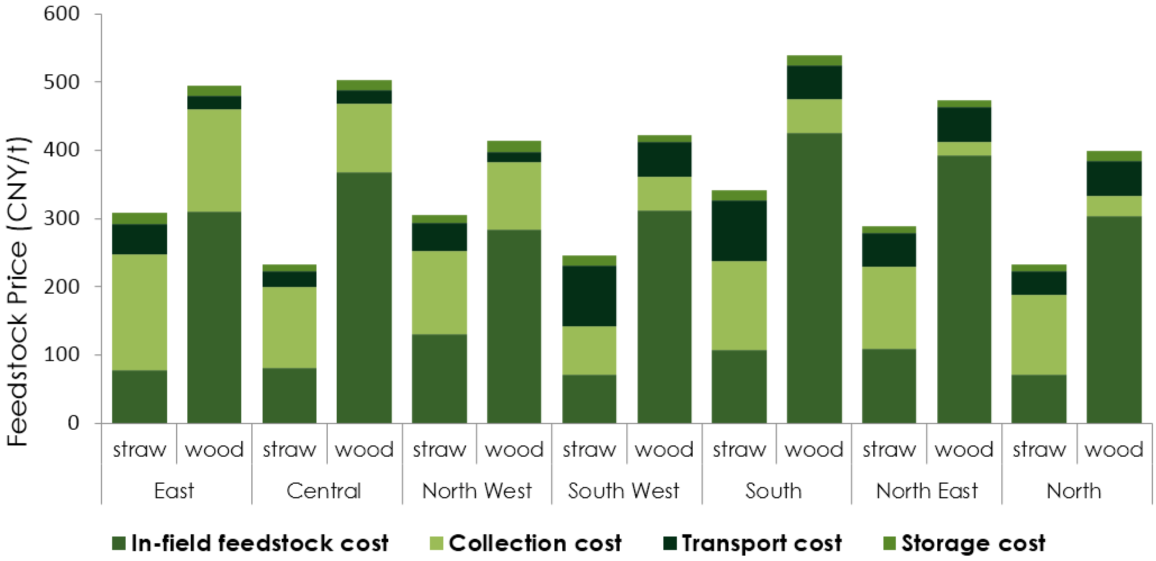


Figure 6. Regional feedstock prices (data source: field investigation).

4.4. Production System Parameters

The BMF production system is composed of four sectors: Drying, chopping, molding, and cooling & screening. The schematic diagram for the system is shown in Figure 7.

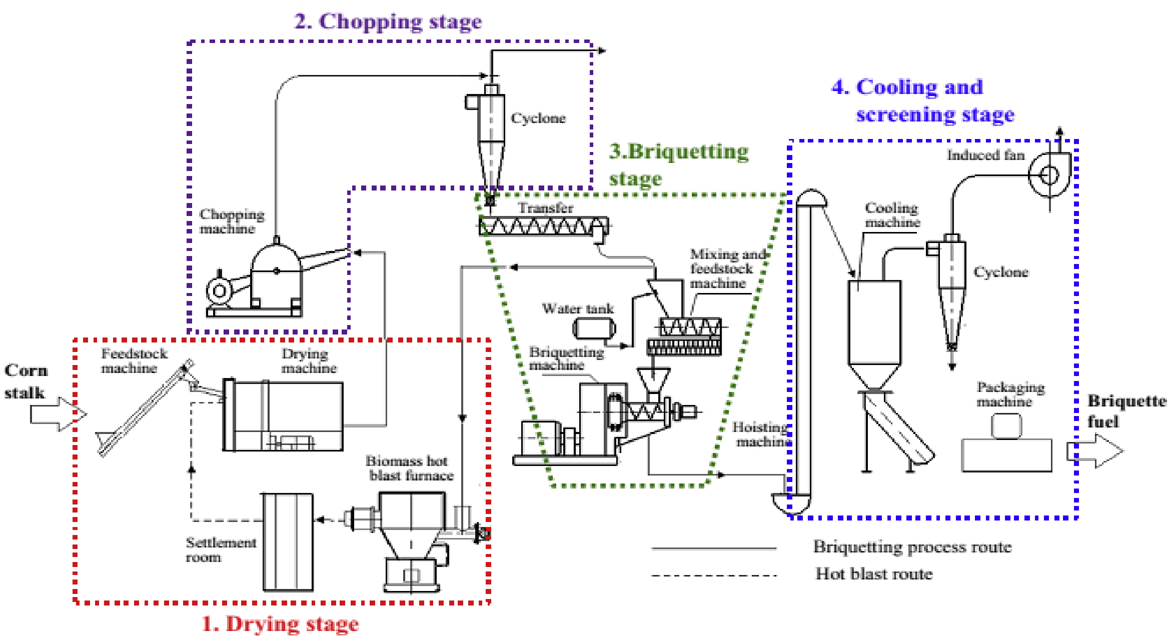


Figure 7. Schematic diagram of the biomass briquette fuel production system [18].

Here we take a BMF production plant with the scale of 20,000 t/a as an example. Details of the production system of that scale are listed in Table 4. Such a production system has a moulding rate of about 95%, and it can produce both straw briquette fuel and WPF. For plants with other scales, their system investments and power consumption could be calculated by the economy of scale function in Section 4.1.

Table 4. Production system parameters of a 20,000 t/a plant.

Number		Name	Sets	Power consumption (kW)		Equipment price (USD)	
				Stand-alone	**Total**	**Stand-alone**	**Total**
I. Drying sector	1	Belt conveyor	3	1.5	4.50	1	4838.71
	2	Dryer	2	25.00	50.00	65	209,677.42
	3	Large angle belt conveyer	2	4.00	8.00	2.65	8548.39
	4	Shaking screen	2	1.10	2.20	2.4	7741.94
	5	Scraper conveyor	3	4.00	12.00	2.85	13,790.32
	6	Bucket elevator	3	3.00	9.00	2.5	12,096.77
	7	Warehouse	3	0	0.00	2.2	10,645.16
	8	Level indicator	5	0	0.00	0.08	645.16
	9	Back material conveyor	3	2.2	6.60	2.21	10,693.55
		Total			**92.30**	**278,677.42**	
II. Chopping sector	1	Grinder	3	45.00	135.00	10.5	50,806.45
	2	Dust collector	3	15.00	45.00	5.5	26,612.90
	3	Scraper conveyer	2	3.00	6.00	3.5	11,290.32
	4	Feedstock loader	2	1.10	2.20	1.1	3548.39
	5	Bag dust collector	2	3	6.00	3	9677.42
	6	Tubular magnet	2	0	0.00	0.85	2741.94
	7	Bucket elevator	2	3.00	6.00	2.5	8064.52
		Total			**200.20**	**112,741.94**	
III. Moulding sector	1	Scraper conveyer	2	2.2	4.40	2.3	7419.35
	2	Pneumatic gate	4	0	0.00	0.16	1032.26
	3	Level indicator	5	0	0.00	0.08	645.16
	4	Feed bin	3	0	0.00	0.8	3870.97
	5	Feeder	3	4	12.00	1.85	8951.61
	6	Molding machine	3	136	408.00	30	145,161.29
	7	V-type belt conveyor	2	2.2	4.40	1.5	4838.71
	8	Suction system	2	3	6.00	2.2	7096.77
		Total			**434.80**	**179,016.13**	
IV. Cooling sector	1	Large angle belt conveyor	2	4	8.00	3.45	11,129.03
	2	Air-locked valves	2	1.5	1.50	0.39	1258.06
	3	Contraflow cooler	2	0	0	4	1,2903.23
	4	Centrifugal dust collector	1	0	0	2.95	4758.06
		Airlock	1	1.10	1.10		
		Ventilator	1	15.00	15.00		
		Ventilation pipe	1	0	0		
	5	Vibrating screen	2	1.10	1.10	1.56	5032.26
	6	Bucket elevator	2	3.00	6.00	2.5	8064.52
	8	Drying buffer bin	2	0	0.00	2.2	7096.77
	9	Level indicator	3	0	0.00	0.08	387.10
		Total			**32.70**	**50,629.03**	

Data source: field investigation.

4.5. Plant Operating Parameters

The plant module is built based on their regional average scales. Below we take an actual BMF factory with a capacity of 20,000 t/a as an example and the corresponding main parameters are listed in Table 5. The regional parameters such as maintenance and overheads costs could be calculated with the economy of scale function described in Section 4.1.

Table 5. The operating parameters of a BMF plant.

Number	Item	Values
1	Construction period	1 year
2	Production system costs (fixed cost)	620,967 USD
3	Maintenance costs (fixed cost)	5,435.48 USD/a
4	Overheads costs (fixed cost)	161,290 USD/a
5	Workers needed (variable cost)	30
6	Period of depreciation	20 years
7	Residual rate	5%
8	Operating hours	6000
9	Income tax rate	25% [28]
10	Value-added tax (VAT) rate 1	17% [29]
11	VAT rate 2	13% [29]
12	Base internal rate of return	10%
13	Discount rate	13% [30]
14	Financing	40% equity
15	Loan terms	10-year loan at 6.9%

4.6. Regional Data

Table 6 gives the regional data used in the model. Land & construction costs are calculated based on the regional land rent, the prices for labor and energy are derived from the average value among the provinces in each region, and the source of original data is from National Bureau of Statistics of China [31] and websites listing coal prices [32–34].

Table 6. Regional data.

Region	Land & construction	Labor price	Electricity	Fuel coal (5000 kcal, tax included)
	USD/a	USD/capita/a	USD/kWh	USD/t
East	88,306	536	0.14	84.35
Central	60,968	407	0.13	66.61
Northwest	60,968	454	0.12	58.06
Southwest	58,871	454	0.12	70.97
South	88,306	536	0.14	114.52
Northeast	60,968	411	0.14	61.77
North	73,065	536	0.11	50.48

5. Results and Discussion

5.1. Calculated Production Cost

Table 7 shows the calculated BMF production costs in each region. In order to validate these results, we compared that data to the local selling prices of the 117 BMF companies that we investigated. Figure 8 demonstrates that the actual average prices of each region show a high degree of consistency with the simulation results.

Table 7. Calculated BMF production costs in each region (USD/t). Woody pellet fuel: WPF; agricultural briquette fuel: ABF.

BMF	East	Central	Northwest	Southwest	South	Northeast	North
ABF (calculated)	104	86	98	87	110	98	86
WPF (calculated)	145	143	124	125	154	138	122

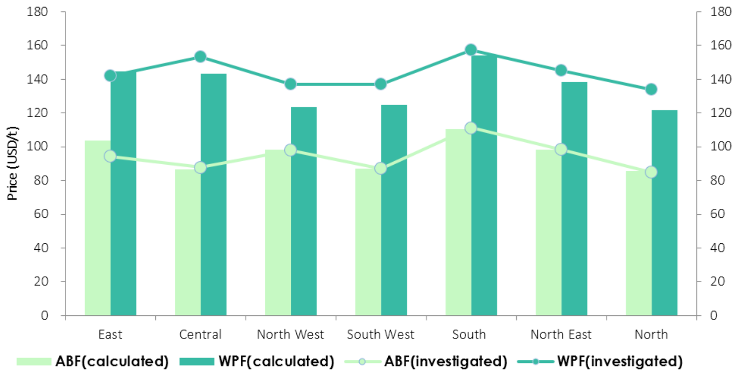


Figure 8. Calculated and investigated regional production costs of BMF in China.

Due to its lower energy density, the average cost of ABF is 40 USD/t less than that of WPF. In order to compare different BMFs equitably, we also calculated the regional unit energy cost of ABF and WPF based on one ton standard coal equivalent. Figure 9 gives the results. In most regions, the energy costs of ABF and WPF are almost equal, but in central China, the energy cost of ABF is lower than that of WPF, whereas in northwest China, WPF's energy cost is lower. For ABF, south China has the highest prices, followed by east, northeast, northwest and southwest China, north and central China have the lowest prices. For WPF, south China again has the highest prices, followed by east, central, northeast, southwest, northwest China, north China has the lowest WPF price.

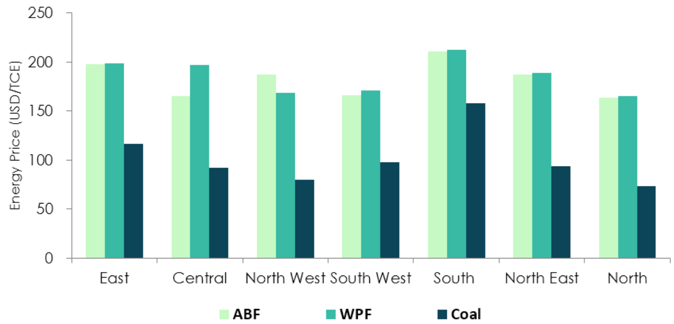


Figure 9. Energy cost of BMF and coal in China's regions.

The reason for this price disparity for BMF in China is the unbalanced regional development. In most regions, BMF is replacing coal for both distributed and centralized heating. However, in developed regions like the south and east, due to a high degree of urbanization, less local feedstock is locally available; in addition, the local governments attach high importance to environmental protection, strictly implementing measures like coal ban regulations. Accordingly, BMF is shipped to these regions to replace natural gas at a higher price. However, natural gas presents only a small part of China's energy consumption and it will be too expensive to provide natural gas heating all over China. From the prospective of mainstream of heating patterns, coal will continue to be the most commonly used fossil fuel in the long run and thus the main competitive target that BMF will seek to replace in most regions in China. From Figure 9 we can observe that in all regions BMF's energy cost is higher than that of coal, especially in the current context of decreasing coal prices, so some incentives should be adopted to protect the BMF industry and maintain BMF's commercial competitiveness.

5.2. Energy Consumption

Figure 10 depicts the relationship between the calculated energy consumption to produce a ton of BMF and the actual values that we obtained from the nationwide investigation. The result shows a high degree of consistency, and that means our assumption of the proportionality factor in economy of scale function is valid. From Figure 10 we also observe that along with the increase of BMF production plant scales, the unit energy consumption represents a decreasing tendency and comes close to some value between 50 kWh/t and 80 kWh/t.

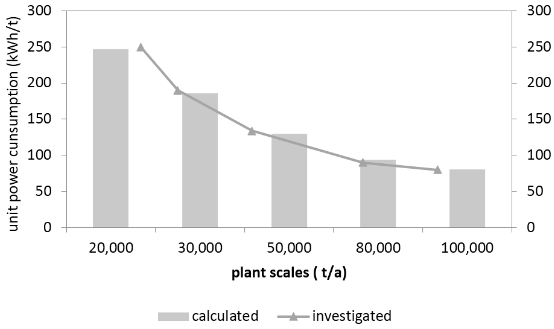


Figure 10. Calculated and investigated energy consumption.

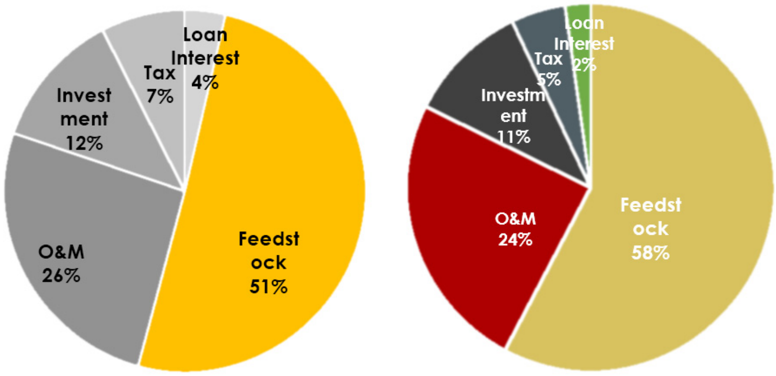
The regional energy consumption for BMF production in each region is shown in Table 8. It is concluded that plants in the east region have the lowest energy consumption to produce a ton of BMF, at about 130 kWh/t, followed by the plants in the northeast region, at about 180kWh/t, while plants in the remaining regions are roughly the same, at about 250 kWh/t. This is because that the energy consumption is mainly related to the plant scales, and east China has more large plants, its integration degree is higher than other regions, and therefore the energy consumption is less.

Table 8. Regional energy consumption data.

Item	East	Central	Northwest	Southeast	South	Northeast	North
Popular plant scale (t/a)	50,000	20,000	20,000	20,000	20,000	30,000	20,000
Power consumption (kWh/t)	130.24	247.35	247.35	247.35	247.35	186.23	247.35

5.3. Cost Structure

According to our simulation results, the regional cost structures show a high degree of similarity. Here we will take BMF in central China as an example, and its cost structure is shown in Figure 11. For ABF, feedstock represents the largest share of the total cost, around 51%, with *O* & *M* costs come second at 26%, followed by investment costs at 12%, tax costs at about 7%, and loan interest costs at 4%. The cost structure for WPF is similar to that for ABF, with a slightly higher feedstock share, about 58%, resulting from the higher energy density and higher price of woody feedstocks. *O* & *M* costs represent a comparable share as in the ABF case at 24%, the investment costs, tax costs and loan interest costs for WPF are 11%, 5% and 2%, respectively.



(**a**) (**b**)

Figure 11. (**a**) Cost structure for ABF in central China; (**b**) cost structure for WPF in central China.

Unlike other renewable energies such as PV and wind energy, the initial investment of BMF is not the greatest part of its production cost, it means that it is easier for SMEs to access to this industry because the capital threshold is relatively low.

5.4. Sensitivity Analysis

In order to identify the most effective policy factors, we carried out a sensitivity analysis based on current incentive policies. The results show that sensitivity for AMF and WPF are similar. Taking ABF in the east region as an example, the results are shown in Figure 12. We can see that feedstock subsidies have by far the greatest positive impact on lowering BMF production costs, followed by equipment subsidies. Loan rate, VAT rate and income tax rate changes have a negative impact on lowering BMF production costs. The dramatic impact of feedstock subsidies results from the cost structures. The feedstock subsidies aim at reducing the feedstock costs, while the VAT and income tax credit and the equipment subsidies aim at reducing the tax and investment costs, respectively. However, in ABF cost structure, the sum of the shares of investment, tax and loan interest is 23%, less than the half of the feedstock share, so feedstock subsidies should be considered as the first choice to stimulate this industry.

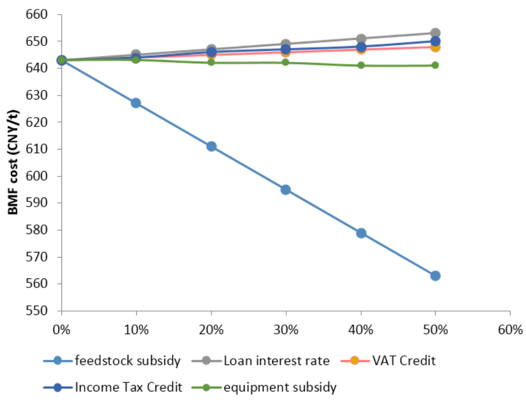


Figure 12. Impact of various BMF incentive options. Note: the variation of each policy factor is based on current incentive measures in China: (1) feedstock subsidy: From 0 USD/t to 22 USD/t (in the figure as 0%–100%); (2) loan interest rate: From 0 to 6.5% (in the figure as 0–100%); (3)VAT credit: From 0% to 100% variation on the base of 14% VAT input rate and 17% VAT output rate; (4) income tax rate: From 0% to100% variation on the base of 25% income tax rate; (5) Equipment subsidy: From 0% to 500,000 CNY/t (80,645.16 USD/t, in the figure as 0%–100%).

5.5. Subsidy and Development Strategy for Each Region

As shown in the aforementioned analysis, feedstock subsidies are the most effective policy, but in different regions, the price of BMF and the price of the target energy to be replaced vary, so the current uniform subsidy standard would not be suitable for all regions. Therefore we calculated how much the local government should subsidize BMF in each region in order to sustain its economic viability. Figure 13 gives the results. For ABF, the subsidy in south is the lowest, at about 20 USD/t, followed by 28 USD/t in southwest China, 30 USD/t in central China, 33 USD/t in east China and 37 USD/t in north China; as it can be seen, the required subsidies in the northeast and northwest are the highest, at around 38 USD/t and 44 USD/t, respectively.

For WPF, the subsidy in south is again the lowest, at about 27 USD/t, followed by 40 USD/t in southwest China, 44 USD/t in east China, 49 USD/t in northwest China, 53 USD/t in northeast China, 55 USD/t in north China and 57 USD/t in central China.

These results are caused by both the local fossil energy prices and BMF production costs. The reason why south China has the highest production costs but needs the least subsidies is that this region is short of coal and its coal prices are relatively high due to the expensive transportation expenses (its coal price is two times of that in north China). Another factor is the local feedstock conditions, as some regions, like north and central China, are rich in agricultural feedstock due to the fact they are covered by massive arable plains and have few mountains where trees grow, so their agricultural feedstock is much cheap than woody ones, even when the energy density is factored into the calculations. Therefore in these regions ABF are recommended to be extensively promoted, but WPF are suggested as subordinate products.

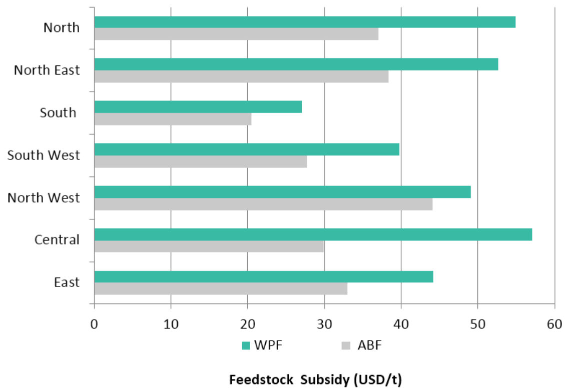


Figure 13. Required feedstock subsides for each region.

However, actual policy implementation is difficult and complex, because it is easy for recipients of the feedstock subsidy to cheat and hard to incentivize BMF consumption. According to our investigation, in order to maximize their subsidy, some plant owners cheat with regard to the total amount of feedstock they purchase, and did not produce as much as BMF they claimed for the subsidy. Therefore, it is better to change the feedstock subsidy to a product-based subsidy, credited only for the BMF actually produced and utilized by consumers. The regional product subsidies are shown in Figure 14: For ABF, the product subsidies are 26 USD/t, 36 USD/t, 39 USD/t, 42 USD/t, 48 USD/t, 49 USD/t and 57 USD/t in the south, southwest, central, east, north, northeast and northwest regions, respectively; for WPF, the product subsidies are 36 USD/t, 52 USD/t, 58 USD/t, 65 USD/t, 69 USD/t, 72 USD/t and 75 UDS/t in south, southwest, east, northwest, northeast, north and central China, respectively.

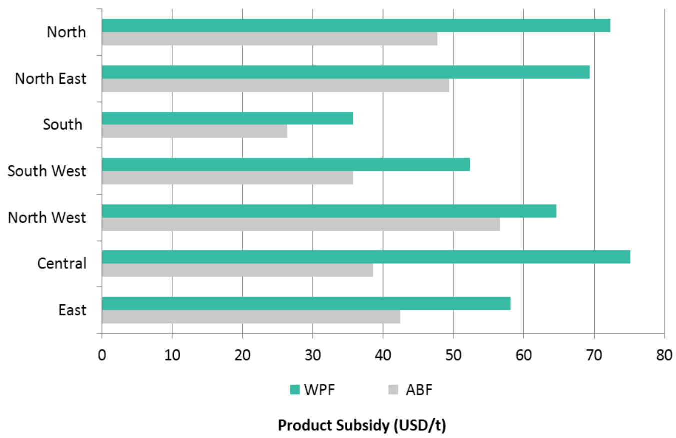


Figure 14. Production-based subsidy for each region.

Also from the subsidy results we can sketch a desired development strategy for BMF in each region. A high subsidy requirement means that it is not economical to develop BMF in that region, Table 9 indicates which regions should develop each type of BMF and at what level: ABF should be developed with priority in the south region, then in the southwest, central, east, north region, and is not recommended in the northeast, northwest; WPF should be developed first in the south, southwest region, then in the east, northwest and northeast region, and is not recommended in the north and central regions.

Table 9. Development strategy of BMF for each region.

BMF	Priority development	Modest development	Not recommended
ABF	South	Southwest, Central, East, North	Northeast, Northwest
WPF	South, Southwest	East, Northwest, Northeast	North, Central

6. Conclusions

At present, there are mainly two kinds of BMF in China: agricultural briquette fuel (ABF) and WPF, and their production costs vary remarkably across China's regions. The cost of ABF varies from 86 USD/t to 110 USD/t between the regions, while WPF's production cost ranges from 122 USD/t to 154 USD/t. The largest part of BMF's cost composition is feedstock, which represents between 50% and 60% of the total cost.

For the foreseeable future, coal will be the main target fossil fuel the BMF will seek to replace, but the energy costs for both ABF and WPF are significantly higher than those of coal in each region. Incentive policies should be adopted to protect this industry and maintain BMF's commercial viability.

Feedstock subsidies are the most effective policy option, but the current uniform subsidy standard is not appropriate for each region. Due to feasibility considerations related to policy implementation, it would be better to replace the current feedstock-based subsidy with a product-based subsidy. The optimal subsidies are calculated for each region: for ABF, the product subsidies vary from 26 USD/t to 57 USD/t between regions, while for WPF, the range is from 36 USD/t to 75 USD/t.

Based on the calculation of production costs, coal prices and optimal subsidy amounts, a regional BMF development strategy is also proposed. ABF should be targeted for priority development in south China, then in the southwest, central, east, north regions, and is not recommended in the northeast or northwest regions; priority WPF development should occur in the south and southwest regions, and then in the east, northwest and northeast regions, and is not recommended in the north or central regions. Moreover, in China's most developed and wealthiest regions, it is recommended to use BMF to replace natural gas first.

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