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Tech-economic evaluation of waste cooking oil to bio-flotation agent technology in the coal flotation industry

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ABSTRACT

Waste cooking oil (WCO) can be converted into a bio-flotation agent (BFA) which can replace diesel and develop into a new coal flotation agent with the Zr-SBA-15 catalyst. A tech-economic assessment of WCO-to-BFA on the basis of the pilot program showed that compared with petro-diesel, WCO-to-BFA technology can help save energy by 13%, reduce CO_2 emission by 76%, and save production costs by 0.003 −0.005 $USD \cdot MJ^{-1}$. WCO-to-BFA technology provided an excellent result regarding BFA substituting diesel as a coal flotation agent, which can lead to reduction of standard coal consumption by 1.2 kg, reduction of CO_2 emission by 5.5 kg, reduction of production costs for each ton of coal slime by 0.836 USD in the whole production chain lifecycle that includes the application of WCO-to-BFA technology into coal flotation process. It has proven that the WCO-to-BFA technology is an efficient, economic and environmentally friendly technique which has widespread applications and bright market prospects.

1. Introduction

With the depletion of fossil fuel, the increase in energy demands and the rising concerns of environmental pollution, it is imperative to develop alternative and renewable sources of energy. Waste cooking oil (WCO) as a waste source but a cheap feedstock is produced around the world with millions of tons of WCO per day (Melero et al., 2012). Synthesis of biodiesel from WCO has revealed attractive interests (Kumaran et al., 2011; Li et al., 2014; Lisboa et al., 2014; Mohammadshirazi et al., 2014), as it can not only reduce biodiesel production costs by 60–90%, but can also overcome disposal and treatment problems of the waste cooking oil (Hama et al., 2013; Wen et al., 2010; Zou et al., 2013). However, in order to pass the EN14214 or ASTM standard of diesel, the biodiesel production from WCO generally requires the pre-treatment of raw oil and the refining of the final product which leads to an increase in the costs of production (Maeda et al., 2011). Moreover, the biodiesel products are not suitable for use in cold environments and will lead to problems of engine durability due to the high viscosity, high solidification point (SP) and high cold filter plugging point (CFPP) of biodiesel (Maeda et al., 2011; Özener et al., 2014; Tüccar et al., 2014).

Using WCO to produce a bio-flotation agent (BFA) that can replace diesel and be responsible for a new coal flotation agent is an economic, efficient and environmentally friendly way for WCO conversion. BFA can not only totally replace conventional diesel as a coal flotation agent in the coal flotation industry, but can also be used as an effective alternative to fossil fuels. BFA products instead of diesel as a coal flotation agent used for coal flotation have presented more obvious advantages compared with the advanced flotation collector (Nalco) and traditional flotation agent, with the dosage of BFA being only about 1/5 of Nalco and 1/13 of diesel, respectively (Yi et al., 2015). More importantly, BFA as a coal flotation agent to replace the fossil diesel for coal flotation has no special requirements or lower standard in terms of the content of

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water, impurities, metal, and methanol, etc., not to mention viscosity and cold filter plugging point. Hence, the way of WCO-to-BFA can simplify the production process and reduce the cost of production.

In this paper, we present a tech-economic assessment of WCO-to-BFA system located in the High-tech Development Zone of Taiyuan City, Shanxi Province, China, along with comparisons with conventional diesel as coal flotation to illustrate the feasibility of WCO-to-BFA technology. The effects of significant influential factors such as the WCO and BFA prices, run time, international oil price, and carbon (greenhouse gas emission) tax on the investigated system are analyzed and discussed in detail. Finally, the application and promotional prospects of WCO-to-BFA are predicted to be connected with coal distribution and pilot cites of kitchen waste recovery in China based on our analysis.

2. Process description

The production process of BFA from WCO is similar to that of biodiesel via transesterification and esterification reactions happening simultaneously (Melero et al., 2009), as shown in Fig. 1. However, the special characteristic of equipment used in the WCO-to-BFA plant is the reactor for WCO conversion to BFA. In our designed reactor (Zhang et al., 2014), the reactions for WCO-to-BFA occur in three phases, which is beneficial to enhance the contact between reactants and the surface activity center of the catalyst. More importantly, the products in the form of liquid can be separated directly from the bottom of the reactor. This particular design is very different from the general reactor that uses a two-phase reaction, in which the products are separated from the top of the reactor in the form of gas by using distillation which requires high temperature (Feng et al., 2011; Melero et al., 2014; Santacesaria et al., 2012), leading to a considerable energy consumption.

WCO is fed to the roof of the reactor tower by the metering pump and is then sprayed downwards to the packing layer of the catalyst and reacts with the rising methanol steam (reverse contact). The methanol is fed in from the bottom of the packing layer of the catalyst, and goes up in the state of gas in the reactor. The products leave the packing layer and continue to flow downwards to the separation kettle and to stratify in the kettle with the top layer being BFA crude oil and the bottom being the mixture of glycerol and water. The methanol is separated from the BFA crude oil through the rectifying tower I, and returns to the stock tank for recycle. The BFA from the bottom of the rectifying tower I enters rectifying tower II. The refined BFA from rectifying tower II is sent to the coal preparation plant to be used as a coal flotation agent. The triglyceride from the bottom of tower III is recycled in the WCO stock feed tank. From the mixture of glycerol and water in the bottom of the separation kettle, the dissolved methanol is distilled through the flash tower, and is recycled in the methanol stock feed tank. The substance from the flash tower bottom goes to rectifying tower IV and the refined glycerol can be obtained and used as a byproduct for sale.

Under the action of the solid acid catalyst Zr-SBA-15, the corresponding BFA and glycerol are produced. The WCO transesterification conversion to BFA contains mainly the following chemical reactions:

$$\mathrm{Tr} + \text{methanol} \rightleftharpoons \mathrm{Di} + \mathrm{FAME}$$

$$\mathrm{Di} + \text{methanol} \leftrightharpoons \mathrm{Mo} + \mathrm{FAME}$$

$$\mathrm{Mo} + \text{methanol} \leftrightharpoons \text{Glycerol} + \mathrm{FAME}$$

where Tr, Di, Mo and FAME are triglycerides, diglyceride, monoglyceride and fatty acid methyl ester, respectively. The main operation parameters such as the reaction time (t), molar ratio of methanol/oil (r), reaction temperature (T) and catalyst dosage (w) have significant impacts on the composition and the yield of BFA. In our previous study (Yi et al., 2015), we have investigated the effects of these main variables on the WCO conversion, and found that the $SO_4^{2-}/Zr-SBA-15$ materials present excellent catalytic activity in the transesterification of WCO with methanol under optimized conditions ($t = 2.5$ h, $r = 40$, $T = 160$ °C and $w = 3$ wt.%), and the Tr conversion and FAME yield achieved 98.5% and 95.2%, respectively. BFA, comprised of the mixture of FAME, Mo, and Di products, can be used as a coal flotation agent for sale directly without extra separation and refining. Glycerol then can be sold as a by-product to help make the process more economically viable, and the income from the sale of glycerol results in an estimated 6% reduction in

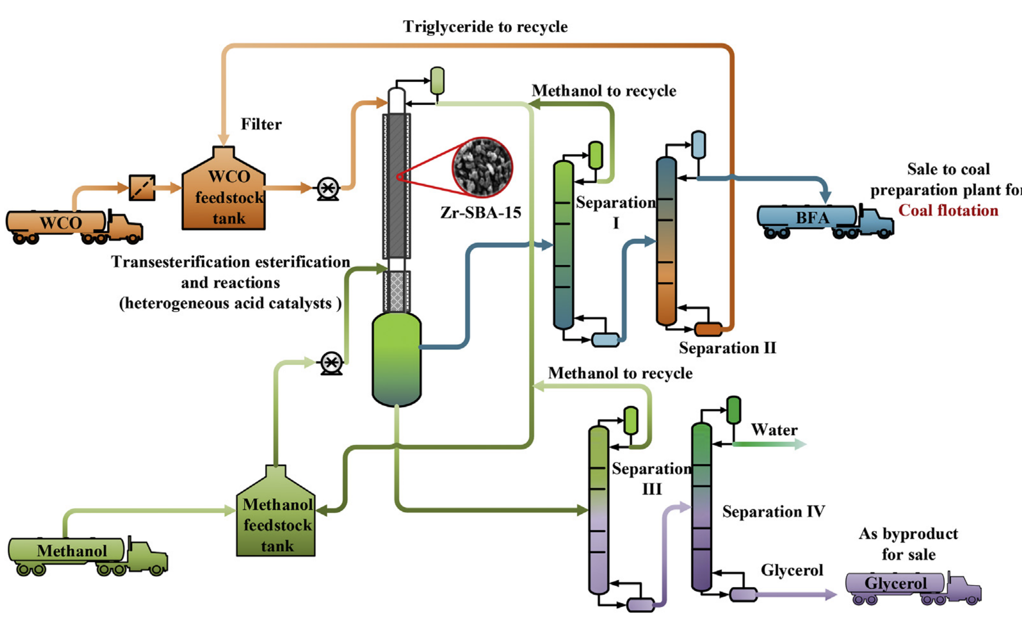


Fig. 1. Production process of WCO-to-BFA over Zr-SBA-15 catalyst.

biodiesel production costs (Haas et al., 2006). We found that WCO revealed a simple conversion process with high utilization in the whole production chain through the WCO-to-BFA technique.

3. Model assumption and criteria

3.1. Capital cost

This study uses the factorial method to calculate the capital cost. The factorial method is more accurate as the capital cost is often estimated from the purchased cost of major equipment items, where additional costs are calculated as factors of the equipment cost (Do et al., 2014). The total capital investment (TCI) reported in this study represents the total plant costs (TPC), which mainly cover total the plant direct cost (TPDC), the total plant indirect cost (TPIC), the contractor's fee and contingency (CFC) and working capital (WC). TPDC includes total purchase equipment cost (TPEC) and installation cost which is 25% of TPEC. TPIC includes the cost of engineering design and construction, which are estimated on the basis of TPDC, and the estimating factor for engineering design and construction are 0.25 and 0.35 (Zeng, 2010), respectively. Based on the TPDC + TPIC, the estimating factor for the contractor's fee is 0.05, and for the contingency is 0.1 (Zeng, 2010). WC is 15% of the total depreciable capital (DFC). TCI estimates are summarized in Table 1.

3.2. Economic assumptions and criteria

Several assumptions were imposed in this economic feasibility analysis, as shown in Table 2. The plant is considered as 100% owned capital and the working time is 300 days per year. The construction time is assumed to be one year. Operation and maintenance (O&M) charges could be estimated on the basis of DFC, with 0.04 as the estimating factor (Larson et al., 2010; Yi et al., 2014). The project life is assumed to be 25 years, an assumption often used for small and medium size plants (Zhu et al., 2012). The depreciation period was set as 10 years, and the straight line depreciation with depreciation rate of 8% is used for the plant. An income tax rate of 15% of gross profit (State administration of taxation, 2014) and a discount rate i of 12% are used (Mulugetta, 2009). There are 350 staff members in the plant, and the salary for each person is 4840 USD$\cdot$y^{-1}. The average market price of by-product glycerol is 970 USD$\cdot$t^{-1}. The feedstock WCO, methanol and diesel purchasing costs are 694 USD$\cdot$t^{-1}, 403 USD$\cdot$t^{-1}, and 1.13 USD$\cdot$L^{-1} respectively. The electricity, steam costs are set to be 0.16 USD$\cdot$kWh^{-1} and 24.2 USD$\cdot$t^{-1}, respectively.

A standardised financial tool, such as the net present value (*NPV*), was employed to assess the profitability of the WCO-to-BFA plant. The *NPV* refers to the difference between the present values of all costs and associated revenues. This is shown in Eq. (1), where i is the discount rate, C_t denotes the net cash flow over year(s) t. An option is economically attractive if it has the *NPV* above zero (Lin et al., 2011). The production cost of BFA (*COB*), another significant economic criterion for WCO-to-BFA plant, can be obtained by Eqs. (2–3), where *CRF* is the capital recovery factor, which is a function of the discount rate (i) and the expected plant lifetime (n). *TVC* represents the total viable cost; S_{bp} is the byproduct glycerol sales revenues, and the yield of glycerol is 0.07 t$\cdot$t^{-1}-BFA; C_{tax} is the tax payment and P is the BFA production scale, 60,000 t$\cdot$y^{-1}.

Table 1
The assessment of capital cost.

Category		Item
TPDC	Total purchase equipment cost (TPEC)	100%TPEC
	Installation and materials	25%TPEC
TPIC	Engineering design	25%TPDC
	Construction	35%TPDC
TPC		TPDC + TPIC
CFC	Contractor's fee	5%TPC
	Contingency	10%TPC
DFC		TPC + CFC
WC		15%DFC
TCI	Total capital investment	DFC + WC

Table 2
Economic assumptions.

Items	Value
Production capacity	100% of designed
Run time (d$\cdot$y^{-1})	300
Methanol price (USD$\cdot$t^{-1})	403
WCO (USD$\cdot$t^{-1})	694
Diesel (USD$\cdot$L^{-1})	1.13
Glycerine (USD$\cdot$t^{-1})	970
Steam (USD$\cdot$t^{-1})	24.2
Electricity (USD$\cdot$kWh^{-1})	0.16
Depreciation life (y)	10
Design life (y)	1.0
Construction life (y)	1.0
Operation (y)	25
Discount ratio (%)	12
Depreciation (%)	8
Tax rate (%)	15
Labor (person)	350

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

$$COB = \frac{DFC \times CRF + TVC - S_{bp}}{P} \tag{2}$$

$$CRF = \frac{i}{1-(1+i)^{-n}} \tag{3}$$

4. Assessment of WCO-to-BFA technology

In order to reveal the potential application and commercial viability of this new technology, a pilot program, which is located in the High-tech Development Zone of Taiyuan City, Shanxi province, China, is evaluated in terms of energy, environmental and economic sustainability in this section. Sustainability analysis and evaluation of the chemical and energy aspects of the process can provide important clues for their improvement. Moreover, it can offer guidance to the design of new processes, reduction of waste release and consumption of material and energy resources (Yang et al., 2013).

In the model, Taiyuan was divided into six main Districts (Yingze district, Wanbailin district, Xinghualing district, Xiaodian district, Jiancaoping district, and Jinyuan district), three counties (Qingxu county, Yangqu county and Loufan county) and Gujiao city. The BFA plant is located in the High-tech Development Zone in the Xiaodian District. As illustrated in Fig. 2, this study considers a WCO supply from WCO collection to the gate of a BFA plant. WCO was collected from each district, and then transported to the BFA plant center. The complete WCO supply chain system includes WCO collection and transportation, as well as BFA production.

4.1. BFA application performance

Table 3 summaries the coal flotation treatment of the as-prepared BFA (BFA-1 to BFA-7) on coal samples from the Zijin and

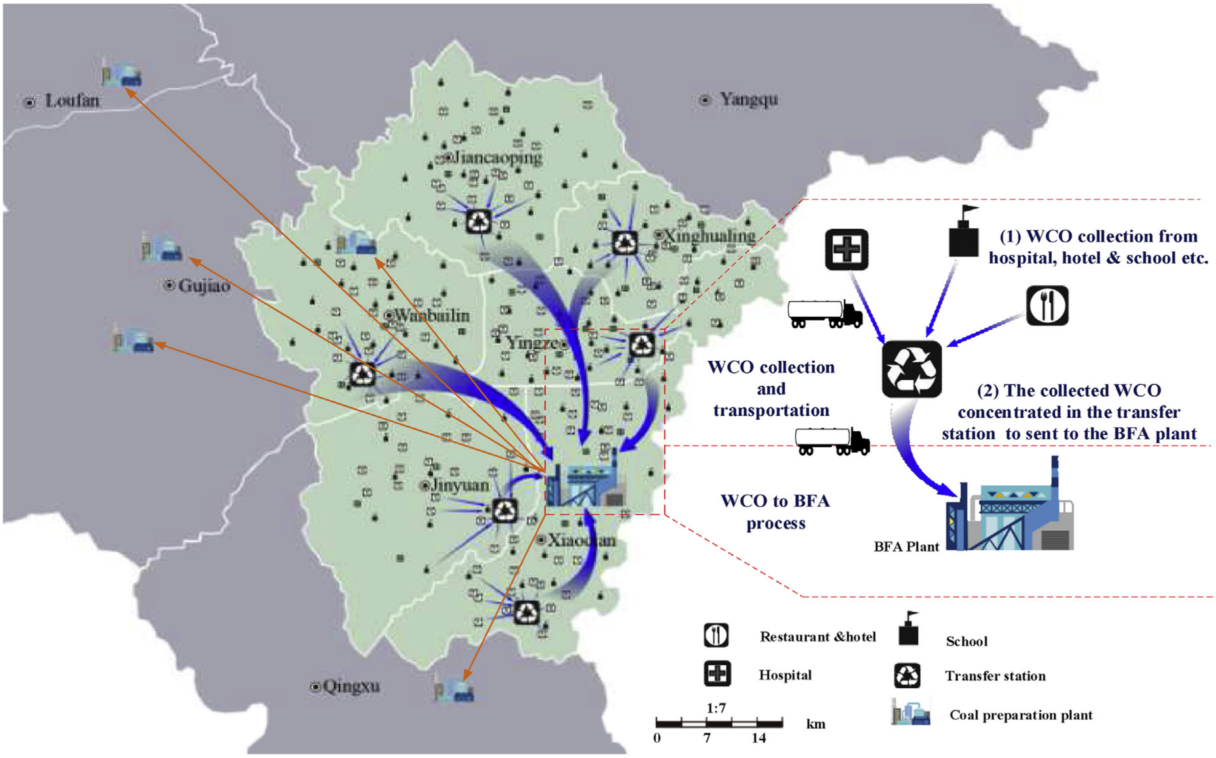


Fig. 2. Assessment model of WCO-to-BFA on the basis of the pilot program sited in High-tech Development Zone of Taiyuan city.

Xinyu coal mines in comparison with the actual results of a coal preparation plant. It can be found that the obtained excellent flotation effects of BFA have a more obvious advantage than the result of the traditional flotation reagents diesel and the advanced flotation agent (Nalco) with respect to dosage. Take the Zijin coal sample for example. The dosage of BFA is 0.07 $kg \cdot t^{-1}$-coal, only 1/13 of diesel consumption, while it has a better effect in reducing fine coal ash content and increasing tail coal ash content compared with diesel. Furthermore, when BFA is used with the same dosage, the fine coal yield exceeds or is almost the same as the result by using Nalco-1. In the application of the Xinyu mine coal sample, the BFA dosage is only 17–25% of Nalco-2 used in the Xinyu mine coal sample, and shows a better flotation effect reflecting in the lower ash content in fine coal and higher ash content in tail coal. It indicates that the highly efficient BFA should become a potential flotation agent and has remarkable market competitiveness compared with Nalco-2 and diesel.

4.2. WCO collection

Currently, Taiyuan produces roughly 320–500 tons of kitchen waste per day. According to the policy about kitchen waste recycling, Taiyuan is seen as the first pilot city to reuse kitchen waste with a scale of 200 tons per day (National development and reform commission of China website, 2014). WCO should be collected and concentrated firstly, and a light truck (a load of about 5–7 tons) is used to transport WCO collection. The number of trucks has been supplied according to the population and economic conditions in different administrative regions as listed in Table 4. In each administrative region, the correlative one or two transfer stations have been established for concentrating WCO which will be transported to the BFA plant center by a heavy truck (load is greater than 30 tons). Qingxu county, Yangqu county, Loufan county and Gujiao city, due to lower economic conditions and smaller populations, are not considered as the places for WCO collection in this study.

Table 3
Compare the effect of different flotation agent.

Flotation results												
Flotation agent[a]		Name	BFA-1	BFA-2	BFA-3	BFA-4	BFA-5	BFA-6	BFA-7	Diesel[b]	Nalco-1	Nalco-2[c]
		Consumption/$kg \cdot t^{-1}$	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.90	0.07	0.30–0.40
Coal sample	Products											
From Zijin coal mine	Fine coal	Yield/%	75.48	76.61	75.73	77.03	76.1	75.03	77.5	–	76.0	–
		Ash/%	9.71	10.26	9.65	9.22	10.11	9.74	10.44	11–13	10.42	–
	Tailing	Ash/%	60.24	65.58	64.84	63.1	62.48	59.75	65.34	50–63	63.74	–
From Xinyu coal mine	Fine coal	Yield/%	84.06	84.26	85.47	84.50	85.17	84.80	84.93	–	–	–
		Ash/%	8.42	8.5	9.34	8.84	9.08	9.04	8.74	–	–	9.5–10.0
	Tailing	Ash/%	65.43	65.42	66.6	64.94	65.95	65.87	66.54	–	–	57.0–61.0

[a] The dosage of frother is 0.13 $kg \cdot t^{-1}$-coal.
[b] The data of flotation results from production site in Zijin coal mine.
[c] The data of flotation results from production site in Xinyu coal mine.

Table 4
Development situation of administrative region in Taiyuan city and trucks for WCO collection.

District	Area/m^2	Population/$\times 10^4$	Economic conditions	Number of light trucks	Distance for light truck, $km \cdot d^{-1}$	Number of heavy trucks	Distance for heavy truck, $km \cdot d^{-1}$
Yingze	117	58.8	Good	5	20	1	30
Wanbailin	305	74.9	Good	8	20	2	60
Xinghualing	170	63.4	Good	5	20	1	80
Xiaodian	295	75	Common	5	20	1	20
Jiancaoping	286	41.6	Common	5	20	1	100
Jinyuan	287	22.2	Common	5	20	1	50

4.3. *Energy conversion*

In the WCO-to-BFA processes, energy requirements in the whole production chain include WCO collection and transportation as well as BFA production. The diesel consumption of light and heavy trucks are 0.12 $L \cdot km^{-1}$ and 0.3 $L \cdot km^{-1}$, respectively. On the basis of the investigation data in Table 4, the total consumption of WCO collection and transportation is 38.41 $MJ \cdot t^{-1}$, as can been seen in Table 5, which is apparently lower than that in the BFA production processes (3464.93 $MJ \cdot t^{-1}$, steam and electricity). Steam consumption is the primary energy consumption in the BFA production process.

4.4. *Environmental emission*

The production of BFA requires the consumption of raw materials and energy, which leads to resource depletion. Simultaneously, the waste from the production and final consumption of BFA are released, and cause environmental degradation. Therefore, the reduction of waste as well as the efficient and clean use of resources should always be the objective. There are three environmental indicators for the BFA process assessment: CO_2, SO_2 and NO_x emissions. The indicators include SO_2, NO_x and CO_2 emitted from the 1 ton BFA (BFA production processes can be seen in Table 6). Pollution gases are produced in the WCO collection and transportation. 1 L diesel for a truck contributes to 2670, 15.11 and 83.80 $g \cdot L^{-1}$ in emission of CO_2, SO_2 and NO_x, respectively. The total pollution gases emitted in the WCO collection and transportation are CO_2 (2661.31 $g \cdot t^{-1}$), SO_2 (15.06 $g \cdot t^{-1}$) and NO_x (83.46 $g \cdot t^{-1}$). In the BFA production processes, much more pollution gases are produced (such as 669,446 $g \cdot t^{-1}$ CO_2, 1204.12 $g \cdot t^{-1}$ SO_2 and 1834.53 $g \cdot t^{-1}$ NO_x), and account for over 95% of the total pollution gas emission in the WCO-to-BFA production chain.

4.5. *Economy*

The capital investment of the plant is on the basis of construction budget of the project. The total depreciable capital and working capital are 9.82 and 1.47 million USD, respectively. The TVC are composed of cost of the WCO collection and transportation, O&M, feedstock, electricity, steam and labor, etc. WCO market price is 694 $USD \cdot t^{-1}$, and the total purchase cost of WCO is 4.41 million $USD \cdot y^{-1}$. O&M costs are 4% of DFC. WCO collection and transportation costs could be calculated based on the driving distance of trucks, then the cost of WCO collection and transportation is 67.5 thousand $USD \cdot y^{-1}$ in total. The salary for the total labor is 1.7 million $USD \cdot y^{-1}$. The costs of methanol, electricity, steam are 0.29, 0.02 and 0.17 million $USD \cdot y^{-1}$, respectively. It can be seen in Table 7 that the feedstock costs account for over 90% of the TVC. Feedstock cost directly determines the production cost of BFA. According to Table 2, it can be obtained that the BFA production cost is about 804.4 $USD \cdot t^{-1}$, and NPV is 97.02 million USD. Payback period is the time length necessary for the total money return to be equal to the fixed capital investment (Do et al., 2014). For the WCO-to-BFA plant, the payback is less than five years when the production capacity is 85–100% of the designed capacity. From the above analysis, it can be concluded that BFA has a better comprehensive performance compared with diesel. As seen in Table 8, with the same 1 MJ production output, the BFA shows 13% higher results than diesel in aspect of energy utilization, and CO_2 emission of BFA is only about 24% of that produced in diesel production. Without desulfurization and denitrification in the BFA production process, SO_2 and NO_x emissions are a little higher than that of diesel production. However, the production cost of BFA, 0.003–0.005 $USD \cdot MJ^{-1}$ (about 322–484 $USD \cdot t^{-1}$), is lower than that of diesel.

Table 5
Energy input for 1 ton BFA production in WCO-to-BFA production processes chain.

WCO collection and transportation	Light trucks consumption, $MJ \cdot t^{-1}$	Heavy trucks consumption, $MJ \cdot t^{-1}$
Yingze	2.31	1.74
Wanbailin	3.70	6.94
Xinghualing	2.31	4.63
Xiaodian	2.31	1.16
Jiancaoping	2.31	5.78
Jinyuan	2.31	2.89
Subtotal	15.27	23.14
BFA production processes	**$t \cdot (t\text{-BFA})^{-1}$**	**$MJ \cdot (t\text{-BFA})^{-1}$**
WCO (without water)	1.06	40,901.2
Methanol	0.12	2784
Steam	1.17	3182.4
Electricity	21.8 kWh	78.48 kWh
Subtotal		47,150.1

5. Sensitivity analysis

5.1. *Effects of WCO price*

The effect of WCO on the NPV and production cost of the BFA is described in Fig. 3. The relationship between WCO and the two

Table 6
Pollution gas emission from 1 ton BFA production.

Item	CO_2 emission, $g \cdot t^{-1}$		SO_2 emission, $g \cdot t^{-1}$		NO_x emission, $g \cdot t^{-1}$	
	Light truck	Heavy truck	Light truck	Heavy truck	Light truck	Heavy truck
WCO collection and transportation						
Yingze	160.32	120.24	0.91	0.68	5.03	3.77
Wanbailin	256.51	480.96	1.45	2.72	8.04	15.08
Xinghualing	160.32	320.64	0.91	1.81	5.03	10.06
Xiaodian	160.32	80.16	0.91	0.45	5.03	2.51
Jiancaoping	160.32	400.80	0.91	2.27	5.03	12.57
Jinyuan	160.32	200.40	0.91	1.13	5.03	6.29
Subtotal	1058.11	1603.20	5.99	9.07	33.18	50.28
BFA production process						
Methanol	306,000		20		810	
Steam	340,600		1110		960	
Electricity	22,846		74.12		64.53	
Subtotal	669,446		1204.12		1834.53	
Total	672,107.31		1219.18		1917.99	

Table 7
The total investment in the WCO-to-BFA plant.

Item	Data/Unit	Description
Capital cost	**$\times 10^4$ USD**	
Workshop equipment (TEPC1)	393.0	Reaction kettle, distillation tower, feed pump, Heater exchanger, flash equipment etc.
Workshop outside equipment (TEPC2)	34.0	cooling tower, methanol storage tank, circulating water Pump, crude glycerol storage tank, etc.
Installation and materials	106.7	25% × (TEPC1 + TEPC2)
Cost of installation materials	44.8	Installation and test cost for all equipment and pipes.
Installation and test cost	30.2	Installation and debugging of artificial cost for all equipment and pipes.
Automatic control system	24.9	Industrial control computer, user software, temperature control, pressure control, level control, etc.
Paint and heat preservation	6.8	Painting and heat preservation cost for all equipment and pipes.
Subtotal (TPDC)	533.6	
Engineering design and construction (TPIC)	320.2	Engineering design = 0.25 × TPDC, construction = 0.35 × TPDC.
Contractor's fee and contingency (CFC)	128.1	Contractor's fee = 0.05 × (TPDC + TPIC), contingency = 0.1 × (TPDC + TPIC).
The total depreciable capital (DFC)	981.9	DFC = TPDC + TPIC + CFC.
Working capital (WC)	147.3	15% × DFC
Variable costs	**$\times 10^4$ USD·y^{-1}**	
WCO	4411.0	WCO cost = WCO price × WCO consumption = 694 USD·t^{-1} × 60,000 × 1.06 t·y^{-1}.
WCO collection and transportation	6.7	Diesel price (1.13 USD·L^{-1}) × driving distance, based on Table 1.
Methanol	290.3	Methanol cost = methanol price × methanol consumption = 403 USD·t^{-1} × 7200 t·y^{-1}.
Electricity	21.1	Electricity cost = electricity price × electricity consumption = 0.16 USD·(kWh)$^{-1}$ × 1,308,000 kWh·y^{-1}
Steam	169.8	Steam cost = steam price × steam consumption = 24.2 USD·t^{-1} × 70,200 t·y^{-1}.
Maintenance and operation	39.3	4% × DFC.
Labor cost	169.4	350 persons; plant labor cost 4840 USD·person^{-1}·y^{-1}
Total variable costs (TVC)	5107.6	
The production cost of BFA/USD·t^{-1}	804.4	
NPV/million USD	97.02	
Payback period/y	3–5	The production capacity is 85–100% of the designed capacity

indicators (NPV and production cost of the BFA) is linear, as would be expected. It can also be seen that if the WCO price is lower than 915 USD·t^{-1}, the NPV all will be above zero in the range of a low discount rate (i = 0.08) to high discount rate (i = 0.15), and the production cost of the BFA will be lower than 1050 USD·t^{-1}. Nowadays, the WCO price is between 690 and 810 USD·t^{-1} (including transportation cost), which indicates that WCO-to-BFA plant has tremendous competitive advantage.

5.2. Effects of products price

Revenues from BFA and glycerol sales are essential, particularly for the economic viability of the WCO-to-BFA plant. In general, a low BFA price is acceptable for a low production cost in a WCO-to-BFA plant. As shown in Fig. 4, NPV increases dramatically with the increase of BFA price. It is obvious that the NPV will be above zero when the BFA price is higher than 820 USD·t^{-1} at both a high discount rate (15%) and a low discount rate (8%), which implies that a WCO-to-BFA plant is economically feasible. Furthermore, the BFA price is 1050–1130 USD·t^{-1} on current market, compared with the current fossil diesel price of 1350–1450 USD·t^{-1}, which means BFA has a tremendous competitive advantage over fossil diesel in price, let alone high flotation efficiency. Therefore, the WCO-to-BFA plant has huge profit margins and presents excellent economic performance. Fig. 5 presents the effects of the revenue from the by-product glycerol sales on NPV and BFA production cost. According to current glycerol prices, the glycerol sales can bring about 1.4% reduction of the BFA production cost and a 5% increase of NPV for different discount rates i = 0.08, 0.10, 0.12, and 0.15, respectively, as the glycerol price increases from 850 to 1000 USD·t^{-1}.

Table 8
The comprehensive performance of 1 MJ production of BFA or diesel.

Item	BFA	Diesel
Total energy consumption/MJ	1.20	1.42
Total energy utilization/%	83.3	70.4
CO_2 emission/g	17.26	72.31
SO_2 emission/g	0.031	0.015
NO_x emission/g	0.049	0.007
Production cost/USD·MJ^{-1}	0.021–0.024	0.024–0.029

5.3. Effects of run time

Fig. 6 summarized the NPV and BFA production costs versus annual operational hours. There is a major effect of annual operational hours on NPV and BFA production costs. The production costs of BFA falls sharply, while NPV rises remarkably as annual operational hours increase. In general, high operating rate requires high continuity and stability of feedstock supplying. However, due to the problems of large WCO collection and storage quantity etc., it is very difficult to keep the stability of WCO supplying and make a high operating rate (above 90%) for the plant. Nevertheless, for the WCO-to-BFA plant, it can still obtain a low BFA production cost of 811–823 USD·t^{-1}, and high NPV (76–107 million USD) even at a low operating rate of 68.5% (6000 h) for different discount rates (i = 0.08, 0.10, 0.12, and 0.15), as shown in Fig. 6, which indicates that the WCO-to-BFA plant has strong ability to resist market risk.

5.4. Sensitive analysis to NPV

In this section, the effects of changing the model input parameters on the NPV are evaluated. Ten different system variables have been chosen for the sensitivity analysis over the expected range of parameters variation. Discount rate i of 10%, 12%, and 15% were used, and plant life was set to be 20, 25, and 30 years. The variation range was set to be ±30% of the capital cost, and ±20% for the other variables. The results for the sensitivity analysis are presented for the most influential parameters in Fig. 7. Since the annual sales revenue is contributed mainly by the BFA and glycerol sales, NPV is sensitive to the changing of the BFA price and glycerol price. Variation of them by 20% may lead to NPV changes about 84.9 and 5.4 million USD, respectively. The WCO cost has a considerable impact on NPV. It can bring about 60.6% of the variation in NPV when the WCO price rises or drops by 20%. Moreover, discount rates also have a remarkable impact on the NPV. When the discount rate i is reduced from 12% to 10%, the NPV will increase by 16.7 million USD,

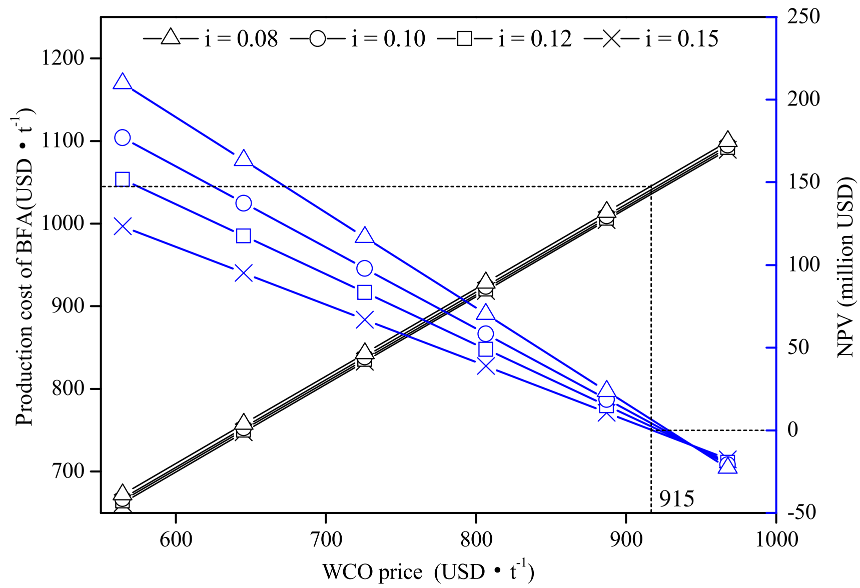


Fig. 3. Effects of WCO price on NPV and BFA production cost.

and when the discount rate i increases from 12% to 15%, the NPV will be reduced by 18.7 million USD. Other parameters such as plant life, steam & water cost, O & M cost, labor cost and capital cost have slight influences on NPV.

5.5. *The effect of oil price on different coal flotation agent price*

The oil prices were in the range of 100–110 USD·barrel^{-1} before June, 2014 (Oil price, 2014), and the price of diesel, Nalco, WCO, BFA were 1350–1450, 4030–4520, 690–810, and 1050–1130 USD·t^{-1}, respectively. If the sale price of BFA only corresponds to the sale price of diesel, the minimum profit of BFA will be between 550 and 600 USD·t^{-1} when oil price is 100–110 USD·barrel^{-1}. As shown in Fig. 8, the higher the oil prices are, the more profits of BFA are. For instance, when the international oil prices go up from 100 to 150 USD·barrel^{-1}, the minimum profit of BFA will increase from 560 to 870 USD·t^{-1} compared with diesel. Meanwhile, Nalco prices will stay in the range of 4030–4840 USD·t^{-1}. Thus, with the increasing international oil price, BFA will become an obvious potential flotation agent on the international market and reflect significant economic and social benefits. However, the oil prices were reduced from 110 to 50 USD·barrel^{-1} in the second half of 2014, which implies that the BFA price will be affected. In order to obtain minimum profit (NPV > 0) from BFA in the plant life period (25 years), the minimum price of BFA must be above 954 USD t^{-1}, no matter how the oil price changes.

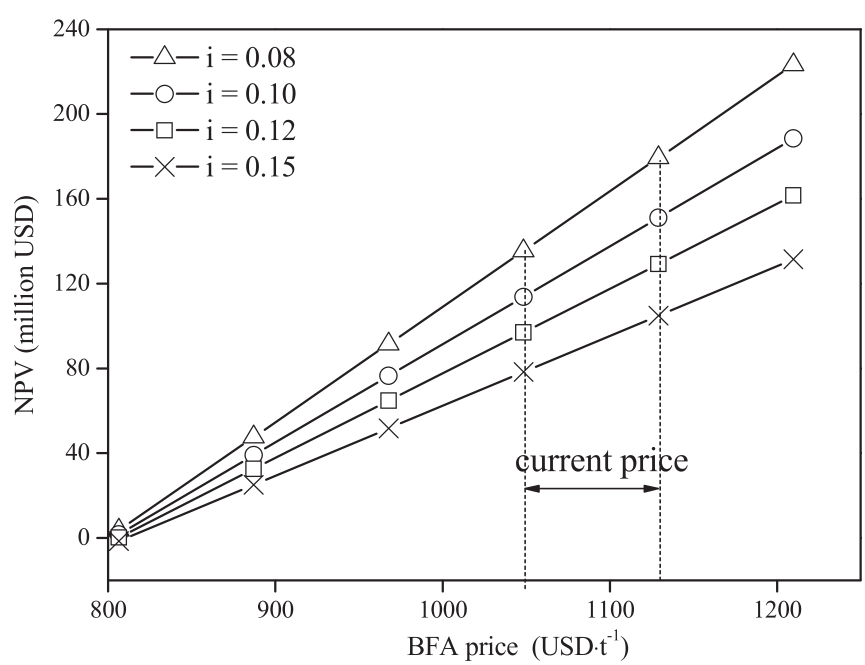


Fig. 4. Effects of BFA price on NPV.

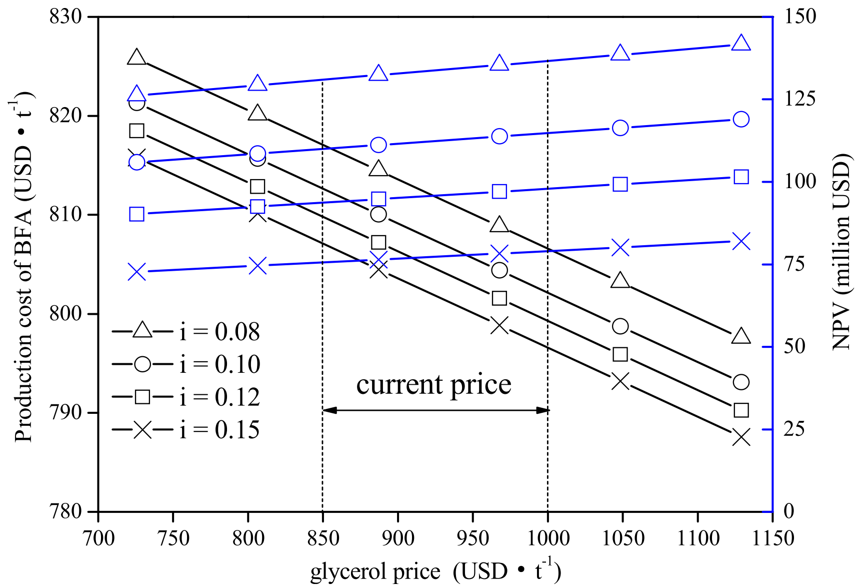


Fig. 5. Effects of by-product glycerol price on NPV and BFA production cost.

5.6. The potential of CO_2 emission reduction and effect of carbon tax on BFA cost

Fig. 9 shows the comparison of CO_2 emissions in the lifecycle for diesel and BFA as coal flotation agents in different scale of the coal preparation plant. It can be clearly seen that both CO_2 emissions in the process of diesel production (from crude oil to diesel) and coal flotation (diesel used in coal flotation) are more than those (WCO production including WCO collection, transportation, and conversion, and BFA used in coal flotation) of BFA. The ability of CO_2 emission reduction for BFA increases remarkably with the increasing coal flotation scale of the coal preparation plant. For instance, the amount of CO_2 emission reduction will be increased from 2400 to 6000 $t \cdot y^{-1}$ when the scale of coal preparation plant is enlarged from 2 to 5 million tons per year (coal slime content is about 10–15%). Under the consideration of the carbon tax policy, the associative economic benefits will be rather noteworthy, such as the obtained profit of CO_2 emission reduction being improved from 3800 to 193,000 $USD \cdot y^{-1}$ if carbon tax increases from 1.6 (the situation in a developing country) to 32.2 $USD \cdot t^{-1}$ (the situation in a developed country) on the basis of different coal preparation plant scales. In general, the higher the carbon tax is, the more profit there is.

6. Development prospect of WCO-to-BFA technology

Take China as an example to demonstrate the development potential of WCO-to-BFA. In China, 25–85% of clean coal can be recycled from coal slime by coal flotation, and the recovery profit will be between 2.42 and 2.74 billion USD (Qu and Zhang, 2007). However, at present, kerosene or light diesel oil and other petroleum products as collecting agents are used in coal preparation, and

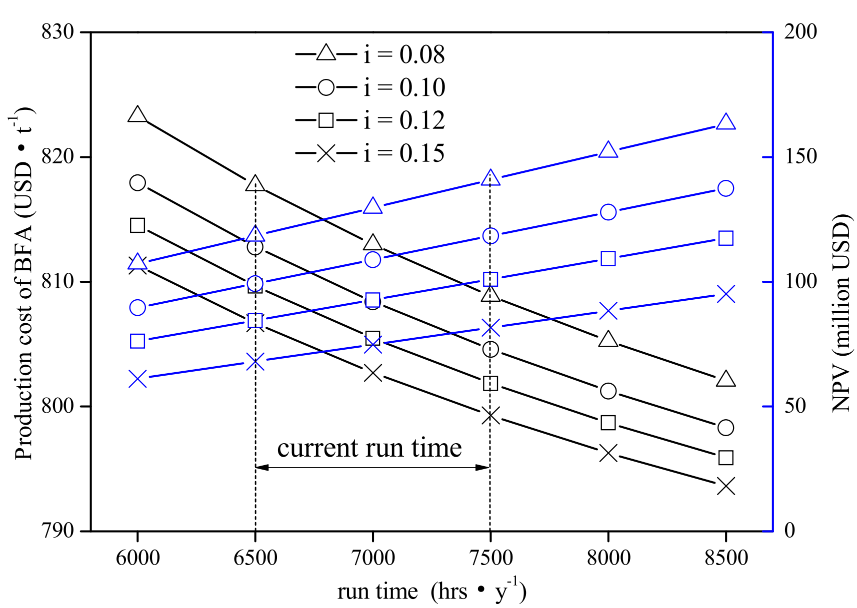


Fig. 6. NPV and BFA production cost versus annual operational hours.

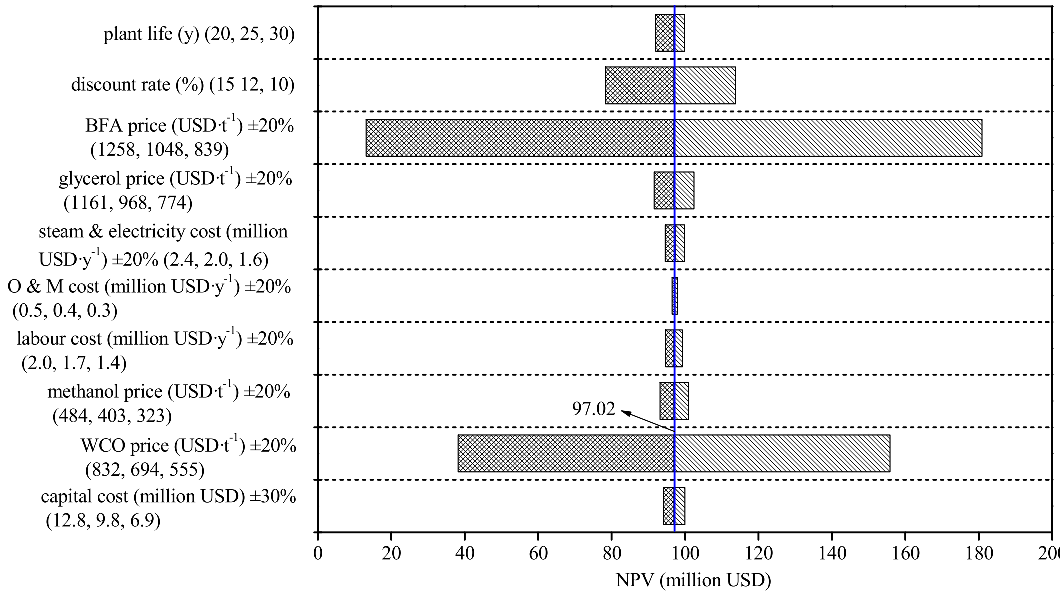


Fig. 7. Sensitive analysis to NPV.

nearly 300,000 tons of oil products are consumed every year, which leads to petroleum resource shortage, and which increases the production cost of coal preparation year after year.

The total production of WCO was 4.5 million tons in China in 2013. In order to make full recycle use of WCO, the first and second batches of pilot cities for kitchen waste recovery are approved by the Energy Administration and the National Development and Reform Commission of China, and the pilot cities are distributed in the 14 coal bases (Ministry of finance of China website, 2014; National development and reform commission of China website, 2011) which are shown in Fig. 10. In 2013, the total coal production was 3.7 billion tons, about 91% of which is from the 14 coal bases (3.37 billion tons) (National bureau of statistics of the People's Republic of China, 2014). According to the 12th five-year plan of energy development, the proportion of coal washing is about 65% of the total raw coal production (the 12th five-year plan energy development, 2014). The coal slime production is about 15% of the coal washing amount, and the flotation amount of coal slime is 0.33 billion tons in 2013. Therefore, the diesel demand (0.9 kg·t^{-1}-coal) for coal flotation is 295,700 tons. If part of the kitchen waste (about 174.26 million tons) in those cities is used to produce BFA (BFA consumption is 0.07–0.4 kg·t^{-1}-coal for different coals, and 0.36 kg·t^{-1}-coal is used in this study. For an amount of 0.33 billion tons in coal slime, the BFA demand is 0.12 million tons), which substitutes for diesel as a coal flotation agent, 0.39 million tons of standard coal can be saved, 1.8 million tons of CO_2 can be reduced, and 0.276 billion USD can be saved. Furthermore, BFA as coal flotation instead of diesel will save about 0.7 million tons of

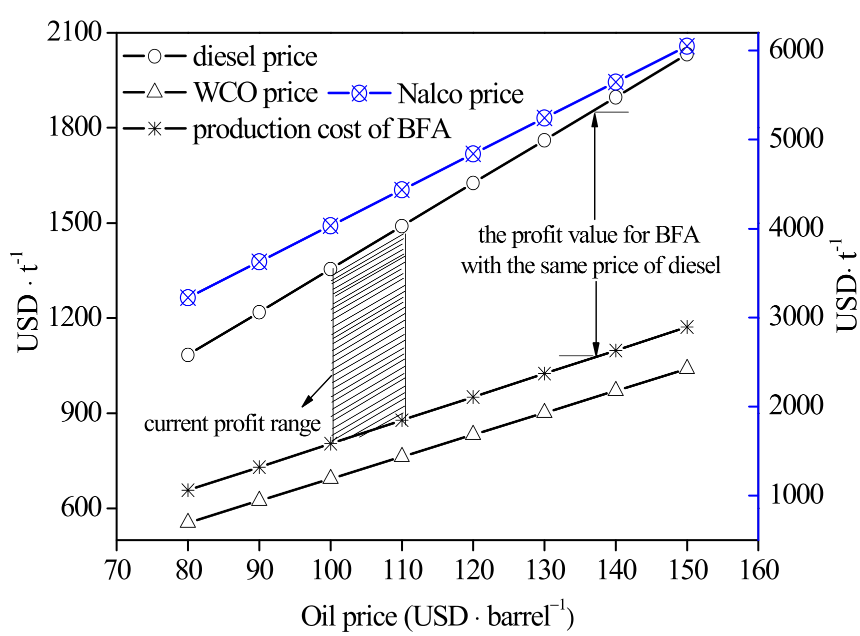


Fig. 8. Effects of oil price on different coal flotation agent prices.

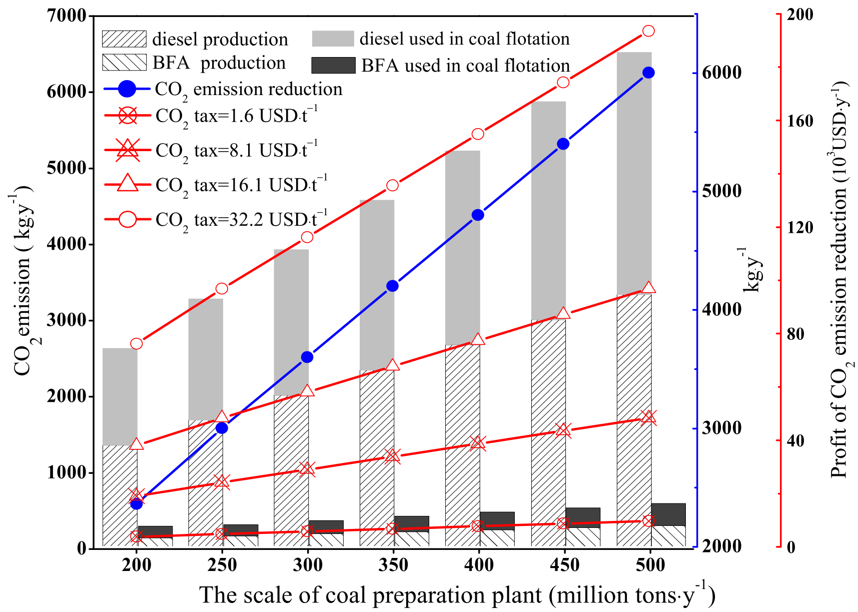
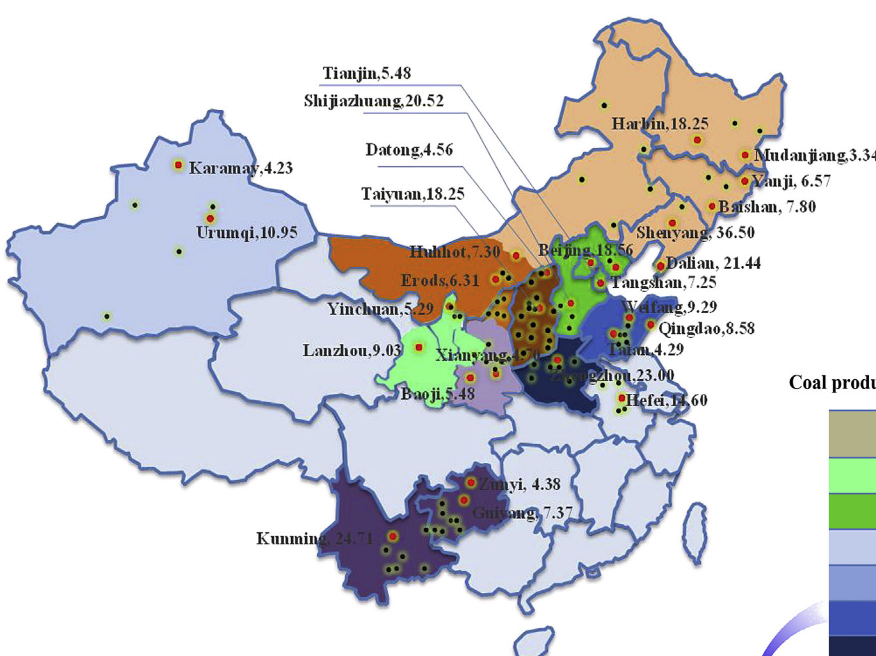


Fig. 9. Comparison of CO_2 emission reduction and carbon tax effect between diesel and BFA.

standard coal (0.334 million tons of oil equivalent), and reduce 3.2 million tons of CO_2 for the coal production in the world, i.e. 7.86 billion tons (the proportion of coal flotation is assumed to be about 50% of the total world coal production in the year of 2012) (BP Statistical Review, 2013). The WCO-to-BFA technology may have the great potential to be applied in the coal flotation industry around the world in the future.

7. Conclusions

A tech-economic assessment of WCO-to-BFA technology based on the pilot program showed that the most influential parameters on the economic performance of the plant are the prices of WCO and BFA. With respect to BFA substituting diesel as a coal flotation agent, the WCO-to-BFA technology can lead to a reduction of



Coal production in 14 coal bases, 3.37 billion tons

Coal base	Coal production, million tons
Ningdong	79.43
Jizhong	86.22
Xinjiang	135.26
Lianghuai	139.02
Luxi	140.46
Henan	142.60
Shanbei & Huanglong	259.15
Yungui	275.28
Eastern inner Mongol	957.91
Shendong	244.56
Jin zhong, Jin bei & Jin dong	910.24

Performance comparison of diesel and BFA as coal flotation agent for coal flotation

	Demand for coal flotation, tons	Energy consumption, GJ	CO_2 emission, 10^3t	Cost, billion USD
Diesel	295700	17.00	1940	0.400
BFA	118800	5.58	115	0.124

Fig. 10. The distribution of coal bases and the pilot cities of kitchen waste in China.

energy by 1.2 kg of standard coal, 5.5 kg of CO_2 emission, 0.836 USD of production costs for each ton of coal slime in the whole production chain including the WCO-to-BFA-to-CFP (coal flotation process). Otherwise, the economic evaluation showed that the production cost of BFA was only about 804.4 USD t^{-1} and the NPV of the plant was 97.02 million USD. The minimum profit (NPV > 0) from BFA in the plant life period (25 years) required that the minimum price of BFA must be above 954 USD$\cdot t^{-1}$. More importantly, the plant also presented an excellent economic performance even at low operational hours (6000–6500 h), which indicates that the WCO-to-BFA technology has great potential applicability in coal flotation industry.

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Nomenclature

Capital letters

BFA	bio-flotation agent
CFC	contractor's fee and contingency
COB	cost of BFA
CRF	the capital recovery factor
DFC	the total depreciable capital
Di	diglyceride
EN14214	European standard for biodiesel
FAME	fatty acid methyl ester
IRR	internal rate of return
Mo	monoglyceride
O&M	operation and maintenance
TCI	the total capital investment
TPC	the total plant costs
TPDC	the total plant direct cost
TPEC	the total purchase equipment cost
TPIC	the total plant indirect cost
Tr	triglycerides
TVC	the total variable costs

Acronyms

ASTM	American Society for Testing Material
CFP	coal flotation process
CFPP	cold filter plugging point
USD	USA dollar
FAME	fatty acid methyl ester
NPV	net present value
SP	solidification point
USD	USA dollar
WC	working capital
WCO	waste cooking oil

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