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The Environmental Performance of Biomass Densified Solid Fuel for Heating in China

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China has a large amount of agricultural and forestry residues that can be used as energy, and biomass densified solid fuel (BSDF) is an important pathway to use them as energy, especially for heating. One of the challenges facing the development of BSDF is that its environmental performance, including conventional air pollutants emissions and greenhouse gas (GHG) emission, is still doubted because previous studies have not yet reached a consensus. The aim of this manuscript is to evaluate the GHG emissions and conventional air pollutants emissions of BSDF for heating by Life Cycle Assessment (LCA) method, and propose policy suggestions for BSDF development. In this study, a 3E (energy, environment and economy) inventory model is established and applied to a recently commercialized case of BSDF for heating, and data quality is ensured by plenty of on-site survey. The results indicate that BSDF for heating can realise clean and environment friendly heating production in the investigated cases, and it is suggested to further deploy BSDF for heating, especially in industrial heating area where this technology can be competitive in the market compare to coal, natural gas and electricity for heating.

1. Introduction

China has 460 Mt of coal equivalent (tce)/y (NEA, 2016) of biomass resources that could be used for energy utilisation, including agricultural and forestry residues, livestock manure, living garbage and organic waste water and solid waste. Among it, solid agricultural and forestry residues take 200 Mtce/y (NEA, 2016). BSDF is an important utilisation way of biomass, especially for heating. By 2015, only 7.6 % biomass resources that could be used for energy utilisation is utilised in China (NEA, 2016), and large amounts of agricultural and forestry resources were discarded. Crop straw on-site burning brought severe air pollutions and fire hazards in some areas (Jiang, 2015). According to the 13th Five-Year-Plan (2016-2020), Chinese government planned to increase BSDF utilisation from 4 Mtce in 2015 to 15 Mtce by 2020 (NEA, 2016), which means an annual increase of 30 % in average. However, referring to the experiences of the 12th Five-Year-Plan (2011-2015), BSDF developed more slowly than expected in the plan. In conferences of *China BSDF Heating Experience Exchange Seminar* held in Changchun and Hangzhou in 2016, feedbacks from government officials and industrial experts implied that the development of BSDF for heating would come across many difficulties in the 13th Five-Year. One of the challenges is that the environmental performance of BSDF for heating, including emissions of air pollutants and GHG, is still doubted. The lack of social consensus on BSDF development, especially in restricted areas of highly-polluting fuels (NPC, 2016) brings difficulties of project approval and technology commercialisation (Ni et al., 2017).
Referring to literature review, energy, environmental and economic (3E) performance analysis based on LCA is a popular method to study the environmental performance. For examples, Cherubini and Strømman (2011) reviewed the energy, environmental performance of BSDF for heating. Akhtari et al. (2011) reviewed the economic feasibility of utilising forest biomass in district energy systems. This study (Cahyono et al., 2017) analysed the effect of binder concentration on the biomass briquettes properties. However, in spite of the rapid change of technology advancement and commercial mode of BSDF for heating in China, few studies have

focused on LCA analysis of energy, environmental and economic performance of actual and recent cases of BSDF for heating in China. Thus, this research provides an up-to-date reference for project decision-making and policy making of BSDF for heating in China. The main contribution of this study is the 3E data derived by a LCA analysis on a commercial project operated in 2015, which can reflect the recent advancement of technology and commerce.
This study aims to quantify 3E performance of BSDF for heating by LCA method on recently commercialized cases in China. In the rest contents, LCA models of fossil energy consumption, GHG emissions and emissions of air pollutants and economical model of BSDF for heating are established, and the case selection and data inventory are introduced in Section 2. Section 3 explains the results, and Section 4 summarised main conclusions and policy implications.

2. Methods and data

Life Cycle Assessment (LCA) (ISO, 2006) is the main method used in this study, which includes steps of goal and scope definition, inventory analysis, impact assessment and interpretation.

2.1 Goal and scope of BSDF for heating LCA

The goal of this study is to investigate fossil energy consumption, GHG emissions and conventional air pollutants emissions of BSDF for providing 1 MJ heat by LCA method, to evaluate the economic performance of the heating case, and to finally obtain 3E performance and inventory data of BSDF for heating.
The investigation scope starts from biomass materials collection to 1 MJ heat supply from heat source station. The physical processes of BSDF for heating are shown in Figure 1, which involves biomass materials collection, biomass materials transportation and storage, BSDF production, BSDF transportation and storage, BSDF combustion into heat and heat sales to end users. The 3E inventory analysis covers relevant fossil energy consumption, GHG emissions, and air pollutants including SO_2, NO_x, and particulate matters.

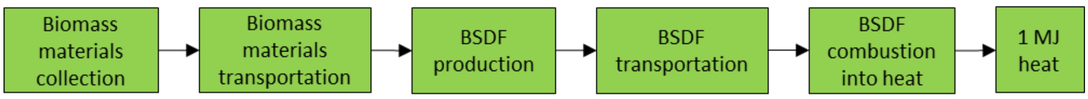

Figure 1: Physical processes of BSDF for heating

2.2 3E assessment models of BSDF for heating LCA

2.2.1 Energy and environment analysis models of BSDF heating LCA

The model is designed according to LCA framework and physical processes of BSDF for heating. Since biomass is carbon-neutral renewable energy, direct GHG emissions and direct fossil energy consumption of BSDF is set to be zero. Previous studies (Liu et al., 2014) established a fossil energy consumption calculation model of BSDF for heating from a LCA view, as is shown in Eq(1). Calculation models of GHG emissions and emissions of air pollutants are similar to that of fossil energy consumption.

$$BIO_{eng} = \left(\sum_{k}\sum_{j} share_{k} \times EF_{eng,j} \times EF_{j,k}\right) / \eta_{conv} + \sum_{k'}\sum_{j} share_{k'} \times EF_{eng,j} \times EF_{j,k'} \tag{1}$$

Eq. 1 shows the fossil energy consumption model, where BIO_{eng} is energy consumed during energy utilization, k represents BSDF production processes, k' represents BSDF utilization Processes, j represents energy varieties in end-use process, $share_k$ is distribution factor in process k, $share_{k'}$ is distribution factor in process k', $EF_{eng,j}$ is fossil energy consumption of end-use energy j, $EF_{j,k}$ is consumption of end-use energy j in process k, $EF_{j,k'}$ is consumption of end-use energy j in process k' and η_{conv} is thermal efficiency of combustion conversion equipment.

2.2.2 Economic analysis of BSDF for heating LCA

As urban central heating is one of the main applications of BSDF, a cost model of urban central heating is established with heating supply enterprises as the core with reference to the cost model of providing heating services by Song et al. (2017).

2.3 Case study and data inventory

2.3.1 Case selection

Referring to information collected by the authors by participating in many professional exhibitions and forums of BSDF for heating and also interviewing government officials and industry experts, the heating case of

Changchun Faway Automobile Company, which belongs to Great Resources Company, was selected. The heating project of Faway is newly-built, and BSDF provides heating for a plant of auto parts production. Because of the high mechanisation of the production line, the production workshop needs to maintain above 10℃ for the whole year, which is a special industrial heating project and requires a new distributed heating system. The project construction began in June 2015, and heat supply has started since 25th October 2015. The case reflects the development level of BSDF for heating technology in recent years, and is a successful example explored by the industry towards large-scale development of BSEF for heating.

2.3.2 Data inventories of Faway's Case

In the case of Faway, BSDF as heating fuel is made from corn straw in Changchun, Jilin. The BSDF is cylinder-shaped with 8 mm in diameter and 6 cm in length, the heating value of which is about 15.048 MJ/kg supplemented by other types of BSDF. Supplying heating service for 100 thousand m^2, the physical processes of the case are shown in Figure 1. A 10 t vapor/h and a 15 t vapor/h BSDF boilers are equipped in this case, one is used and one for spare. Thermal efficiency of the BSDF boilers is 83 %, equipped with a cyclone dust collector and a bag filter.

Based on the LCA models, fossil energy consumption, GHG emissions and conventional air pollutants emissions are mainly produced in four stages, including crop straw collection and transportation, BSDF production, BSDF combustion in the heat source station and heat station system operation. According to field survey, data inventories of the four stages are as follows.

a) Crop straw collection and transportation

According to field research, crop straw used for the heating project are collected mechanically, consuming 2.69E-04 kg diesel for 1 MJ heat in the collection stage.

By field research and interviews with the specialised straw transportation staff, raw straw bags are generally transported by diesel trucks with the load of 8 t, and BSDF by diesel trucks with the load of 55 t. Table 1 shows the data of the diesel fuel consumption summarised from field research and calculation.

Table 1: Summarised data sheet of corn straw materials and BSDF transportation according to survey

Transporting vehicle	Transportation fuel consumption l/(t·km)	Load distance (km)	Fuel consumption (l/kg)	Diesel consumption (kg/kg)	Total diesel consumption (kg/MJ)
Truck of 55 t load	1.11E-02	5.00E+01	1.85E-03	1.54E-03	1.16E-04
Truck of 8 t load	2.00E-02	1.00E+01	2.00E-04	1.67E-04	

b) BSDF production

Corn straw are crushed by crushing before being sent to BSDF production line. Each flat die BSDF production line produces 10 kt/y, the production processes of which are referenced from the literature (Song et al., 2017). BSDF product is packaged 50 kg per bag. From producers' experience, power consumption by BSDF production is 110~150 kWh/t and is set to be 137.5 kWh/t in this study, and diesel fuel consumption in plant transshipment of BSDF production is 5.29E-02 kg/t. According to calculations, for 1 MJ heat, diesel fuel consumption is 3.59E-06 kg/MJ and power consumption is 9.34E-03 kWh/MJ in the fuel production stage.

c) System operation of the heat source station

Average power consumption during the system operation of the heat source station is 2.2 kWh/m^2 and heat load factor of the production plant heating is set to be 50 W/m^2. According to Song et al. (2017), the calculated annual consumption of heat per unit area is 478 MJ/m^2 in this case. Therefore, power consumption of per unit of heat during system operation of the heat station is 2.95E-03 kWh/MJ. The diesel fuel consumption in plant transshipment of BSDF is 2.02E-01 kg/t.

d) BSDF combustion in the heat source station

On-site monitored and calculated air pollutants emission factors of the BSDF boiler in the heat source station are shown in Table 2.

Table 2: Air pollutants emission factors of BSDF boiler of the heat source station

Type	PM (g/kg)	SO_2 (g/kg)	NO_x (g/kg)
Emission factor	0.0615	0.0362	1.0501

e) Main emission factors

In this study, power consumed in the life cycle of BSDF for heating is assumed to come from local coal-fired power. Fossil energy consumption, GHG emissions and air pollutants emission factors of a coal-fired power and a diesel truck are listed in Table 3 according to literature reviews.

f) Relevant economic data of the Faway case

Much operating economic data are gained from the Faway case through 167 d operation in the heating season of 2015~2016, main data of which are shown in Table 4.

Table 3: Fossil energy consumption, GHG emissions (Song et al., 2017) and conventional air pollutants emission factors (He et al., 2012) of a coal-fired power and a diesel truck ($CO_{2,\ e}$ refers to carbon dioxide equivalent)

Type	Fossil energy consumption (MJ)	GHG ($gCO_{2,e}$)	PM (g)	SO_2 (g)	NO_x (g)
Emission factor (/kWh)	8.27	928.84	0.13	0.16	3.40
Emission factor (/kg)	52.45	4,325.32	6.70	4.00	19.60

Table 4: Inventory of main economic data for the Faway case

Type	Heating area (10,000 m^2)	BSDF ($/t)	Heating cost ($/$m^2$)	Investment in fixed capital (10,000 $)
Number	9.1	108.9	4.5	21.8

3. Results and discussion

3.1 Energy and environmental effect

The data of the four stages in the Faway case are used in the LCA calculation model to obtain inventories of fossil energy consumption, GHG emissions and air pollutants emissions, as are listed in Table 5.

Table 5: LCA result inventory of the Faway case

Type	Fossil energy consumption (MJ/MJ)	GHG ($gCO_{2,e}$/MJ)	PM (g/MJ)	SO_2 (g/MJ)	NO_x (g/MJ)
Result list for 1 MJ heat	0.143	15.298	0.009	0.007	0.149
Biomass materials collection and transportation	17.05 %	13.13 %	26.96 %	25.81 %	9.70 %
BSDF production	65.26 %	68.46 %	15.05 %	25.48 %	25.72 %
BSDF combustion system operation	17.69 %	18.40 %	4.84 %	7.54 %	7.07 %
BSDF combustion	0.00 %	0.00 %	53.14 %	41.17 %	57.51 %

3.2 Air pollutants emissions

Table 6 compares the air pollutants emissions of the Faway case with coal and natural gas for heating. PM emissions of BSDF for heating are close to those of natural gas for heating when equipped with BSDF-specific boiler and two-stage dust removal devices. SO_2 emissions of BSDF for heating are much less than those of coal and natural gas for heating since the sulfur content of BSDF is lower. BSDF for heating emits less NO_x than coal for heating because of a lower boiler temperature and emits a little more NO_x than natural gas for heating.

Table 6: Comparison of air pollutant emissions of the Faway case with coal and natural gas for heating

Type	PM (g/MJ)	SO_2 (g/MJ)	NO_x (g/MJ)
Faway case	0.0095	0.0072	0.1495
Coal layer combustion boiler (He et al., 2012)	0.8341	0.1220	0.268
Natural gas boiler (He et al., 2012)	0.0040	0.0112	0.0540

The ratio of fossil energy input and BSDF heating output from LCA of the case is 1:7, which means considerable fossil energy saving. With only 18.2 % out of 83.9 $gCO_{2,\ e}$/MJ (IPCC, 2006) direct GHG emissions of coal-fired boiler, GHG emissions are well controlled for BSDF for heating. Fossil energy consumption and GHG emissions are mainly produced in BSDF production, accounting for 65 % and 68 %. PM emissions are mainly produced in the BSDF combustion and SO_2 emissions are mainly produced in the

BSDF collection and transportation. While NO_x emissions mainly result from BSDF combustion and BSDF production. Life-cycle emission control of the BSDF-specialised boilers is still the focus of air pollutants emission reduction.

2,300 t BSDF is consumed annually in the Faway case, substituting for 1,710 t coal. BSDF for heating benefits energy structure optimisation, especially the substitution for coal and the utilisation of corn straw. BSDF for heating improves bioenergy utilisation efficiency and enables local decentralised biomass energy to be commercially utilised.

The fossil energy consumption and GHG emissions from BSDF heating production could be decreased by optimising biomass materials collection and utilisation processes and shorten load distance. The results indicate that PM, SO_2 and NO_x emissions of BSDF-fired heating when equipped with BSDF-specified boilers and two-stage dust removal devices, which enables less air pollutants emissions and is worth promoting, are far less than those of coal-fired heating and close to those of natural gas-fired heating. Direct combustion emissions from BSDF boilers can be controlled by optimising designs of BSDF-specialised boilers and flue gas treatment facilities and strengthening environmental regulations.

3.3 Economic analysis

The heat supply enterprise could gain 22.5 % net profit calculated by 4.5 $/m^2, guiding price of industrial concentrated heating in Changchun City. To be noticed, BSDF cost which accounts for 75 % of the total costs is higher than 50 % fuel cost of common coal-fired heating projects. If calculated by 3.8 $/m^2, the government-guided price of residential concentrated heating of Changchun City, net profit of heat supply enterprises could only be 2.5 %, which is poor economic performance.

3.3.1 Sensitivity analysis of the heating enterprise's profit margins

Market price of BSDF is unstable with frequent price changes and main cost factors like fixed capital investment, payback period, discount rate, labor costs and tax rate also vary with economic and social development. Therefore, the above cost factors are chosen for sensitivity analysis and Figure 2 shows how profitability of heat supply enterprises change with them.

In order of significance, BSDF price, tax rate, fixed capital investment, labor costs and discount rate are factors critical to profitability of heat supply enterprises according to the above sensitivity analysis. Among the crucial factors, the government could adjust the economic performance of BSDF-fired heating projects by regulating BSDF price, tax rate, and fixed capital investment to promote BSDF utilisation.

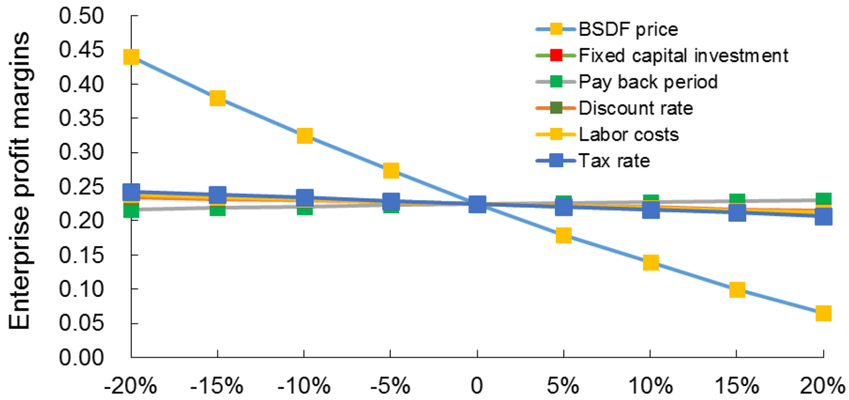

Figure 2: The changing trend of enterprise profit margins with cost factors

Table 7: Unit effective heating costs of several commonly used heating fuels

Fuel type	Heat value (kJ/kg & m^3 & kWh)	Heating cost		Efficiency of combustion devices	Unit effective heating cost	
		$/t	$/GJ		$/GJ	Ratio
BSDF	14.7	108.9	7.4	0.83	8.9	1.00
Coal	20.9	123.6	5.9	0.65	9.1	1.02
Natural gas	36.0	0.5	12.9	0.92	14.0	1.57
Industrial power	0.36	0.1	28.3	0.97	29.1	3.27

3.3.2 Economic performance of different heating fuels

Heating values, fuel prices and technical parameters in Table 7 are obtained from field research and interviews with enterprise managers and relevant experts in Changchun City during November of 2016. Table

7 also shows per unit effective heating costs of several commonly used heating fuels. The ratio equals to heating costs of other heating fuels to those of BSDF when providing 1 unit of effective heat.

Economic comparison shows that heating costs of BSDF-fired heating is close to those of coal-fired heating in current market conditions, which offers a good chance for BSDF to replace coal. The prices of BSDF and coal are determined by market supplies and demands that are quite uncertain. The unit effective heating costs of BSDF and power are 1.6 times and 3.3 times of those of natural gas. Natural gas and industrial power prices are guided by the government and fluctuates little.

4. Conclusions and policy implications

In this study, LCA calculation models of fossil energy consumption, GHG emissions and emissions of main air pollutants and economical model of BSDF for heating are established to analyse the BSDF for heating case of Faway. Then emissions of air pollutants of BSDF for heating is compared with those of coal and natural gas for heating, and unit effective heating costs of BSDF, coal, natural gas and power are also compared. Main conclusions of this study are as follows.

1) Fossil energy consumption in the BSDF for heating case of Faway is 0.14 MJ/MJ and the ratio of fossil energy input and BSDF heating output is 1:7. It implies benefits for fossil energy saving. GHG emissions are 15.3 gCO_2, e/MJ, 18.2 % of the direct GHG of coal boilers, which signifies good control of GHG emissions.

2) BSDF cost accounts for 75% of the total costs in the Faway case and enterprises could gain 22.5 % net profit from industrial concentrated heating in Changchun City. It means good economic performance. While economic performance for residential concentrated heating supply is not good, since prices of BSDF for heating are generally higher than those of coal for heating and lower than those of natural gas and power for heating.

With the national targets of energy structure adjustment and GHG emission reduction, development directions of BSDF heating industry promotion are as follows. BSDF for heating achieves renewable energy deployment and resource recycling promotion. End-use subsidy measures should be figured out to improve the policy system and action plans to support the BSDF heating industry, mobilise the enthusiasm of the local government and enterprises and gain commercialisation experience of running distributed heating projects.

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