An Economic and Policy Analysis of a District Heating System Using Corn Straw Densified Fuel: A Case Study in Nong'an County in Jilin Province, China

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Keywords: policy influence, economic model, district heating system, solid densified fuel, corn straw

Abstract:

The development of district heating systems of corn straw densified fuel (CSDF-DHS) is an important option to promote the use of bioenergy on a large scale for sustainable development, especially in China. At present, China's biomass densified solid fuel (BSDF) development lags behind previously planned target, main barriers of which are economic and policy support problems. Accurate case studies are key to analyze these problems. This manuscript takes Nong'an County in Jilin Province of China as an example to establish a techno-economic model to evaluate the economic performance of a CSDF-DHS under two policy scenarios. It calculates the economic performance under a benchmark market scenario (BMS) and the current policy scenario (CPS) and analyzes the influence of various policy instruments, including subsidies, carbon trading, and preferential taxation. The results indicate that: (1) The CSDF-DHS option is not competitive under the BMS or CPS compared to the traditional energy system based mainly on coal and liquefied petroleum gas; (2) Comparatively, the economic performance of corn straw briquette fuel (CSBF) is better than that of corn straw pellet fuel (CSPF); and (3) further policy support can make CSDF-DHSs competitive in the market, especially with subsidies for concentrated heating services and CSDF, carbon trading, and economic compensation to reduce the profit margin of enterprises, which can make both CSPF-DHSs and CSBF-DHSs competitive. The research results could provide scientific basis for relevant policy making and project decision.

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Abstract: The development of district heating systems of corn straw densified fuel (CSDF-DHS) is an important option to promote the use of bioenergy on a large scale for sustainable development, especially in China. At present, China's biomass densified solid fuel (BSDF) development lags behind previously planned target, main barriers of which are economic and policy support problems. Accurate case studies are key to analyze these problems. This manuscript takes Nong'an County in Jilin Province of China as an example to establish a techno-economic model to evaluate the economic performance of a CSDF-DHS under two policy scenarios. It calculates the economic performance under a benchmark market scenario (BMS) and the current policy scenario (CPS) and analyzes the influence of various policy instruments, including subsidies, carbon trading, and preferential taxation. The results indicate that: (1) The CSDF-DHS option is not competitive under the BMS or CPS compared to the traditional energy system based mainly on coal and liquefied petroleum gas; (2) Comparatively, the economic performance of corn straw briquette fuel (CSBF) is better than that of corn straw pellet fuel (CSPF); and (3) further policy support can make CSDF-DHSs competitive in the market, especially with subsidies for concentrated heating services and CSDF, carbon trading, and economic compensation to reduce the profit margin of enterprises, which can make both CSPF-DHSs and CSBF-DHSs competitive. The research results could provide scientific basis for relevant policy making and project decision.

Keywords: corn straw; solid densified fuel; district heating system; economic model; policy influence

1. Introduction

The use of biomass for the production of low carbon energy is recognized as an important goal of sustainable development [1]. Among the various ways to use biomass for energy production, one of the most widely used and commonly available in the market is BSDF [2,3]. BSDF refers to fuel of a certain shape that is of high density and is obtained from loose biomass pressed at a certain temperature and under a certain pressure. The general shape of BSDF can be a pellet, briquette or rod. Its volume is 1/8–1/6 of the biomass raw materials, and the density is 1.0–1.4 t/m^3. With an energy density equal to that of intermediate soft coal, BSDF has attracted widespread attention in recent years [4], including in China. In China, the raw materials of BSDF are mainly forestry and agricultural residues and BSDF is utilized mainly as a clean fuel for heating boilers in communities, industrial parks and other public or industrial facilities. China's total production of BSDF in 2015 was 8 million tonnes [5], which was less than the planned 2015 target of 10 million tonnes [6]. For the year 2020, China's planned target of BSDF production is 30 million tonnes [5], which requires an annual 30% increase of BSDF production, so it is necessary to take measures to promote the healthy and rapid development of China's BSDF industry [3]. Moreover, being a large corn producer with abundant crop straw resources, especially in Liaoning Province, Jilin Province and Heilongjiang Province in northeastern China, China has seen serious air pollution problems arise due to the large scale field incineration of crop straw waste [6–9]. As estimated, China's agricultural residues available for energy use are about 0.2 billion tce [6], which accounts for 4.7% of China's total energy consumption of 4.3 billion tce [10] in 2015. Therefore, to promote the energy use of biomass and also reduce the field incineration of corn straw, the development of corn straw solid densified fuel (CSDF) for heating should be prioritized in the development of China's BSDF industry.

Referring to a literature review, economic analysis is a popular area of international research on the development of BSDF [11], and many studies have applied economic analyses of BSDF heating systems on the district level or building level. For example, Thomson [12] reviewed the suitability of wood pellet heating for domestic households and discussed the advantages, issues, and barriers. Vallios [13] designed biomass district heating systems considering the optimum design of building structures and urban settlements around the plant and carried out an environmental and economic evaluation. Chau [14,15], Michopoulos [16], and Stolarski [17] analyzed the economic performance and other performance of BSDF utilization in buildings heating systems. Hendricks [18] evaluated the cost-effectiveness of biomass district heating in rural communities. Stephen [19] analyzed the economics and influence factors of biomass use for residential and commercial heating in a remote Canadian aboriginal community. Tabata [20] discussed the effectiveness of a woody biomass utilization system with wood pellet production and energy recovery processes for household energy demand, taking the case of Gifu Japan as an example. Ren et al. [21] analyzed and compared the logistics cost of corn stover feedstock supply systems based on China's case. Zhao et al. [22] researched the techno-economic performance of bioethanol production from corn straw in China.

In addition, it is also well recognized that BSDF development policies have a major impact on its economic performance. For example, Toka [23] researched how to manage the diffusion of biomass in the residential energy sector and discussed an illustrative real-world case study. Moiseyev et al. [24] indicated that subsidies were likely to be the major driving force to increase the energy use of woody biomass and found that subsidies and carbon prices can effectively promote the energy use of woody biomass in the E.U. and reduce carbon dioxide emissions. Madlener [25] investigated the innovation diffusion, public policy, and local initiative of using biomass for energy production, taking the case of wood-fueled district heating systems in Austria as an example. Gan [26] researched policy options and co-benefits of bioenergy transition in rural China, pointing out that there is great potential for developing and disseminating household-based biomass technologies in rural areas, especially with energy-efficient modern biomass stoves, which can produce far more economic, social and environmental benefits. Shan [27] proposed a novel and viable village-level BSDF utilization mode based on the field survey of China's BSDF industry and the results from demonstration projects, which is helpful to boost the utilization of BSDF mainly in rural China. Wang et al. [28] assessed densified biomass solid fuel utilization policies and strategies in China based on the supply chain framework. Therefore, it is concluded that economic and policy analysis for district heating system is a key area of international research on BSDF development. Scientific economic analysis system need to be established with field survey and literature review results to analyze the influence of relevant support policies. However, currently, few studies have been published on the economic and policy analysis methods and case studies of CSDF for district heating systems, especially in China.

The aim of this manuscript is to develop a techno-economic model to evaluate the economic performance of a corn straw densified fuel-district heating system (CSDF-DHS) and analyze the influence of polices using a case study of Nong'an County in Jilin Province, China. First, we investigate the system description of a CSDF-DHS and basic information about the case, which are introduced in Section 2. Then, we develop a technical model of a CSDF-DHS, construct a two-stage economic model to evaluate its economic performance, and set two scenarios to analyze the influence of policies. Those methods and data are introduced in Section 3. Finally, we provide the results and discussion in Section 4 and main conclusions and policy implications in Section 5.

2. System Description and Case Information

2.1. System Description of a CSDF-DHS

The basic function of a CSDF-DHS is to turn corn straw into solid densified fuel to provide fuel for heating and cooking in rural areas or for concentrated heating services in urban area. In a CSDF-DHS, corn straw is collected, packaged, transported, and then produced as CSDF. Then, a part of CSDFs is sold to rural residents, and the rest is sold to urban users. The boundaries and correlations of a CSDF-DHS are illustrated in Figure 1. To obtain fuel and heating services in a CSDF-DHS, various inputs with economic costs by various operators are needed, as listed in the left of Figure 1, and these economic costs can be changed by various types of policy support, such as subsidies, tax preferences, and carbon trading.

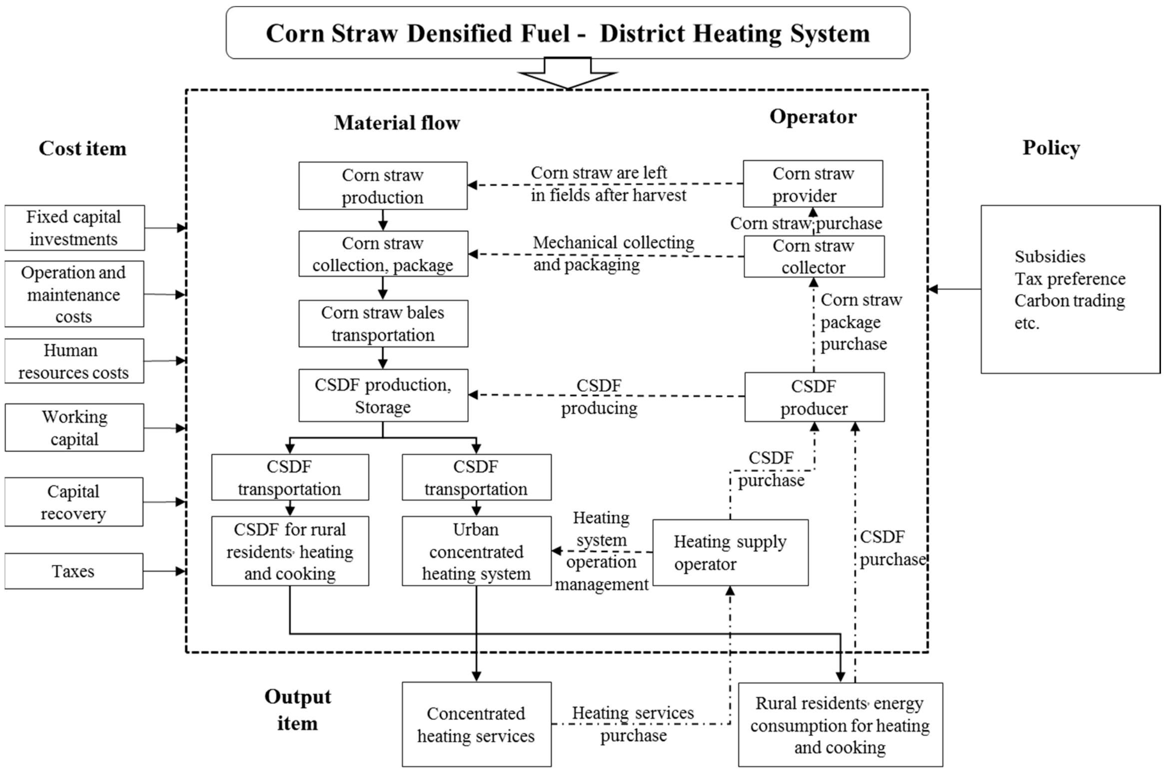

Figure 1. System boundary and correlations of a CSDF-DHS.

2.2. Case Information

Nong'an County in Jilin Province is taken as the example in this study. Its geological location is illustrated in Figure 2. In 2015, the per capita GDP of Nong'an County was \$5068, substantially lower than national average level of \$7095. The county has a population of 1,150,000, covering an area of 5400 km^2, and is located in a severe cold area [29] with 167 days of heating per year. The existing concentrated heating systems for the urban area and fuel systems for rural residents' heating and cooking mainly rely on coal and liquefied petroleum gas (LPG). Statistically [30], one household in the rural area consumes 1.53 tonnes of coal, 0.02 tonnes of LPG and 2.19 tonnes of firewood and corn straw annually on average in Jilin Province. In the downtown area of Nong'an County, the concentrated heating system covers an area of 8,180,000 m^2, with 20 kgce of coal consumption per unit area and approximately 164,000 tce of total coal consumption annually.

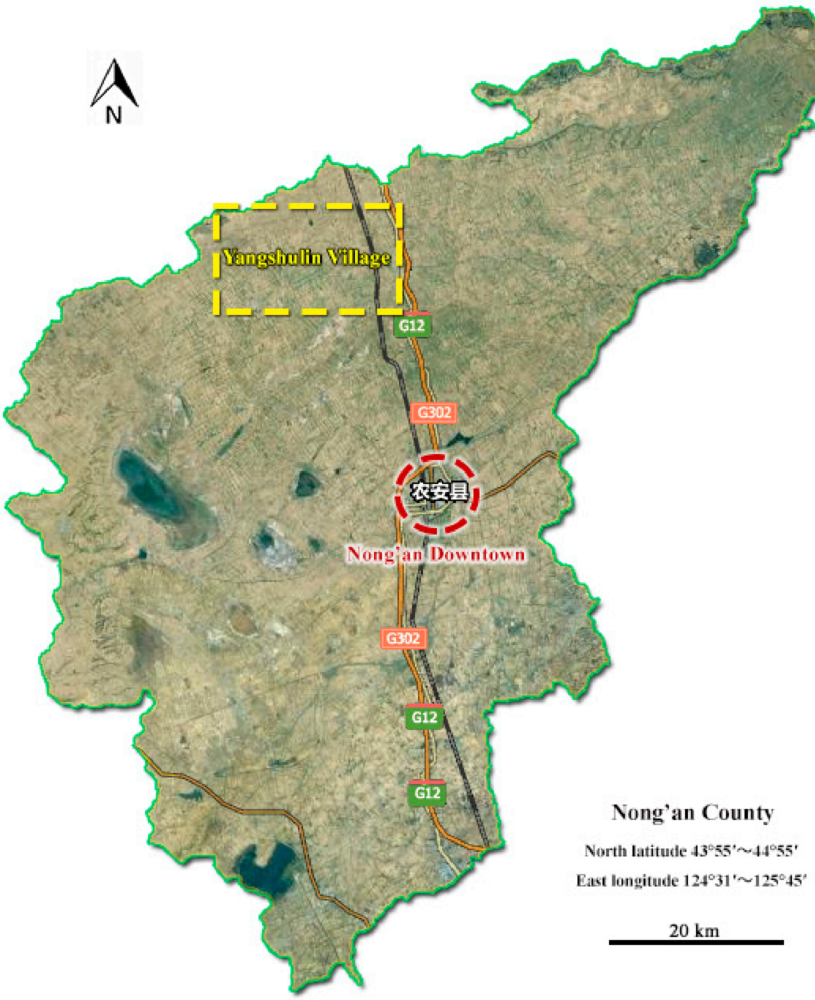

Figure 2. Geological location of Nong'an Country, Jilin Province.

Whereas coal burning causes high CO_2 emissions and air pollution, Nong'an Country, located in the World Gold Corn Belt, has abundant resources of corn straw, amounting to approximately 3 million t/a in total. However, currently, these resources are mostly abandoned and incinerated in the field, which is both a serious waste of resources and a cause of seasonal air pollution. To promote the energy use of corn straw resources, Yangshulin Village of Nong'an Country has established a CSDF-DHS demonstration project, with a scale of 10,000 t/a CSDF. It is urgent for Nong'an Country to further build a larger scale CSDF-DHS and use more corn straw resources to optimize the energy structure, reduce air pollution, create new jobs and increase the incomes of local residents. In this case study, we designed a 55,000 t/a CSDF production in Yangsulin Village, where a part of the CSDF will be sold to the downtown area for urban concentrated heating services, and the rest will be used for the heating and cooking of rural residents in Yangsulin Village.

3. Methods and data

In the following, we first introduce a technical model of a CSDF-DHS and then an economic model in two stages, the first stage from corn straw to CSDF and the second stage from CSDF to heating service. Finally, we present the basic settings of two scenarios for policy analysis.

3.1. Technical Model of the CSDF-DHS

According to Figure 1, the technical processes of a CSDF-DHS include many details, not only the parameters of various stages but also the type and numbers of main machines collecting corn straw and producing CSDF. The technical model is introduced below by stages, including corn straw resources, corn straw collection, CSDF production, and the final use of CSDF in the rural area of Yangshulin Village and the urban area of downtown Nong'an's.

3.1.1. Corn Straw Energy Utilization Resources Assessment

Corn straw resources can be used as energy in Yangshulin Village, as calculated by Equation (1), in which P is the corn straw energy utilization resources, P_{yield} is the output of corn, α is the ratio of straw to grain, β is the actual collection ratio of corn straw, and β' is the energy utilization ratio of corn straw.

$$P = P_{yield} \cdot \alpha \cdot \beta \cdot \beta' \quad (1)$$

According to a field survey and literature review, the basic data for calculating available resources for energy utilization are listed in Table 1.

Table 1. Data of corn straw energy utilization resources assessment in the case district.

Output of Corn (10,000 t)	Unit Yield of Corn (t/ha)	Ratio of Straw to Grain	Total Resources of Straw (10,000 t)	Actual Collectable Ratio	Total Collectable Resources (10,000 t)	Energy Utilization Ratio of Corn Straw
18.0 [31]	7.80 * [32]	1.6 [33]	28.98	0.6 [33]	17.39	1/3

* The unit yield of corn in the literature [32] is 8.37 t/ha, but according to the field survey, the collectable corn straw is 7.50 t/ha. To make the data consistent, we adjusted the unit yield of corn to 7.80 t/ha.

3.1.2. Corn Straw Collection

Referring to the literature [34,35], the mechanical collection of corn straw, including mechanical packaging, collecting, and transporting, is more economically feasible compared with manual collection. In this case, mechanical collection includes a rake machine used to put corn straw together and the machine used for packaging bales. Based on the field survey and interviews with machine producers, mechanical harvesting of corn puts corn and straw into separated places. Then, straw is spread on fields exposed to the sun to dry out. In Nong'an Country, Jilin Province, there are 7.50 tonnes of collectible corn straw per ha. The collection of corn straw is influenced by the season. Each year, operation begins with collecting corn straw already dried out and ends when the fields are covered by heavy snow. Given weather conditions, generally every year, a rake machine can collect corn straw of 1333 ha and a packaging machine can collect corn straw of 667 ha. The corn straw bales are stored in the corn straw collection stations and the storage yards of CSDF production plants. As existing commercial transportation can be used for corn straw bale transportation, a separate design of transportation facilities is not required.

3.1.3. CSDF Production

According to field survey and interviews with machine producers, two main products are determined for our research on CSDF, including CSPF, which is small cylinders with diameters of 5–12 mm and lengths of 10–30 mm, and CSBF, which has square sections of 30 × 30 mm^2 and lengths of 30–80 mm. Moreover, we suppose that CSDF is produced by a 3.5–4 t/h CSPF production line or a 7–8 t/h CSBF production line. The total production capacities of CSPF and CSBF for each line are estimated as 10,800 t/a and 21,600 t/a, respectively, by taking the average production rate and operation time as 16 h/day and 180 days/a, respectively. Figure 3 illustrates a typical schematic diagram of CSDF, which can both be applied to CSPF and CSBF, and the main process includes raw material pretreating and drying, processing, and storing. We only consider the case that the production line is used to produce CSPF only or CSBF only in this case study.

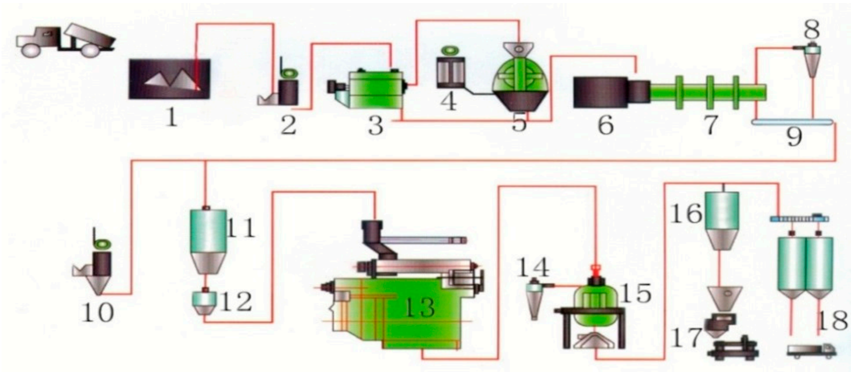

Figure 3. Typical schematic diagram of CSDF processing [36]. 1: Storage yard; 2: Conveyor; 3: Sieving machine; 4: Cyclone dust removal; 5: Intermediate bunker; 6: Hot-blast stove; 7: Dryer; 8: Separator; 9: Spiral conveyor; 10: Conveyor; 11: Processed material bin; 12: Magnetic material cleaners; 13: Forming machine; 14: Cooling fan; 15: Cooler; 16: CSDF storage tank; 17: Wrapper; and 18: Vehicle for transporting CSDF.

The produced CSDFs are stored in the storehouse of CSDF plants. Like the corn straw bale transportation, it is assumed the transportation of CSDF is based on available commercial transportation services.

3.1.4. Final Use for Heating and Cooking in Rural Area

CSDF should firstly meet the needs of rural residents for heating and cooking, as illustrated in Figure 1. CSDF consumption by rural residents for heating and cooking is determined by Equation (2):

$$M_{rural} = m_{rural} \cdot n_{household} \cdot \eta_{rural} \tag{2}$$

In Equation (2), M_{rural} is the rural consumption of CSDF, m_{rural} is the CSDF consumption for heating and cooking per household, $n_{household}$ is the number of total households in a rural area, and η_{rural} is the penetration rate of household heating and cooking by CSDF in the rural area.

Using a field survey, it is estimated that 3.5 t/a of CSDF consumption per household can meet residents' basic needs for heating and cooking in Yangshulin Village, and there are a total of 9428 households. Referring to the document issued by Jilin Province [37], the target penetration rate of CSDF in rural areas is set as 50% in 2016, which means 4714 households should use CSDF.

3.1.5. Final Use for Concentrated Heating Service in Urban Area

The amount of CSDF utilized for concentrated heating services in urban areas is determined by Equation (3):

$$M_{city} = P \cdot (1 - n_{loss}) - M_{rural} \tag{3}$$

In Equation (3), M_{city} is the amount of CSDF available for urban concentrated heating, P and M_{rural} have the same meaning as in Equations (1) and (2), and n_{loss} is the rate of loss of corn straw during CSDF processing, which is assumed to be 5%.

(a) Heating load calculation [38]

$$Q_h = q_h A_c \cdot 10^{-3} \tag{4}$$

In Equation (4), Q_h is the heating load of the building in kW, A_c is the area of the building in m^2, and q_h is the thermal index of the heating area of the building, which equals the heating load per square meter (W/m^2).

According to the field survey on concentrated heating enterprises in Nong'an County, q_h is 45 W/m^2, and A_c is 1.08 million m^2 in this CSDF-DHS.

(b) Annual heat consumption [38]

$$Q_h^a = 0.0864 N Q_h \left(\frac{t_i - t_a}{t_i - t_{o,h}} \right) \quad (5)$$

In Equation (5), Q_h^a is the annual heating consumption on space-heating in GJ/a, N is the days of the heating period in d/a, Q_h is the heating load of the building in kW, t_i is the heating room calculated temperature in °C, t_a is the outdoor average temperature during the heating period in °C, and $t_{o,h}$ is the outdoor average calculated temperature during the heating period in °C.

The heating period is 167 days in this case. According to Nong'an County meteorological data and the survey on heating enterprises, the outdoor average temperature during the heating period is −7.6 °C, the calculated heating temperature is −21.1 °C, and the heating room calculated temperature is 18 °C.

(c) The heat demand for concentrated heating of CSDF

The heat demand for concentrated heating of CSDF in urban areas is determined by Equation (6):

$$m_{district} = \frac{Q_h^a}{\eta \cdot F_{LHV}} \quad (6)$$

In Equation (6), $m_{district}$ is the CSDF consumption per unit area in t/a, η is the thermal efficiency of the boiler, and F_{LHV} is the low heat value of CSDF in GJ/t. According to the field survey on heating enterprises, the thermal efficiency of a biomass boiler is 75%–85%. This study chooses 80% as the thermal efficiency. Based on industrial analysis, the low heat value of CSDF is 14.93 GJ/t.

(d) Concentrated heating area and the heating station

We use the amount of available CSDF for concentrated heating and the annual heat demand per unit area during heating period as parameters to measure the CSDF consumption per unit heating area and total heating area (see Equation (7)). The total concentrated heating area by a CSDF-DHS is the sum of all heating areas contributed by various heating stations:

$$A_{total} = \frac{M_{city}}{m_{district}} \quad (7)$$

In Equation (7), A_{total} is the heating area supported by the concentrated heating system in m^2, and the other two symbols refer to Equations (3) and (6).

According to the documents of the National Energy Administration of China [39], this case takes 20 t vapor/h CSDF boiler as the basic heating station unit, calculates the maximum heating area, determines the number of basic heating station units, and then equally distributes the total heating area to each basic heating station unit. M_{city} and $m_{district}$ are 38,600 t/a and 35.59 kg/a, respectively, in this CSDF-DHS.

3.2. Economic Model from Corn Straw to CSDF

The first stage model includes 4 sub-stages from corn straw to CSDF, and the cost is calculated by Equation (8), where C_{fuel} is the total cost from corn straw to CSDF, $C_{collect}$ is the cost of corn straw collection, C_{trans} is the cost of corn straw bale transportation, C_{prod} is the cost of CSDF production, and C'_{trans} is the cost of CSDF transportation:

$$C_{fuel} = C_{collect} + C_{trans} + C_{prod} + C'_{trans} \quad (8)$$

3.2.1. Corn Straw Collection

The cost of corn straw collection mainly includes the investments in agricultural machinery, the corn straw purchase fee, operation and maintenance costs, human resource fees, profits of collection, and taxes, referring to Equation (9):

$$C_{collect} = \frac{C_{equi} \cdot CRF}{M_{agv}} + C_{purchase} + C_{O\&M} + C_{labor} + C_{management} + C_{profit} + C_{tax} \tag{9}$$

In Equation (9), C_{equi} is the investment of agricultural machinery, M_{agv} is the annual collection corns straw weight, $C_{purchase}$ is the corn straw purchase fee, $C_{O\&M}$ is the operation and maintenance cost, C_{labor} is the human resource fee, $C_{management}$ is the management fee, C_{profit} is the profits of collection, and C_{tax} is the taxes.

The capital recovery factor (CRF) [40,41] is the ratio of constant annuity to the present value of receiving and is calculated by $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$, where i is the discount rate and n is the payback period.

According to the field survey, the summarized calculation of this stage are listed in Table 2.

Table 2. The summarized cost table of corn straw collection (i = 0.08 and n = 10).

Category	Agricultural Machinery Capital Recovery	Corn Straw Price	Operation and Maintenance Costs	Human Resources Costs	Management Fees
Unit price ($/t)	3.0	0.0	6.9	2.9	1.1

3.2.2. Corn Straw Bale Transportation

The cost of corn straw bales transportation includes the tonne-kilometer price of the transportation and handling charge, referring to Equation (10):

$$C_{trans} = W_{straw} \cdot l \cdot Trans_{price} + C_{handling} \tag{10}$$

In Equation (10), W_{straw} is the corn straw weight, l is the transportation distance, $Trans_{price}$ is the tonne-kilometer price of corn straw transportation, and $C_{handling}$ is the handling charge.

According to the field survey, the corn straw bale transportation distance is 10 km around, the price of transportation is $5.3/t, and the handling charge is $3.3/t.

3.2.3. CSDF Production

The cost of CSDF production consists of the investments in production machines and infrastructure, the corn straw bale purchase fee, operation and maintenance costs, human resource fees, profits from collection, and taxes, referring to Equation (11):

$$C_{prod} = \frac{C'_{equi} \cdot CRF}{M_{prod}} + C'_{purchase} + C'_{O\&M} + C'_{labor} + C'_{management} + C'_{profit} + C'_{tax} \tag{11}$$

In Equation (11), C'_{equi} is the investment of production machine and infrastructure, M_{prod} is the annual production CSDF weight, $C'_{purchase}$ is the purchase fee of corn straw bales, $C'_{O\&M}$ is the operation and maintenance cost, C'_{labor} is the human resource fee, $C'_{management}$ is the management fee, C'_{profit} is the profits of production, and C'_{tax} is the taxes.

According to enterprise interviews and field survey, the calculated costs of CSDF production are listed in Table 3.

Table 3. Calculated cost of CSDF production (i = 0.08 and n = 12).

CSDF Type	Capital Recovery	Operation and Maintenance Costs				Human Resources Costs	Management Fees
		Maintenance	Electricity Fees	Wearing Parts	Packing Fees		
CSPF ($/t)	5.6	1.1	9.6	3.6	2.9	2.3	3.0
CSBF ($/t)	1.6	0.3	5.6	2.2	2.9	1.7	2.5

3.2.4. CSDF Transportation

The cost of CSDF transportation includes the tonne-kilometer price of the transportation and handling charge, referring to Equation (12):

$$C'_{trans} = W'_{straw} \cdot l' \cdot Trans'_{price} + C'_{handing} \tag{12}$$

In Equation (12), W'_{straw} is the CSDF weight, l' is the CSDF transportation distance, $Trans'_{price}$ is the tonne-kilometer price of the transportation, and $C'_{handing}$ is the handling charge.

According to the field survey, the transportation distance is 10 km and the price of transportation is \$0.08/t·km in rural areas. When the CSDF produced by Yangshulin Village is transported to Nong'an County, according to geological information, the transportation distance is 48 km, the price of the transportation is \$0.04/t·km, and the handling charge is \$3.62/t.

3.3. Economic Model from CSDF to Heating Service

3.3.1. Rural Residents Cost for Heating and Cooking

The costs from CSDF for heating and cooking rural residents per household consist of the investment recovery of stoves and CSDF cost per household, referring to Equation (13).

$$C_{rural} = C_{furnace} \cdot CRF + m_{household} \cdot C_{fuel} \tag{13}$$

In Equation (13), C_{rural} is the cost from CSDF for heating and cooking of rural residents per household, $C_{furnace}$ is the stove investment per household, $m_{household}$ is the CSDF consumption per household, and C_{fuel} is the CSDF price.

Based on the per capita housing area of rural residents, 24.71 m^2 [42], every household has 4 people in a housing area of 100 m^2, so the heating load of a stove is estimated to be 100 m^2, and the price of one stove is \$194 [43]. Here, i is 0.08 and n is 12 years.

3.3.2. Urban Concentrated Heating Cost

The costs from CSDF for urban concentrated heating per unit area consist of the investment recovery of the concentrated heating system and infrastructure, the CSDF costs, operation and maintenance costs, human resource fees, enterprises profits, and taxes, referring to Equation (14).

$$C_{district} = \frac{C''_{equi} \cdot CRF + M_{district} \cdot C''_{fuel} + C''_{O\&M} + C''_{labor} + C''_{profit} + C''_{tax}}{heat_{area}} \tag{14}$$

In Equation (14), $C_{district}$ is the cost from CSDF to urban concentrated heating per unit area, C''_{equi} is the concentrated heating system and infrastructure investment, $M_{district}$ is the CSDF consumption of the heating stations, C''_{fuel} is the CSDF price for heating stations, $C''_{O\&M}$ is the operation and maintenance costs, C''_{labor} is the human resource fees, C''_{profit} is the profits of concentrated heating stations, C''_{tax} is the taxes, and $heat_{area}$ is the service heating area of heating stations.

According to the field survey, the concentrated heating system and infrastructure investment is shown in Table 4. In the research, the heating system investment is estimated based on the arithmetic mean [44] of the investment. The heating system investment is \$2824/t vapor, and the infrastructure investment is \$1303/t vapor. The operation and maintenance costs account for 2.5% [18] of the concentrated heating system investment. i is 0.08, and n is 20 years.

Table 4. Survey of the heating system and infrastructure investment in heating stations.

Heating Station	Establish-ment Way	CSDF Type	Heating Service Type	Power (t vapor/h)	Equipment Investment (10,000$)	Unit Equipment Investment (10,000$/(t vapor/h))	Infrastructure Investment (10,000$)	Unit Infrastructure Investment (10,000$/(t vapor/h))
A mill factory	Renovation	CSBF	Industrial steam	25	57.9	2.3	10.9	0.4
A feed mill	Newly built	CSBF	Industrial steam	6	25.3	4.2	16.9	2.8
A free trade zone	Newly built	CSPF	Heating	30	118.6	4.0	20.1	0.7
A plant area	Newly built	CSPF	Heating	25	44.7	1.8		
A residential and office area	Renovation	CSBF	Heating	4	7.2	1.8		
Average						2.8		1.3

3.4. Policy Scenario Setting

The policy support to the development of a CSDF-DHS, including subsidies on fixed capital investment, corn straw, CSDF, urban concentrated heating services, carbon trading, and preferential electricity prices, can greatly influence its actual economic performance. To observe the influence of policies on the economic performance of a CSDF-DHS, we designed two policy scenario for the calculation of economic model. One is the benchmark market scenario (BMS) without any policy support, and the other is the current policy scenario (CPS) with some policies currently adopted. The basic settings of the two scenarios are listed in Table 5 and further explained as follows.

- The *benchmark market scenario* (BMS) is a market-oriented scenario without any policy support. Referring to the experiences of the demonstration project in Yangshulin Village, rural residents are willing to freely provide collection enterprises with corn straw with the compensation of a favorable price for CSDF. It is mainly because the manual collection and storage of corn straw by themselves require much more time, manpower, and material resources [34,35].
- The *current policy scenario* (CPS) includes polices current adopted by the government of China [45] and Jilin Province [46] to support the development of a CSDF-DHS. In addition to the tax-free policy for corn straw and CSDF, it also include subsidies for fixed capital investment for CSDF production, stoves, and boilers to increase the competitiveness of the system.

Table 5. Basic settings of the two policy scenarios by stages of a CSDF-DHS.

Scenario	Corn Straw Collection and Bales Transportation	CSDF Production: CSDF Production	CSDF Production: Selling: Heating Station	CSDF Production: Selling: Rural Residents	CSDF Utilization: Rural Residents, Heating Cooking	CSDF Utilization: Concentrated Heating Enterprise
Bench-mark Market Scenario	$C_{purchase}$: zero [1]	Industrial electricity price: $0.08/kWh [1]	C'_{profit}: 30% [1]	C'_{profit}: 10% [1]	No stove subsidy [1]	C''_{profit}: 20% [1]
	C_{tax}: 6% [1]					
	C_{profit}: 30% [1]		C'_{tax}: 6% [1]	C'_{tax}: 6% [1]		C''_{tax}: 6% [1]
	Current agricultural machinery subsidy [2]					
Current Policy Scenario	$C_{purchase}$: zero [1]	Industrial electricity price: $0.08/kWh [1]	C'_{profit}: 30% [1]	C'_{profit}: 10% [1]	Stove subsidy: 70% [3]	C''_{profit}: 20% [1]
	C_{profit}: 30% [1]					C''_{tax}: 6% [1]
	Current agricultural machinery subsidy	Fixed capital investment subsidy: 10% [2]	C'_{tax}: tax-free [3]	C'_{tax}: tax-free [3]		Fixed capital investment subsidy: 100,000/t vapor [3]
	C_{tax}: tax-free [3]					

Notes: [1] Field survey by authors; [2] The proportion of current agricultural machinery subsidies is 5.3% referring to field survey; [3] Current Government Document and Policy [45,46].

4. Results and Discussion

4.1. The Technical Process of a CSDF-DHS

The technical process of a CSDF-DHS decided by the technical model is illustrated by Table 6 (from corn straw resources to CSDF production) and Table 7 (CSDF utilization in rural and urban areas). The total utilization scale is 58,000 t/a corn straw, and the CSDF produced can serve for 4714 households in rural areas and 1.08 million m^2 of concentrated heating service in urban areas. The CSDF production is either CSPF or CSBF in Table 6.

Table 6. Technical process from corn straw resources to CSDF production.

Category	Corn Straw Resources		Collecting Equipment		CSDF Production	
	Energy Utilization (10,000 t/a)	Collect Area (667 ha)	Packaging Machine (Sets)	Rake (Sets)	CSPF 3.5–4 t/h Production Line	CSBF 7–8 t/h Production Line
Quantities	5.80	11.54	10	5	5	3

Table 7. Technical process of CSDF utilization.

Category	Rural Residents Heating and Cooking		Urban Concentrated Heating				
	Households	CSDF Total Consumption (10,000 t)	CSDF Total Consumption (10,000 t)	Unit Heating Load (MJ/m^2·a)	Heating CSDF Consumption (kg/m^2·a)	20 t vapor/h Boiler Quantity of Heating Station	Heating Area (10,000 m^2)
Quantities	4714	1.65	3.86	425	35.59	4	108

4.2. Economic Performance in the Benchmark Market Scenario

The results of the economic model in the BMS are listed in Tables 8 and 9. The costs of CSPF and heating services provided by CSPF are both higher than those of CSBF because CSPF has higher investment and operation and maintenance costs than CSPF. However, CSPF is more beneficial for the local economy, with higher taxes, profits, and labor income created.

Table 8. Cost of corn straw and CSDF in the BMS.

Category	Corn Straw Cost		CSDF Cost	
	Corn Straw in the Fields ($/t)	Corn Straw Bales in the Factory ($/t)	Rural Residents Heating and Cooking CSDF ($/t)	Urban Concentrated Heating CSDF ($/t)
CSPF	0	30.8	71.2	88.8
CSBF			51.8	73.3

Table 9. Cost of heating service and economic indicators of a CSDF-DHS in the BMS.

Category	Heating Service Price		Economy Indicators		
	Rural Residents, Heating and Cooking ($/household·a)	Urban Concentrated Heating Price ($/m^2·a)	Taxes ($10,000)	Profits ($10,000)	Labor Income ($10,000)
CSPF	275	5.1	59.7	204.3	73.6
CSBF	229	4.4	54.7	177.5	66.3

In this case, CSDF is used to replace traditional energy, mainly coal, LPG, and directly burned firewood and corn straw. According to data collected in Nong'an County, the local price of coal is approximately $101/t and that of LPG is approximately $1.3/kg. Firewood and corn straw have no economic expenses. Therefore, it is estimated that the annual expense of heating and cooking per household is $181/a, which is lower than the expense using CSDF. However, using CSDF can benefit the local economy because it can avoid the payment flowing to other regions to buy coal and LPG. The total payment of 684 households on coal and LPG is 0.85 million USD.

In urban concentrated heating, CSDF mainly replaces coal. The current government-guided price for concentrated heating services mainly by coal is \$3.8/m^2, which is lower than that of CSDF and means poor economic performance by a CSDF-DHS in the BMS. However, using CSDF for urban heating can also avoid the payment of coal flowing to other regions. According to the field survey, the concentrated heating coal consumption in Nong'an County is approximately 20 kgce/m^2, the price of purchased coal is approximately \$109/tce, and the total expense of coal is approximately 2.35 million USD with a heating area of 1.08 million m^2.

In potential, the total expense of traditional energy flowing out of Nong'an is approximately 3.21 million USD. Using CSDF can avoid this outflow of payments and create taxes, profits, and labor income to help local economic growth, though CSDF has poor economic performance compared to traditional energy in the BMS.

4.3. Economic Performance in the Current Policy Scenario

The results of the economic model in the CPS are listed in Tables 10 and 11. Compared to the BMS, the cost of corn straw and CSPF/CSBF are cut by 5.6% and 8.2%–8.7%/8.7%–9.2%, respectively, because of tax-free policies and subsidies for fixed capital investment. The cost of heating services by CSPF/CSBF for rural residents and urban concentrated heating is reduced by 14.3%/16.1% and 8.8%/9.1%, respectively because of the policies, whereas the taxes and profits created by the CSDF-DHS are also reduced to a certain extent. However, the costs of heating services for rural and urban areas are still higher than those of the traditional energy benchmark (\$181/household·a and \$3.8/m^2), though the economic performance has been improved by policy support totaling 2.0 million USD subsidies and tax-free for corn straw collection and CSPF production.

Table 10. Cost of corn straw and CSDF in the CPS.

Category	Corn Straw Cost		CSDF Cost	
	Corn Straw in the Fields (\$/t)	Corn Straw Bales in the Factory (\$/t)	Rural Residents, Heating and Cooking CSDF (\$/t)	Urban Concentrated Heating CSDF (\$/t)
CSPF	0	29.1	65.0	81.5
CSBF			52.7	66.9

Table 11. Cost of heating service and economic indicators of a CSDF-DHS in the CPS.

Category	Heating Service Cost		Economy Indicator			Government Subsidies	
	Rural Residents, Heating and Cooking (\$/household·a)	Urban Concentrated Heating Price (\$/m^2·a)	Taxes (\$10,000)	Profits (\$10,000)	Labor Income (\$10,000)	The First Year Subsidies (\$10,000)	Annual Subsidies (\$10,000)
CSPF	235	4.7	24.5	196.2	73.6	202.6	0
CSBF	192	4.0	24.5	170.0	66.3	202.6	0

4.4. Influencing Factors of Economic Performance under the CPS

The economic performance of this CSDF-DHS case is poor even with the current policy support. Therefore, we discuss the influence factors of economic performance under the Current Policy Scenario (CPS). These factors includes the subsidy for fixed capital investment, the corn straw price, the CSDF price, the concentrated heating price, carbon trading, and the preferential electricity price, which can be further intervened by government policy in the future.

4.4.1. Influence of Fixed Capital Investment Subsidy

The influence of economic performance on CSDF-DHS heating service costs for a fixed capital investment subsidy is shown in Figures 4 and 5. To discuss the influence of the subsidy proportion changes on heating service cost under the CPS, we set the proportion of fixed capital investment subsidies from 0% to 100%. First, we analyze the urban concentrated heating cost. The results indicate that if the subsidy proportion increased by 10%, the urban concentrated heating cost would decrease by \$0.07/m^2.

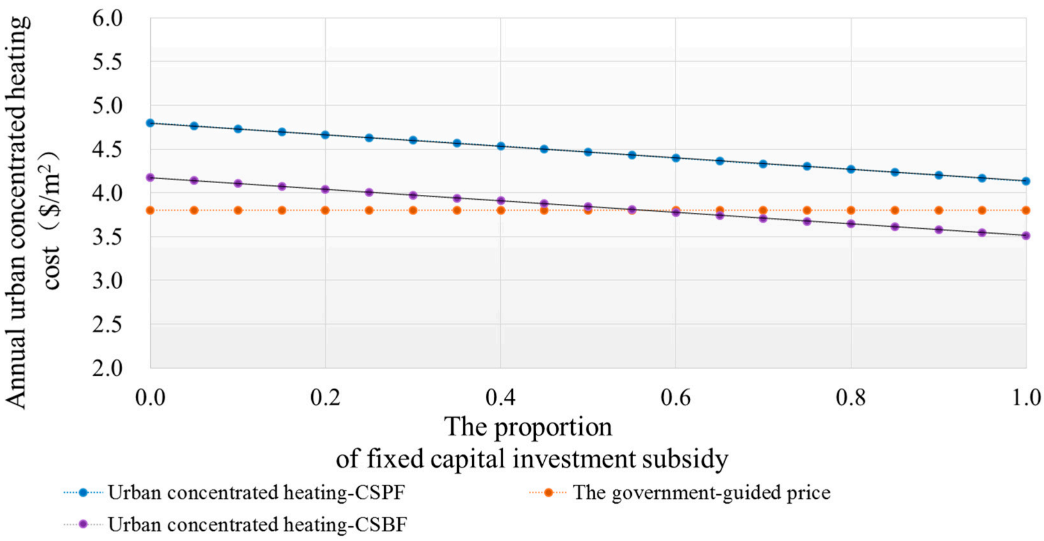

Figure 4. Influence of fixed capital investment subsidy on the economic performance of CSDF for urban concentrated heating.

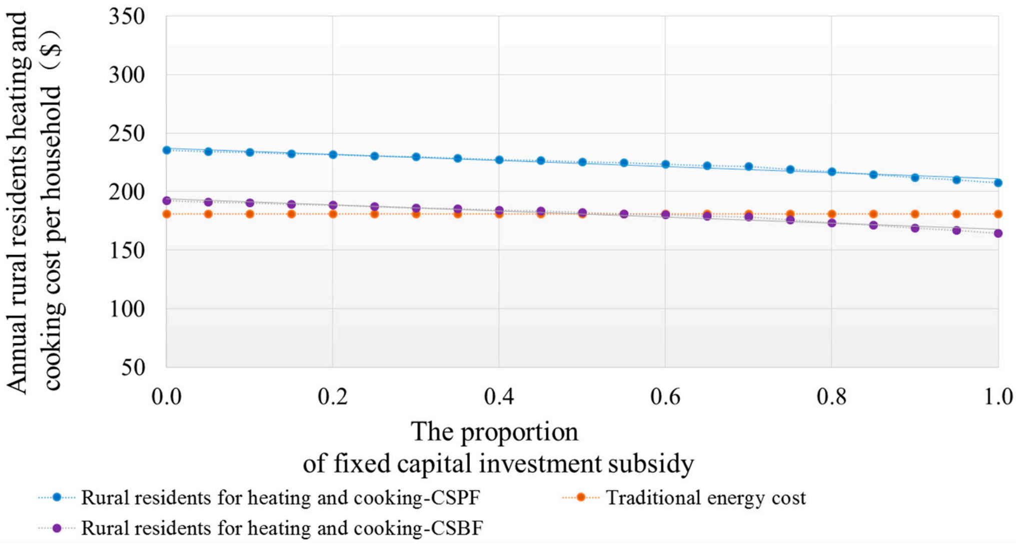

Figure 5. Influence of fixed capital investment subsidy on the economic performance of CSDF for rural residents' heating and cooking.

For CSPF, the urban concentrated heating cost is always higher than the government-guided price. For CSBF, if the subsidy proportion reached 49.0% or higher, the urban concentrated heating cost would be lower than the government-guided price, being competitive in the market. Second, we analyze rural residents' heating and cooking costs. The results show that if the subsidy proportion increased by 10%, the rural residents heating and cooking cost would decrease by $2.6 per household. For CSPF, rural residents' heating and cooking costs are always higher than the cost of traditional energy. For CSBF, if the subsidy proportion reached 62.0% or higher, rural residents' heating and cooking cost would be lower than the cost of traditional energy, being competitive in the market.

4.4.2. Influence of Corn Straw Price

The purchase price of corn straw is set to be zero in both two scenarios. However, when the corn straws are utilized in a large scale as an energy source, the purchase price of corn straw may increase. In addition, to support CSDF-DHS development, the government can also consider corn straw price subsidy to achieve a negative corn straw purchase price, meaning that the collection enterprises can even be paid to obtain corn straw for free, which actually happens in some regions of China because local government tends to reduce field incineration of corn straw to alleviate air pollution by CSDF-DHS.

Under the CPS, we set the purchase price of corn straw to change from −$11.6/t to $11.6/t. The influence of corn straw price on the economic performance of a CSDF-DHS heating service is shown in Figures 6 and 7. The results indicate that if the corn straw price increased by $1.4, the urban concentrated heating cost will rise by $0.12/m^2. The urban concentrated heating cost for CSPF and CSBF can reach government-guided price when the corn straw price subsidies are at least $10.7/t and $3.3/t, respectively, indicating corn straw prices of −$10.7/t and −$3.3/t, respectively. In terms of rural residents' heating and cooking costs, if the corn straw price increased by $1.4, the rural residents heating and cooking cost will rise by $8.4 per household. The rural residents' heating and cooking costs for CSPF and CSBF can be equal to the average cost of traditional energy per household when the corn straw price subsidies are $9.4/t and $1.9/t, respectively, which indicates that the corn straw price are −$9.4/t and −$1.9/t, respectively.

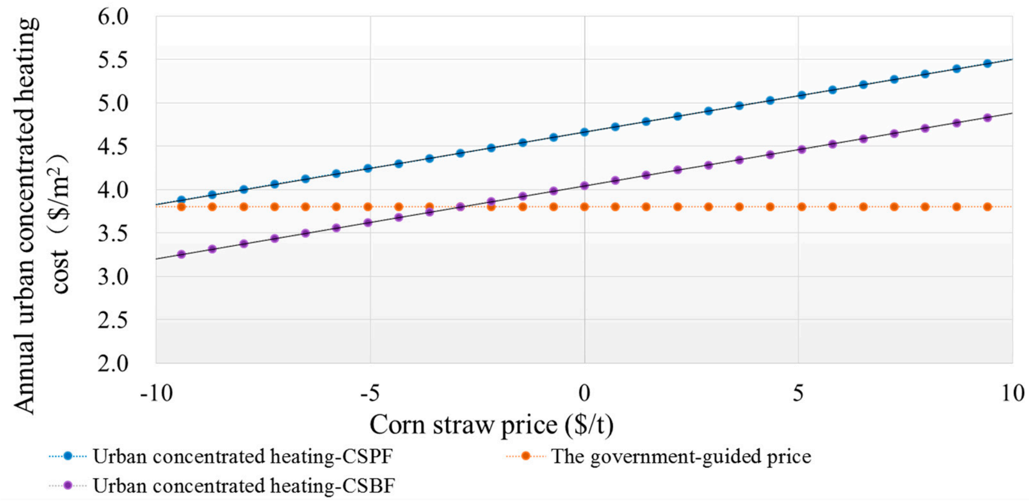

Figure 6. Influence of corn straw price on the economic performance of CSDF for urban concentrated heating.

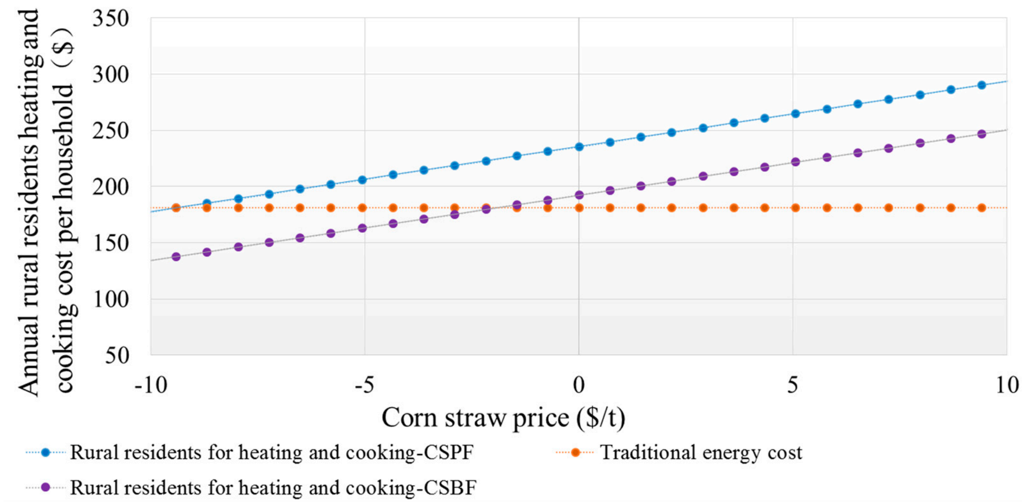

Figure 7. Influence of corn straw price on the economic performance of CSDF for rural residents' heating and cooking.

4.4.3. Influence of Concentrated Heating Fee Subsidy and CSDF Subsidy

Subsidies for urban concentrated heating fees and CSDF subsidies for rural residents can directly reduce final service costs. According to the first law of thermodynamics, an urban concentrated heating fee subsidy can be calculated by the following expression: $a' = \frac{\eta \cdot F_{LHV}}{Q_h^a} \cdot a$, where a' is the CSDF subsidy ($/t), a is the heating fee subsidy ($/m^2), η is the boiler efficiency, F_{LHV} is the low heating value of CSDF (GJ/t) and Q_h^a is the annual heating consumption on space-heating (GJ/m^2·a). The influence of subsidies for urban concentrated heating fees and CSDF subsidies for rural residents on the economic performance of a CSDF-DHS heating service is shown in Figures 8 and 9. The results indicate that for urban concentrated heating cost, when the urban concentrated heating fee subsidy increases by $0.14/m^2, the urban concentrated heating cost decreases by $0.2/m^2 for both CSPF and CSBF. The urban concentrated heating cost reaches the government-guided price when the heating fee subsidies are $0.75/m^2 and $0.23/m^2, respectively. In terms of rural residents' heating and cooking cost, when the rural CSDF subsidy increases by $1.4, the rural residents heating and cooking cost decreases by $5.1 and $4.1 per household for CSPF and CSBF, respectively. Rural residents' heating and cooking costs for CSPF and CSBF can meet average traditional energy costs per household when their subsidy prices are $18.4/t and $3.2/t, respectively.

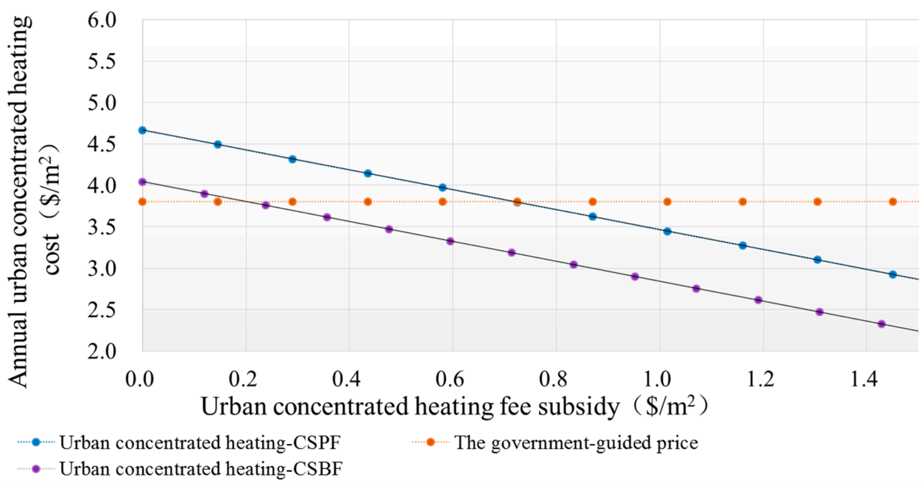

Figure 8. Influence of urban concentrated heating subsidy on economic performance of a CSDF-DHS.

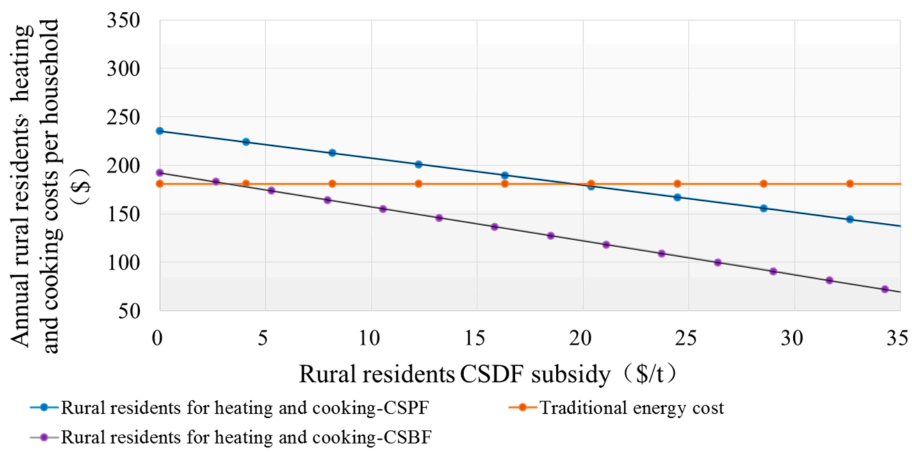

Figure 9. Influence of CSDF subsidy for rural residents' heating and cooking on economic performance of a CSDF-DHS.

4.4.4. Influence of Carbon Trading

Recognized as a renewable energy project, the economic performance of a CSDF-DHS can be improved through carbon trading. Sun [47] studied CDM project development and found that one tonne CSDF can create 1.37 t CO_2,e reduction. Accordingly, we set the carbon trading price from 0 to \$14.5/t CO_2,e. The influence of carbon trading on the economic performance of a CSDF-DHS is illustrated in Figures 10 and 11. The results indicate that, the urban concentrated heating costs of taking CSPF and CSBF reach government-guided prices when carbon trading prices are \$15.3/tCO_2,e and \$4.8/tCO_2,e respectively, and rural residents' heating and cooking costs of taking CSPF and CSBF can meet average traditional energy cost per household when carbon trading prices are \$11.3/tCO_2,e and \$2.3/tCO_2,e respectively.

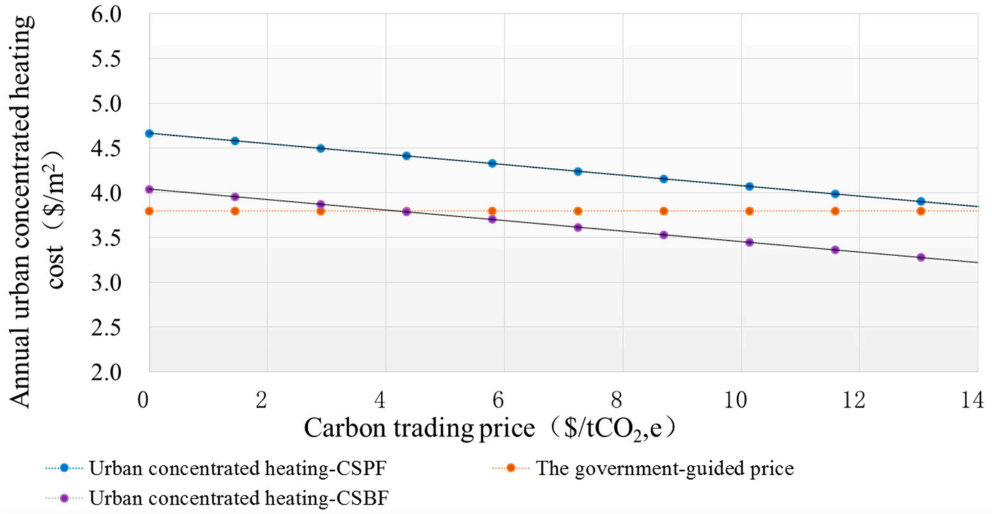

Figure 10. Influence of carbon trading on the economic performance of CSDF for urban concentrated heating.

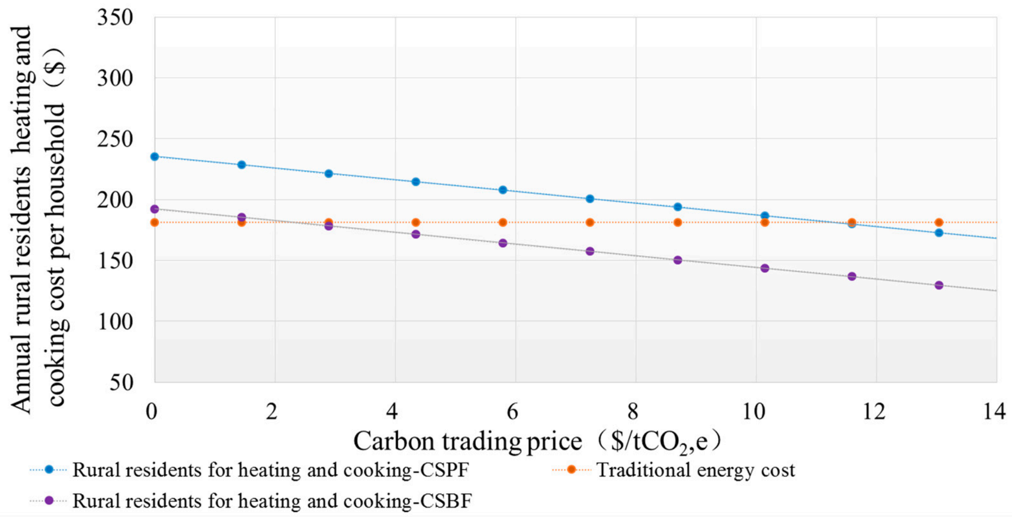

Figure 11. Influence of carbon trading on the economic performance of CSDF for rural residents' heating and cooking.

4.4.5. Influence of Preferential Electricity Price of CSDF Production

China has launched a preferential electricity price policy for the pretreating industry of agricultural products [48]. Some experts argue that CSDF production should be listed in the catalog of the pretreating industry of agricultural products to decrease costs of CSDF production. According to the field survey, the electricity price for agricultural production is 27% lower than that of commerce and industry. The influence of this preferential electricity price for agriculture production on the economic performance of a CSDF-DHS heating service is shown in Table 12.

Table 12. The heating service cost of a CSDF-DHS with preferential electricity price.

Policy Support	CSDF Type	Heating Services Costs	
		Rural Residents, Heating and Cooking Costs ($/household·a)	Urban Concentrated Heating Cost ($/m^2·a)
Preferential electricity price	CSPF	225 (reduced by 10.6)	4.5 (reduced by 0.14)
	CSBF	186 (reduced by 6.1)	4.0 (reduced by 0.09)

The heating service cost of a CSDF-DHS under this policy is reduced compared to that under the CPS, but is still higher than that of traditional energy.

4.4.6. Influence of Enterprise Profit Margins

Under the CPS, enterprise profit margins in the three stages of a CSDF-DHS, which are: (1) corn straw collection and bale transportation; (2) CSDF production; and (3) CSDF utilization, are set to be (1) 30%; (2) 30% for urban heating and 10% for rural residents; and (3) 20%, respectively. Based on current enterprise profit margins, enterprises will adjust the profit margins according to the change of market price in CSDF. We set the enterprise profit margins to be increased by 50% or to be reduced by 50% for sensitivity analysis. In the case of increased margins, the profit increase is: (1) 45%; (2) 45% for urban heating and 15% for rural residents; and (3) 30%. In the case of decreased margins, the profit decrease is: (1) 15%; (2) 15% for urban heating and 5% for rural residents; and (3) 10%. The influence of enterprise profit margins in the supply chain on the economic performance of a CSDF-DHS is shown in Figures 12 and 13.

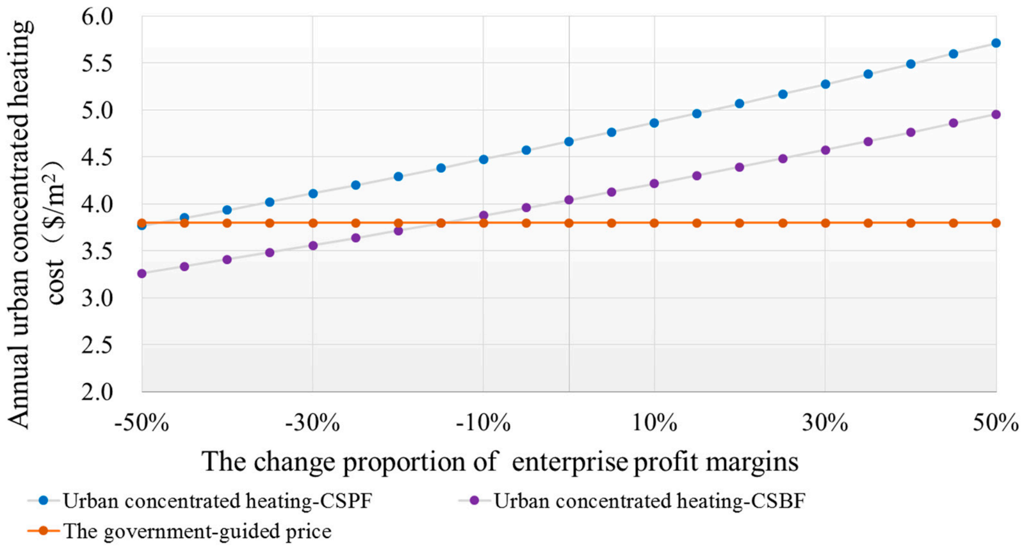

Figure 12. Influence of enterprise profit margin on the economic performance of CSDF for urban concentrated heating.

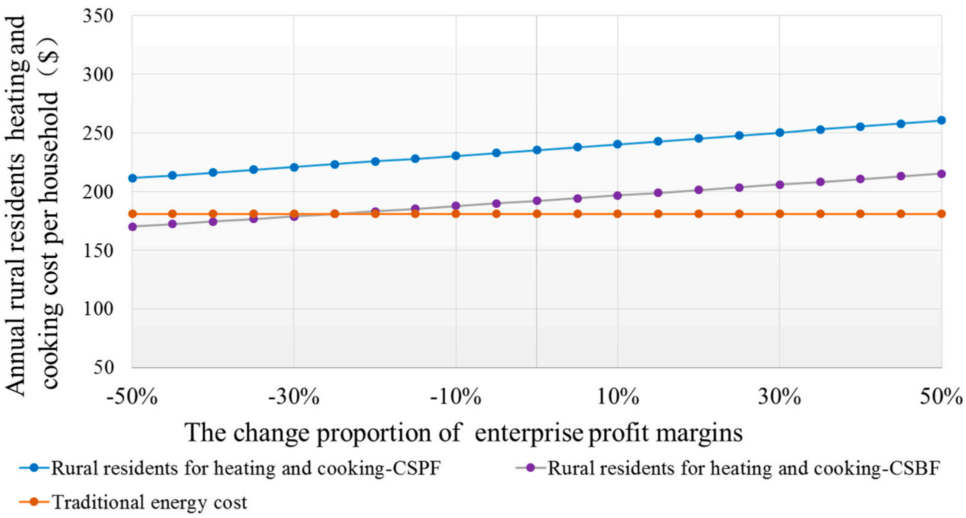

Figure 13. Influence of enterprise profit margin on the economic performance of CSDF for rural residents' heating and cooking.

The results indicate that, in terms of CSPF and CSBF, urban concentrated heating costs reach a government-guided price when enterprise profit margins in the supply chain reduce by 47.8% and 17.8%, respectively. In terms of CSPF and CSBF, rural residents' heating and cooking costs can meet average traditional energy costs when enterprise profit margins in the supply chain reduce by 111.2% and 25.0%, respectively.

4.4.7. Influence of the Boiler Efficiency of Urban Concentrated Heating Station

Improving energy efficiency of CSDF boilers can also reduce heating service cost. How heating station boiler efficiency influences the economic performance of a CSDF-DHS is shown in Figure 14. The results indicate that when CSDF quantity is constant, the urban concentrated heating service area increases with improvement in the energy efficiency of CSDF boilers and the urban concentrated heating cost declines. When the energy efficiency of CSBF boilers is 87.7%, the urban concentrated heating cost can reach the government-guided price. Also, the urban concentrated heating cost for CSPF is always higher than the government-guided price.

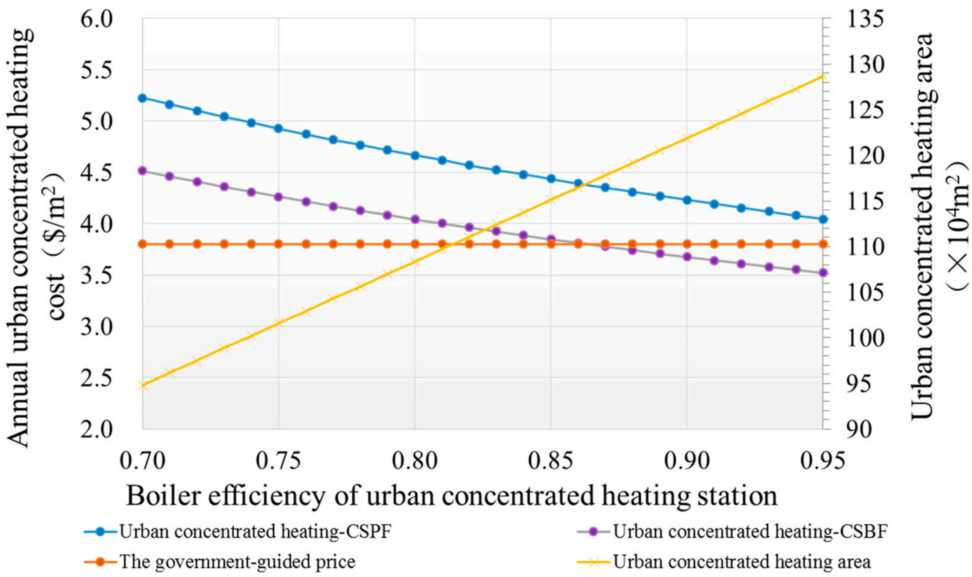

Figure 14. Influence of boiler energy efficiency on the economic performance of a CSDF-DHS.

4.5. Data Uncertainty

Many data used referring to the above in this case study are obtained by a field survey and expert interviews, which are basically constant with the average and rough level of the selected samples but may be different to a certain extent with actual data or statistics accounted by other methods.

5. Conclusions and Policy Implications

This paper established a technical model and economic model of a CSDF-DHS and analyzed its economic performance based on a case study of Nong'an Country in Jilin Province. In addition, this paper analyzes the influence of policy support on its economic performance by scenario analysis. The main conclusions and policy implications are summarized as follows:

- Under the benchmark market scenario oriented by a market without policy support, service prices of CSPF and CSPF as rural residents' heating and cooking fuels are $275/household·a and $229/household·a, which are higher than that of traditional energy of $181/household·a. Service prices of CSPF and CSPF for urban concentrated heating are $5.1/m^2·a and $4.4/m^2·a, which are also higher than that of traditional energy of $3.8/m^2·a.The economic performance measured by the service cost of the CSDF-DHS is poor compared to that of a traditional energy system mainly based on fossil fuels, and producing CSBF is comparatively more economical than producing CSPF. However, a CSDF-DHS has the advantage of extra economic and social benefits created for Nong'an County, including higher taxes ($590,000 for CSPF and $547,000 for CSBF), higher profits ($2,043,000 for CSPF and $1,775,000 for CSBF), and labor income ($736,000 for CSPF and $663,000 for CSBF), compared to a traditional energy system purchasing most of the fossil fuel from other regions. Therefore, it is implicated that current projects of CSDF-DHSs must get policy support, otherwise they will not be competitive in the market, and the policy input can be compensated by its regional economic and environmental benefits to rural areas.
- Under the current policy scenario with current policy support, service prices of CSPF and CSPF as rural residents' heating and cooking fuels are $235/household·a and $192/household·a, which are higher than that of traditional energy. Service prices of CSPF and CSPF for urban concentrated heating are $4.7/m^2·a and $4.0/m^2·a, which are also higher than that of traditional energy. The economic performance of a CSDF-DHS can be improved considerably but is still not competitive compared to tradition energy system. Therefore, it is implicated more policy support must be considered to make a CSDF-DHS competitive in the market.
- Within the range of influencing factor analysis in this paper, a preferential electricity price still cannot make the CSDF-DHS competitive. Providing a subsidy of fixed capital investment, reducing the profit margins of enterprises by economic compensation, and improving the boiler efficiency can make the CSBF-DHS competitive, but the CSPF-DHS remains expensive. The subsidy of concentrated heating price and of CSDF used for rural residents, carbon trading, and negative corn straw prices can make both CSBF-DHS and CSPF-DHS competitive. Therefore, it is implicated the policy support can be staged to gradually open the market, such as first focus on the commercialization of CSBF-DHSs which are easier to be competitive, and then CSPF-DHSs. Meanwhile, the most powerful policy options are suggested as the subsidy of concentrated heating price and of CSDF used for rural residents, carbon trading, and negative corn straw prices.

In next step of this study, to implement a rapid and healthy development of CSDF-DHSs, the social acceptance of CSDF-DHSs by various operators must be further considered, requiring stakeholder analysis and strategic level research.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

BSDF	biomass solid densified fuel
CSDF	corn straw densified fuel
CSPF	corn straw pellet fuel
CSBF	corn straw briquettes fuel
DHS	district heating system
CSDF-DHS	corn straw densified fuel - district heating system
BMS	Benchmark Market Scenario
CPS	Current Policy Scenario
ha	hectare
kgce	kg coal equivalent
tce	tonne coal equivalent
CO_2,e	CO_2 equivalent

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