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Trade-Offs between Economic and Environmental Optimization of the Forest Biomass Generation Supply Chain in Inner Mongolia, China

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Abstract: The utilization of forest residue to produce forest biomass energy can mitigate CO_2 emissions and generate additional revenue for related eco-enterprises and farmers. In China, however, the benefit of this utilization is still in question because of high costs and CO_2 emissions in the entire supply chain. In this paper, a multi-objective linear programming model (MLP) is employed to analyze the trade-offs between the economic and environmental benefits of all nodes within the forest biomass power generation supply chain. The MLP model is tested in the Mao Wu Su biomass Thermoelectric Company. The optimization results show that (1) the total cost and CO_2 emissions are decreased by US\$98.4 thousand and 60.6 thousand kg, respectively; 3750 thousand kg of waste-wood products is reduced and 3750 thousand kg of sandy shrub stubble residue is increased; (2) 64% of chipped sandy shrub residue is transported directly from the forestland to the power plant, 36% of non-chipped sandy shrub residue is transported from the forestland to the power plant via the chipping plant; (3) transportation and chipping play a significant role in the supply chain; and (4) the results of a sensitivity analysis show that the farmer's average transportation distance should be 84.13 km and unit chipping cost should be \$0.01022 thousand for the optimization supply cost and CO_2 emissions. Finally, we suggest the following: (1) develop long-term cooperation with farmers; (2) buy chain-saws for regularly used farmers; (3) build several chipping plants in areas that are rich in sandy shrub.

Keywords: CO_2 emissions; supply cost; sandy shrub stubble residue; wood-chipping residue; waste-wood products; residue-recycling; transportation path

1. Introduction

Strong dependence on fossil fuels such as coal, oil, and gas has caused energy shortage problems and massive greenhouse gas (GHG) emissions, which has exacerbated the conflicts between economic growth and environmental sustainability [1–3]. In China, the government has officially made the commitment that the carbon intensity per unit of gross domestic product (GDP) should be reduced by 40–45% by 2020 in relation to 2005 levels [4]; the government has also moved toward sustainability by minimizing the usage of non-renewable energy [5]. Therefore, it is necessary to search for alternative sources of renewable energy [1], including bioenergy and residue-resources to cope with energy shortage and CO_2 emissions. China's biomass resources show great potential, producing the equivalent of 46 million tons of standard coal for energy use [6]. Specifically, forest biomass energy is a priority for energy development and target planning due to its high fuel value and low carbon

output [7]. As such, forests are the most important source of biomass energy from the perspective of resource potential [8,9].

Forest biomass energy can be classified as traditional forest wood-fuel and modern forest biomass energy [10,11]. Traditional forest wood-fuel has been used for many years in rural areas, while modern forest biomass energy is generated by transforming forest wood resources into energy products including pellet fuel, biodiesel, bio-ethanol, forest biomass power generation and gas fuel. Forest biomass power generation in particular has gained attention in many developed countries and in the energy industry. There are now more than 300 power plants fueled by agricultural and forest biomass in European countries including Denmark, Finland, Sweden, and The Netherlands [12]. Developing countries and regions such as India, Brazil and Southeast Asia have also actively introduced technology to build biomass power generation projects. In China, the forest biomass power generation industry is growing rapidly, with about 254 projects involving agricultural and forest biomass power generation providing an annual electricity capacity of 29.85 billion kWh in 2016 [13]. The recent growth in this industry includes the establishment of Mao Wu Su biomass thermoelectric company in Inner Mongolia which is China's first sandy shrub biomass power plant and serves as the world's first demonstration project that uses sandy shrub stubble residue for direct combustion in semi-arid areas. This success story was featured by United Nations news in 2012 [14].

In Inner Mongolia, growth of the national sandy shrub can not only act as protection against wind and sand, but can also be directly burned as raw material for biomass power generation. In addition, the regular stubble tending of sandy shrub provides an important foundation for the enterprise. However, since sandy shrub is a low-density fuel resource that is scattered around a large geographic region [15], it is expensive to collect, chip, and transport. Moreover, the availability varies monthly and is dependent on traditional harvesting operations [16]. In order to prevent stock shortages, the company needs to store the raw material in advance, which leads to high storage costs. In general, low density, broad dispersion, uneven seasonal supply, and long chipping distances significantly increase the transportation and shortage costs of sandy shrub residue. On the other hand, compared to fossil fuels, sandy shrub residue is more environmentally friendly although the node of planting, harvesting, skidding, storage, transportation and chipping will involve non-renewable energy inputs and inevitably contribute to emissions [17]. In order to make profits and control CO_2 emissions in the long-term, there is a need to develop a model for the Mao Wu Su biomass Thermoelectric Company to optimize their raw material supply chain and optimize its economic and ecological benefits.
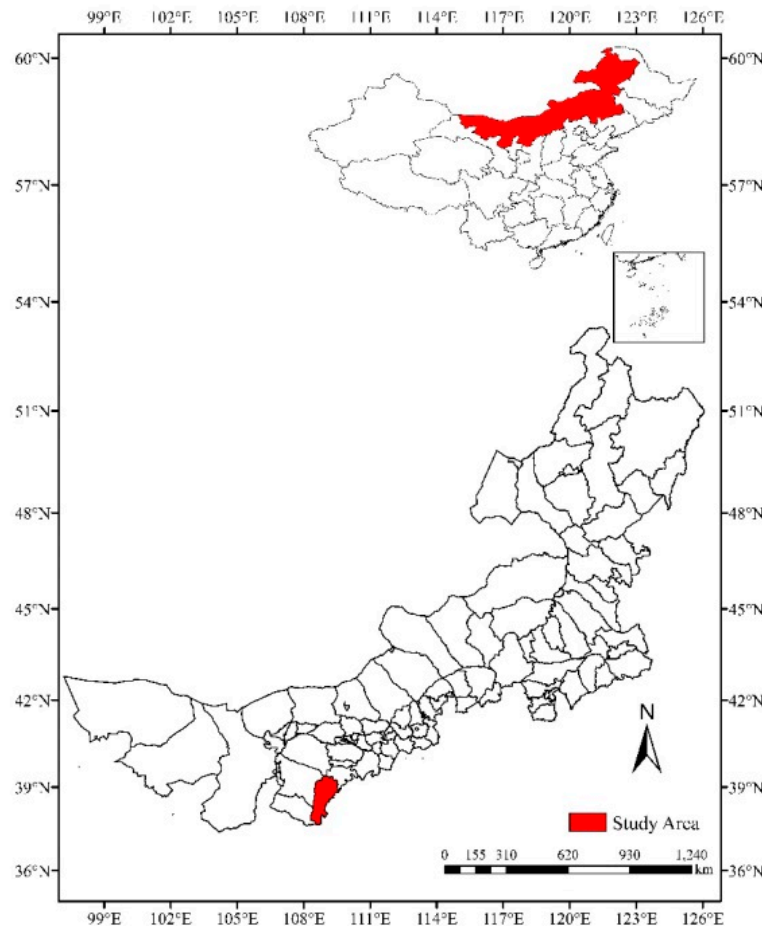
Previous research has focused on impact assessment of developing a forest-biomass power generation industry [18,19], energy price forecasting [20,21] and industrial development policy [22–24] by local equilibrium models and system dynamics (SD) to study forest biomass energy supply and demand at the global or national scale. On the other hand, some scholars have used qualitative methods to study the pricing mechanism of renewable energy [25], industry policy [26] and existing problems [27,28] in the country or from a small-scale point of view. With regard to the supply of raw materials for the industry, research is focused on the optimization of cost and CO_2 emissions [29,30] concerning the harvesting [31], transportation [32] and storing nodes [33] and the whole optimization of the forest biomass supply chain [34–36]. Particularly, there is also some research on the optimization of the wood biomass energy industry [37–40]. However, little research has included an in-depth study on forest biomass residue for residue-recycling, which has high bioenergy potential.

In this paper, a multi-objective linear programming model (MLP) is developed to analyze the trade-offs between the economic and environmental benefits of all nodes within the forest biomass power generation supply chain, including residues, and it is tested on the Mao Wu Su biomass Thermoelectric Company.
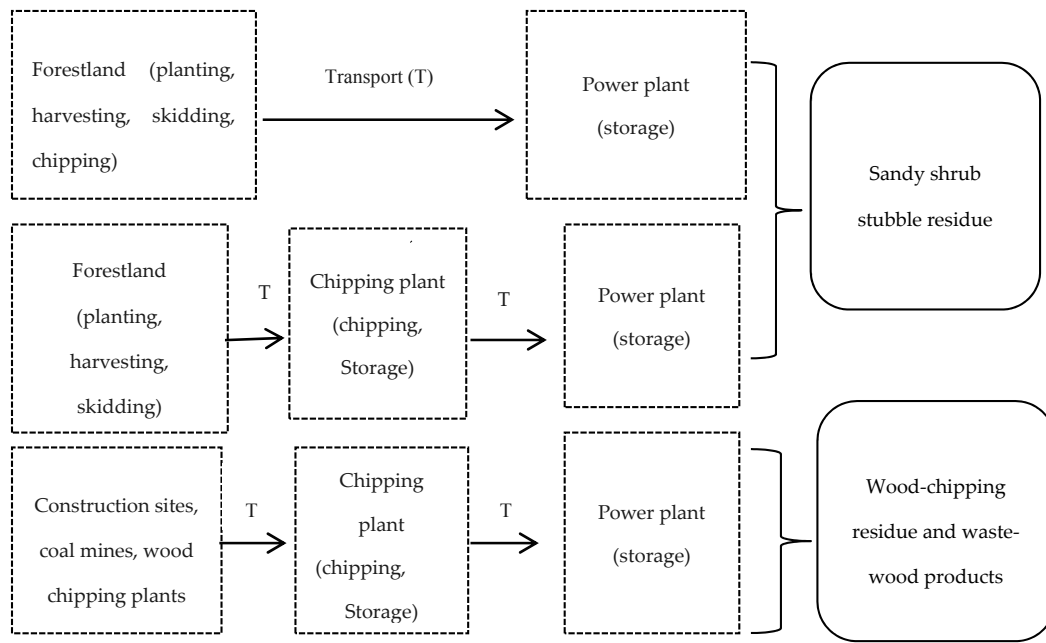
2. Materials and Methods

The Mao Wu Su biomass Thermoelectric Company is located in the Wu Shen banner of Ordos, Inner Mongolia Autonomous Region in China (Figure 1), which is rich with sandy shrub but suffers

from harsh ecological conditions. It was registered in 2006 and formally entered into business in 2009. It has perfectly combined forest biomass energy exploitation and desertification prevention. This provided a meaningful basis for an in-depth study on the supply chain in the forest biomass power generation industry.

Figure 1. Study area. Wu Shen banner of Ordos, Inner Mongolia Autonomous Region in northern China.

Supply chain theory, the MLP method, and a sensitivity analysis are employed to conduct empirical research. The supply chain is seen as a network that consists of logistics, information and capital flow in order to effectively deliver the product to the consumer with the lowest cost. There are various MLP models currently used in practical work. The first method is to transform several goals into a relatively single target, such as the linear weighting method. The second method is the hierarchical sequence method. The third method is the analytic hierarchy process (AHP), which is suitable for the multi-objective analysis without necessary data and serves as a kind of qualitative and quantitative combination. A sensitivity analysis is used to explore the relationship between relevant factors and key indicators [41]. In this paper, the supply chain of the forest biomass industry concerns planting, harvesting, skidding, storage, chipping and transportation and optimizes the entire supply chain process with the goal of minimizing the total cost. The three key raw materials in this paper are sandy shrub stubble residue, wood-chipping residue and waste-wood products; the transportation path of three key raw materials is shown in Figure 2. The first MLP method is applied to optimize the trade-offs between the economic and environmental benefits by the Solver, including λ_c λ_e which are the weight of cost and CO_2 function, respectively. The sensitivity analysis is employed to explore the impact of the key parameters in transportation and chipping on the optimal supply chain solution.

Figure 2. The transportation path of three kinds of raw materials in the biomass supply chain for the Mao Wu Su biomass Thermoelectric Company. Note: the transportation path is from the case study questionnaire.

2.1. Model

2.1.1. Objective Function

A multi-objective linear programming model was developed in Equation (1) with supply cost function (Equation (2)) and the CO_2 emissions function (Equation (3)). The assumptions are described due to research limitations: the raw materials demand of the power plant is definite and the labor salary keeps steady; the cost and CO_2 emissions of wood-chipping residue and waste-wood products for residue-recycling in planting, harvesting and skidding are zero.

$$\min(\varphi) = \lambda_c \times f_c + \lambda_e \times f_e \tag{1}$$

$$\min(f_c) = C^{plant} + C^{harv} + C^{skid} + C^{stor} + C^{chip} + C^{trans} \tag{2}$$

$$\min(f_e) = E^{plant} + E^{harv} + E^{skid} + E^{trans} + E^{stor} + E^{chip} \tag{3}$$

Note that in Equation (1), λ_c and λ_e represent the weight of supply cost and CO_2 emissions respectively; f_c and f_e represent the function value of supply cost and CO_2 emissions respectively. In Equations (2) and (3), C^{plant}, C^{harv}, C^{skid}, C^{stor}, C^{chip} and C^{trans} indicate the supply cost in planting, harvesting, skidding, storage, chipping and transportation, in \$; E^{plant}, E^{harv}, E^{skid}, E^{trans}, E^{stor} and E^{chip} refer to the amount of CO_2 emissions at each node of the supply chain, in kg.

2.1.2. Cost Functions

The parameters which are the set themselves in the overall model are shown in Appendix A. The cost functions for each stage of the supply chain are as follows:

$$C^{plant} = \sum_{i \in M_i} A_i \times cp_i \tag{4}$$

$$cp_i = cp_{i1} + cp_{i2} + cp_{i3} + cp_{i4} \tag{5}$$

$$cp_{i2} = \sum_{i \in M_i} lp_i \times Pp_i \tag{6}$$

where M_i refers to the set of three key raw materials i; A_i represents the total planting area of materials, in ha; cp_i is the unit planting cost which encompasses land costs (cp_{i1}), labor costs (cp_{i2}), equipment costs (cp_{i3}) and other material costs (cp_{i4}), in \$·ha^{-1}; lp_i is the amount of labor, in worker·h·ha^{-1}; and Pp_i is the unit labor salary, in \$·worker^{-1}·h^{-1}.

$$C^{harv} = \sum_{i \in M_i} B_i \times ch_i \tag{7}$$

$$ch_i = ch_{i1} + ch_{i2} + ch_{i3} \tag{8}$$

$$ch_{i1} = \sum_{i \in M_i} lh_i \times Ph_i \tag{9}$$

where B_i represents the harvesting amount of raw materials, in kg; ch_i is the unit harvesting cost which contains labor costs (ch_{i1}), equipment costs (ch_{i2}) and other material costs (ch_{i3}), in \$·kg^{-1}; lh_i is the amount of labor, in worker·h·ha^{-1}; and Ph_i is the unit labor salary, in \$·worker^{-1}·h^{-1}.

$$C^{skid} = \sum_{i \in M_i} \sum_{d \in D_d} csk_{id} \times D_{id} \tag{10}$$

$$csk_{id} = csk_{id1} + csk_{id2} + csk_{id3} \tag{11}$$

$$csk_{id1} = \sum_{i \in M_i} \sum_{d \in D_d} lsk_{id} \times Psk_{id} \tag{12}$$

where D_d represents the set of skidding points d; D_{id} represents the amount of skidding, in kg; csk_{id} is the unit skidding cost which consists of labor costs (csk_{id1}), equipment investment costs (csk_{id2}) and other material costs (csk_{id3}), in \$·kg^{-1}; lsk_{id} is the amount of labor, in worker·h·kg^{-1}; and Psk_{id} is the unit labor salary, in \$·worker^{-1}·h^{-1}.

$$C^{stor} = C^{sfix} + C^{svar} \tag{13}$$

$$C^{sfix} = \sum_{i \in M_i} \sum_{s \in D_s} cstf_{is} \tag{14}$$

$$C^{svar} = \sum_{i \in M_i} \sum_{s \in D_s} cstv_{is} \times N_{is} \tag{15}$$

$$cstv_{is} = cstv_{is1} + cstv_{is2} \tag{16}$$

$$cstv_{is1} = \sum_{i \in M_i} \sum_{s \in D_s} lstv_{is} \times Pstv_{is} \tag{17}$$

where D_s represents the set of storage points s; C^{sfix} is the fixed storage cost which includes land costs ($cstf_{is1}$) and construction costs ($cstf_{is2}$), in \$; C^{svar} is the variable storage cost; N_{is} is the storage amount of raw materials, in kg; $cstv_{is}$ is the unit variable storage costs which are related to labor costs ($cstv_{is1}$) and other material costs ($cstv_{is2}$), in \$·kg^{-1}; $lstv_{is}$ is the amount of labor, in worker·h·kg^{-1}; $Pstv_{is}$ represents the unit labor salary, in \$·worker^{-1}·h^{-1}.

$$C^{chip} = \sum_{i \in M_i} \sum_{c \in D_c} cc_{ic} \times N_{ic} \tag{18}$$

$$cc_{ic} = cc_{ic1} + cc_{ic2} + cc_{ic3} \tag{19}$$

$$cc_{ic1} = \sum_{i \in M_i} \sum_{c \in D_c} lc_{ic} \times Pc_{ic} \tag{20}$$

where D_c is the set of chipping points c; N_{ic} is the amount of raw materials chipped in the chipping plant, in kg; cc_{ic} is the unit chipping costs which include labor costs (cc_{ic1}), equipment investment (cc_{ic2}) and other material costs (cc_{ic3}), in \$·kg^{-1}. lc_{ic} represents the amount of labor, in worker·h·kg^{-1}; Pc_{ic} represents the unit labor salary, in \$·worket^{-1}·h^{-1}.

$$C^{trans} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} ct_{ijky1} \times x_{ijky} \times d_j + \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} ct_{ijky2} \times x_{ijky} \tag{21}$$

$$ct_{ijky1} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} \left(lt_{ijky11} \times Pt_{ijky11} + ct_{ijky12} \right) \tag{22}$$

$$ct_{ijky2} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} lt_{ijky21} \times Pt_{ijky21} \tag{23}$$

where T_j represents the set of transportation paths j; K_k represents the form of the raw material k; Y_y is the transportation equipment y; d_j is the transportation distance of path j, in km; x_{ijky} is the quantity of raw materials, in kg; the first section of Equation (21) is the transportation costs and the second section of Equation (21) is the loading and unloading costs, in \$; ct_{ijky1} is the unit transportation costs, in \$·kg^{-1}·km^{-1}; lt_{ijky11} is the amount of labor involved in transportation, in worker·h·kg^{-1}; Pt_{ijky11} is the labor salary in transportation, in \$·worker^{-1}·h^{-1}; ct_{ijky12} is the other material costs, in \$·kg^{-1}·km^{-1}; ct_{ijky2} is the unit loading and unloading costs, in \$·kg^{-1}; lt_{ijky21} refers to the amount of labor involved in in loading and unloading, in worker·h·kg^{-1}; Pt_{ijky21} is the labor salary in loading and unloading, in \$·worker^{-1}·h^{-1}.

2.1.3. Carbon Dioxide Emissions Functions

$$E^{plant} = \sum_{i \in M_i} (ep_{i1} + ep_{i2} + ep_{i3}) \tag{24}$$

$$ep_{i1} = \sum_{i \in M_i} ep\_l_i \times A_i \tag{25}$$

$$ep_{i2} = \sum_{i \in M_i} \sum_{u \in U_u} ep_{iu} \times Tp_{iu} \tag{26}$$

$$ep_{iu} = \varepsilon_u \times \sum_{i \in M_i} \sum_{u \in U_u} Np_{iu} \tag{27}$$

$$ep_{i3} = \sum_{i \in M_i} el_i \times lp_i \times A_i \tag{28}$$

where U_u represents the set of planting equipment u; ep_{i1}, ep_{i2} and ep_{i3} represent the CO_2 emissions from seedlings, machinery and labor, respectively, in kg; ep_l_i is the CO_2 emissions factor per unit area of land, in kg·ha^{-1}; Tp_{iu} represents the usage hour of equipment, in h; ep_{iu} is the CO_2 emissions factor of equipment, in kg·h^{-1}; ε_u is the CO_2 emissions coefficient of equipment, in kg·L^{-1}; Np_{iu} is the energy consumption per hour, L·h^{-1}; el_i is the CO_2 emissions factor of labor, in kg·worker^{-1}·h^{-1}.

$$E^{harv} = \sum_{i \in M_i} (eh_{i1} + eh_{i2}) \tag{29}$$

$$eh_{i1} = \sum_{i \in M_i} el_i \times lh_i \times B_i \tag{30}$$

$$ep_{i2} = \sum_{i \in M_i} \sum_{v \in V_v} eh_{iv} \times Th_{iv} \tag{31}$$

$$eh_{iv} = \varepsilon_v \times \sum_{i \in M_i} \sum_{v \in V_v} Nh_{iv} \tag{32}$$

where V_v represents the set of harvesting equipment v; eh_{i1} and eh_{i2} represent the CO_2 emissions from labor and equipment, in kg; eh_{iv} is the CO_2 emissions factor of the equipment, in kg·h^{-1}; Th_{iv} represents the equipment operating time, in h; ε_v is the CO_2 emissions coefficient, in kg·L^{-1}; Nh_{iv} is the energy consumption per hour, in L·h^{-1};

$$E^{skid} = \sum_{i \in M_i} (esk_{i1} + esk_{i2}) \tag{33}$$

$$esk_{i1} = \sum_{i \in M_i} \sum_{d \in D_d} el_i \times lsk_{id} \times D_{id} \tag{34}$$

$$esk_{i2} = \sum_{i \in M_i} \sum_{w \in W_w} esk_{iw} \times Tsk_{iw} \tag{35}$$

$$esk_{iw} = \varepsilon_w \times \sum_{i \in M_i} \sum_{w \in W_w} Nsk_{iw} \tag{36}$$

where W_w is the set of skidding equipment w; esk_{i1} and esk_{i2} are the CO_2 emissions from labor and equipment, respectively, in kg; esk_{iw} is the CO_2 emissions factor of the equipment, in kg·h^{-1}; Tsk_{iw} is the equipment operating time, in h; ε_w is the the CO_2 emissions coefficient of the equipment, in kg·L^{-1}; Nsk_{iw} is the energy consumption per hour, in L·h^{-1}.

$$E^{stor} = \sum_{i \in M_i} \sum_{s \in D_s} (estf_{is} + estv_{is}) \tag{37}$$

$$estf_{is} = \sum_{i \in M_i} \sum_{s \in D_s} (estf_{is1} \times Sstf_{is} + estf_{is2}) \tag{38}$$

$$estv_{is} = \sum_{i \in M_i} \sum_{x \in D_s} (estv_{is1} \times Tstv_{is} + lstv_{is} \times N_{is} \times el_i) \tag{39}$$

$$estv_{is1} = \varepsilon_s \times \sum_{i \in M_i} \sum_{s \in D_s} Nstv_{is} \tag{40}$$

where $estf_{is}$ is fixed CO_2 emissions, in kg; $estv_{is}$ is variable CO_2 emissions, in kg; $estf_{is1}$ is the land emissions factor, in kg·ha^{-1}; $Sstf_{is}$ is the land area, in ha; $estf_{is2}$ is the amount of CO_2 emissions in construction, in kg; $estv_{is1}$ is the CO_2 emissions factor of the site, in kg·h^{-1}; $Tstv_{is}$ is the operating hour of sites, in h; ε_s is the CO_2 emissions coefficient of the site, in kg·L^{-1}; $Nstv_{is}$ is the energy consumption per hour, in L·h^{-1}.

$$E^{chip} = \sum_{i \in M_i} \sum_{c \in D_c} (ec_{ic1} + ec_{ic2}) \tag{41}$$

$$ec_{ic1} = \sum_{i \in M_i} \sum_{c \in D_c} \sum_{x \in X_x} ec_{icx} \times Tc_{ic} \tag{42}$$

$$ec_{icx} = \varepsilon_x \times \sum_{i \in M_i} \sum_{c \in D_c} \sum_{x \in X_x} Nc_{icx} \tag{43}$$

$$ec_{ic2} = \sum_{i \in M_i} \sum_{c \in D_c} lc_{ic} \times N_{ic} \times el_i \tag{44}$$

where ec_{ic1} and ec_{ic2} are the CO_2 emissions of the equipment and the labor, respectively, in kg; ec_{icx} is the CO_2 emissions factor of the equipment, in kg·h^{-1}; Tc_{ic} is the equipment operating time, in h; ε_x is the CO_2 emissions coefficient, in kg·L^{-1}; Nc_{icx} is energy consumption per hour, in L·h^{-1}.

$$E^{trans} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} (et_{ijky1} + et_{ijky2}) \tag{45}$$

$$et_{ijky1} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} et_y \times x_{ijky} \times d_j \tag{46}$$

$$et_y = \varepsilon_y \times \sum_{y \in Y_y} Nt_y \tag{47}$$

$$et_{ijky2} = \sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} \sum_{y \in Y_y} el_i \times \left(lt_{ijky11} + lt_{ijky21} \right) \tag{48}$$

where et_{ijky1} and et_{ijky2} are the CO_2 emissions of vehicles and labor, respectively, in kg; et_y is the CO_2 emissions factor of equipment y, in kg·kg^{-1}·km^{-1}; ε_y is the CO_2 emissions coefficient, in kg·L^{-1}; Nt_y is energy consumption per hour, in L·kg^{-1}·km^{-1}.

2.1.4. Constraints

The biomass power generation industry is a resource-constrained industry and there is a need for a certain amount of biomass resources to maintain the normal operation of the enterprise. Therefore, the supply chain optimization is constrained by the amount of resources. It restricts the total amount of raw materials that can be procured from the region in Equation (49); the total amount of skidding biomass is equal to the amount of harvesting biomass in Equation (50); the total amount of skidding biomass is equal to the amount of harvesting biomass in Equation (51); the amount of raw materials in chipping should not be more than the amount in storage which should not be greater than the total amount of raw materials in harvesting in Equation (52).

$$\sum_{i \in M_i} B_i \leq Z_0 \tag{49}$$

$$\sum_{i \in M_i} \sum_{d \in D_d} D_{id} = \sum_{i \in M_i} B_i \tag{50}$$

$$\sum_{i \in M_i} A_i \geq \sum_{i \in M_i} \frac{B_i}{BI_i} \tag{51}$$

$$\sum_{i \in M_i} B_i \geq \sum_{i \in M_i} \sum_{s \in D_s} N_{is} \underset{i}{} \geq \sum_{i \in M_i} \sum_{c \in D_c} N_{ic} \tag{52}$$

where Z_0 is the total resources in this region, in kg; BI_i is the collection of raw material i in unit area, in kg·ha^{-1}.

Forest biomass resources are uneven in seasonal supply. The optimization is subject to the supply and demand. Equation (53) ensures that the total amount of raw materials must satisfy the requirement of the total demand; the total supply cost of raw material is limited to the purchase price paid by the power plant in Equation (54):

$$\sum_{i \in M_i} \sum_{j \in T_j} \sum_{k \in K_k} x_{ijk} \geq D_0 \tag{53}$$

$$f_c \leq P_0 \tag{54}$$

where D_0 is the raw material demand, in kg.

The optimization of the supply chain is limited by the radius of raw material collection. The longest transport path must be in the radius of the plant's raw material collection in Equation (55)

$$\max_{j \in T_j} d_j \leq R_0 \tag{55}$$

where R_0 is the collecting radius, in km.

2.2. Data Source

Data was gathered from two channels: statistical data collection and field investigation. The former was obtained from China Statistical Yearbook 2016 [42], China Energy Statistical Yearbook 2014 [43] and the Inner Mongolia Autonomous Region Forestry Department website [44]. The latter is

first-hand data derived from interviews and questionnaires conducted among forest biomass power generation enterprises, middlemen, and farmers in the Inner Mongolia Autonomous Region. For the company, the average purchase price of sandy shrub stubble residue, wood-chipping residue and waste-wood products in 2015 was $58.64, $54.13 and $57.14 per thousand kg, respectively. The detailed parameters in each node of this company are presented as follows.

In planting, the CO_2 emissions of the same kind of raw material are similar and there is no use of machinery equipment, only manual labor. The average need for planting per ha of Salix is 2.098 workers and the ratio between the households and the workers is 1:0.788. The average daily wage is $2.23 per worker per hour. The cost of other materials (mainly pesticides) is $7.54 per ha.

In harvesting, the equipment conditions and personnel operation level have no impact on CO_2 emissions; there is no limit on the number of harvesting tools with the same power, fuel type and efficiency. The average unit labor input in harvesting is 1.347 workers per hour per thousand kg and the average harvest per ha is 7845 kg. There are two types of machinery used in harvesting. Small hand-held harvesters ($v = 1$) incur a purchase cost of $178.61, a life span of 3 years and average yearly maintenance costs of $29.76, and the fuel is gasoline with a consumption of 2.5×10^{-3} L per kg of raw materials. A medium-sized harvester ($v = 2$) has a purchase cost of $416.77, a service life of 5 years, average yearly maintenance costs of $178.61 and the fuel is diesel, with consumption of 3.5×10^{-3} L on average per kg of raw materials. Characteristics of different energy sources are provided in Table 1.

Table 1. Reference factors of different energy sources [38].

Energy	Unit Price ($\cdot$L^{-1})	Density (kg$\cdot$L^{-1})	Average Low Calorific Value (kJ$\cdot$kg^{-1})	Carbon Emissions Coefficient (kg$\cdot$L^{-1})
Gasoline	6.41	0.728	43,070	2.925
Diesel	5.94	0.84	42,652	3.095

In skidding, storage and chipping, the point can be set numbers and have the greatest capacity limit; there is no limit on the number of skidding tools with the same power, fuel type and efficiency. The input in skidding is closely related to harvesting, chipping and transportation, so the parameters used in the model are merged into these nodes.

The daily storage in the company is up to 4500 thousand kg with 6.66 ha of open space. Assuming that the power plant operates for 24 h, it is estimated that the storage needs two workers per day with an average of $5.36 thousand per worker every year. There are no additional costs in the plant. The CO_2 emissions merely originate from the workers' activity.

The chipping site of raw material for the company consists of two types: forestland chipping ($x = 1$) and chipping plant ($x = 2$). The chipping equipment parameters are involved in the forestland and chipping plant shown in Table 2. There is an assumption that the only difference between each chipping plant is distance to the power plant.

In transportation, there is no limit on the number of transportation vehicles; and the speed, fuel and maximum load of each type of vehicle are similar; all kinds of transportation run at a constant speed and the road conditions and weather have no effect on CO_2 emissions; all raw materials are under the same transportation conditions and a vehicle can be filled with all materials at the same time. The sandy shrub stubble residue can be acquired in two transportation ways: directly from the forestland to the power plant ($j = 1$) and from the forestland to the power plant via the chipping plant (middleman) ($j = 2$), while wood-chipping residue and waste-wood products are mainly from the chipping plant (middleman) to the power plant ($j = 3$).

Table 2. The parameters of chipping equipment involved in the forestland and chipping plant.

Equipment Parameters	Forestland	Chipping Plant	Unit
Purchase cost	2.75	29.77 [a]	thousand $
Service life	8	5	year
Annual maintenance costs	0.37	0.74	thousand $
Power	53×10^3	120×10^3	w
Energy consumption per h	1.47	2.41	L
Carbon emissions factor	3.82	7.91	$kg \cdot h^{-1}$
Labor input per day	1.50	15	worker
Labor price per day	0.02	0.01	thousand $
Amount of raw materials processed per h	0.63	25	thousand kg

Note: [a] Equipment includes transformers, conveyor belts and chippers; the data is from the case study questionnaire.

The radius of the company is 200 km, covering six towns including Wu Shen Zhao town, Ga Lu To town, Wu Ding He town, Tooke town, Ulan Tau Err town, and Su Zhen Lied. Transportation includes two types of vehicles: agricultural tricycles ($y = 1$) and trucks ($y = 2$). Agricultural tricycles are used for transporting sandy shrub stubble residue from the forestland to the chipping plant and trucks are often used to directly transport residue to power plants; waste-wood and wood-chipping residue is usually transported to the power plant by truck. The transport parameters of the vehicles are shown in Table 3.

Table 3. Parameters in transportation.

Parameters	Value
Maximum unit load of agricultural tricycle	1.5×10^3 kg
Agricultural tricycle fuel consumption 100 km	8 L
Carbon emissions factor of agricultural tricycle	$0.171 \ kg \cdot km^{-1}$
Maximum unit load of truck	10×10^3 kg
Trucks fuel consumption of 100 km	38.5 L
Carbon emissions factor of truck	$0.481 \ kg \cdot km^{-1}$

Note: the data is from the case study questionnaire.

3. Results

The supply cost and the amount of CO_2 emissions in each node were optimized simultaneously by Solver for trade-offs between the economic and environmental benefits in the supply chain of forest biomass generation.

As shown in Table 4, the optimal results are as follows: the total amount of sandy shrub stubble residue, wood-chipping residue and waste-wood products is 93,750 thousand kg, 40,000 thousand kg and 46,250 thousand kg. Compared to the current supply, the power plant can achieve maximum economic and environmental benefits when 3750 thousand kg of waste-wood products is reduced, 3750 thousand kg of sandy shrub stubble residue is increased and the wood-chipping residue maintains the same supply as the current situation. Meanwhile, 64% of chipped sandy stubble residue should be directly transported to the power plant from the forestland, and 36% of non-chipped sandy stubble residue should be transported from the forestland to the power plant via the chipping plant.

The differences between the total supply cost of each node and three key raw materials in the current situation and the optimization are shown in Table 5. The total cost of the supply chain is $7451 thousand after optimization which is decreased by $98.4 thousand compared to the current condition. For each node, the total cost is reduced by different amounts; particularly, the total cost in the transportation node and chipping node is largely decreased with a reduction of $36.2 thousand and $35.4 thousand, respectively. For the three key raw materials, the total supply cost and the unit supply cost per thousand kg of the sandy shrub stubble residue (chipped in forestland) are optimized simultaneously; the total supply cost and the unit supply cost per thousand kg of sandy shrub stubble

residue (chipped in the chipping plant) increase by exactly $195.8 thousand and $0.0009 thousand; the unit supply cost per thousand kg of the sandy shrub stubble residue (chipped in the chipping plant) is $0.049 thousand which is larger than that of sandy shrub stubble residue (chipped in the forestland) after optimization; the total supply cost and the unit cost of wood-chipping residue keep steady; the total supply cost of waste-wood products is optimized but the unit supply cost per thousand kg increased by $0.0002 thousand.

Table 4. The differences between the supply amount of three key raw materials in two situations (current supply amount and optimization supply amount) (Unit: thousand kg).

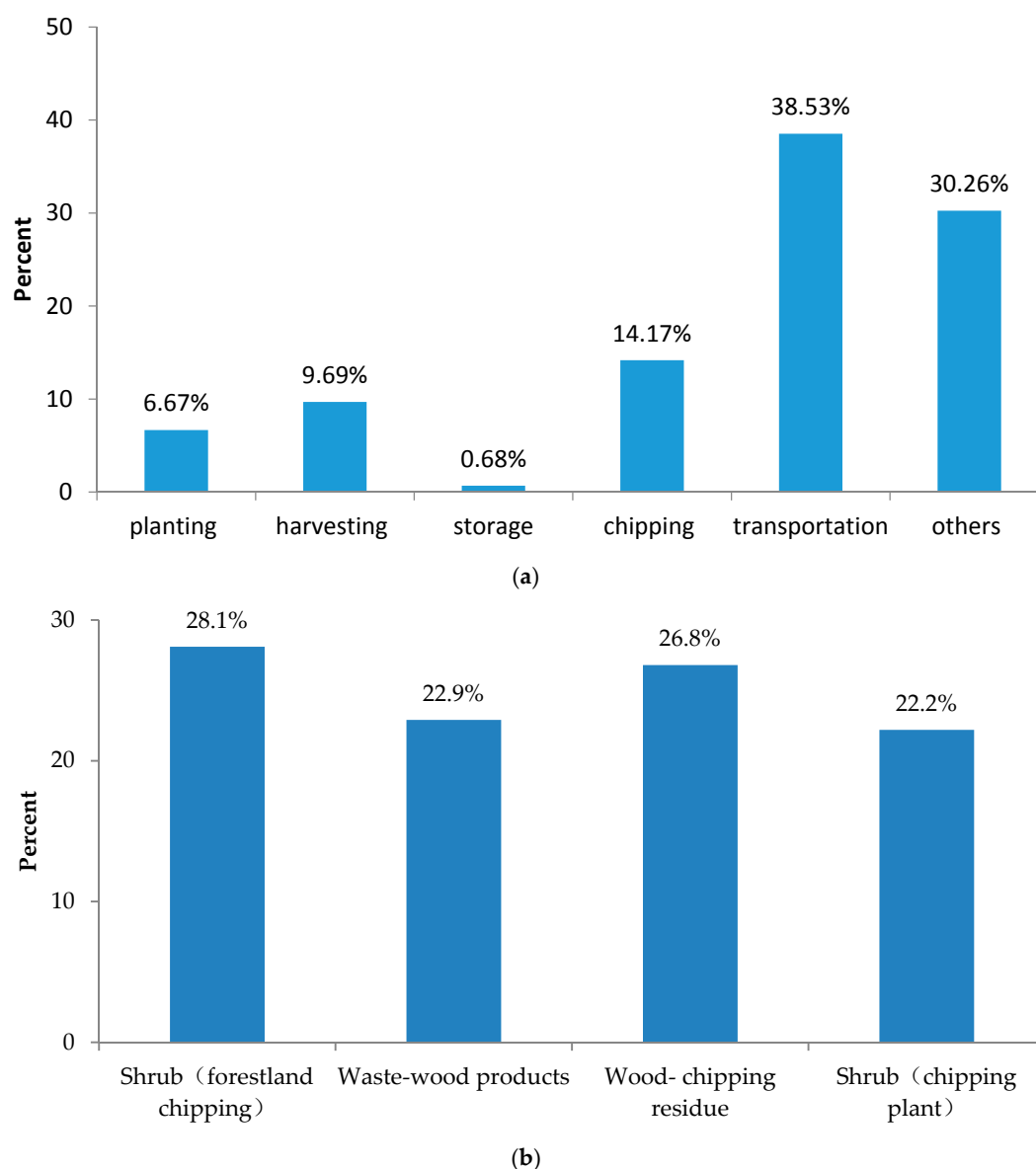| Three Key Raw Materials	Current Supply Amount	Optimization Supply Amount	Differences
Sandy shrub stubble residue	90,000	93,750	3750
Wood-chipping residue	40,000	40,000	0
Waste-wood products	50,000	46,250	−3750
Total	180,000	180,000	0

Note: the data is from the case study questionnaire.

Table 5. The differences between the total supply cost of each node and three key raw materials under the current situation and optimization (Unit: thousand $).

Supply Cost		Shrub (Forest Land)	Shrub (Chipping Plant)	Wood-Chipping Residue	Waste-Wood Products	Total Cost of Each Node	Differences between the Total Cost of Each Node in Two Situations (b − a)
Planting	a	355.8	148.9	0	0	504.7	−8.2
	b	317.8	178.7	0	0	496.5	
Harvesting	a	479.3	259.1	0	0	738.4	−16.2
	b	462.2	260	0	0	722.2	
Storage	a	7	15	13.5	16.9	52.5	−1.3
	b	6.8	15.2	13.5	15.6	51.2	
Chipping	a	648.7	165.8	0	276.3	1090.8	−35.4
	b	613.3	186.5	0	255.6	1055.4	
Transportation	a	745	575.7	705.1	881.4	2907.1	−36.2
	b	695	647.6	705.1	881.4	2871	
Others	a	0	288.7	989.7	977.4	2255.9	−1.1
	b	0	360.9	989.7	904.1	2254.8	
Total cost of raw materials	a	2235.8	1453.2	1708.4	2152	7549.4	−98.4
	b	2095	1649	1708.4	1998.6	7451	
Differences between total cost of raw materials in two situations (b − a)		−140.8	195.8	0	−153.4	−98.4	–
The unit cost per thousand kg of raw materials	a	0.037	0.048	0.043	0.043	– –	
	b	0.035	0.049	0.043	0.043	– –	
Differences between the unit cost per thousand kg of raw materials in two situations (b − a)		−0.0023	0.0009	0	0.0002	–	–

Notes: "a" represents the current condition; "b" represents the optimization; "Others" refers to the acquisition costs of mainly waste-wood products and wood-chipping residue; the data is from the case study questionnaire.

The optimal supply cost percentages of each node and three key raw materials are presented in Figure 3a,b. In Figure 3a, the transportation cost accounts for 38.53% of the total cost, which represents a significant portion; the percentage of others is 30.26%; the third largest is the cost of chipping, accounting for 14.17%. In Figure 3b, the largest percentage of sandy shrub stubble residue (chipped in the forestland) is 28.1% and the smallest percentage of sandy shrub stubble residue (chipped in the chipping plant) is 22.2%.

Figure 3. Percentage of the optimal supply cost of each node (**a**) and three key raw materials (**b**).

The differences between the total CO_2 emissions of each node and three key raw materials under the current situation and the optimization are shown in Table 6. The total CO_2 emissions of the supply chain are 5683.8 thousand kg which is decreased by 60.6 thousand kg compared to the current condition. For each node, the total CO_2 emissions are reduced by different amounts; the total CO_2 emissions in transportation and chipping nodes are largely decreased with a reduction of 44.8 thousand kg and 24.9 thousand kg. As for the three key raw materials, the overall CO_2 emissions and the unit CO_2 emissions of sandy shrub stubble residue (chipped in the chipping plant) are optimized at the same time, but the overall CO_2 emissions and the unit CO_2 emissions per thousand kg of the sandy shrub stubble residue (chipped in the forestland) increase by exactly 10 thousand kg and 0.0002 thousand kg, respectively; the unit CO_2 emissions per thousand kg of the sandy shrub stubble residue (chipped in forestland) are 0.0317 thousand kg which is larger than that of sandy shrub stubble residue (chipped in the chipping plant) after optimization; the overall CO_2 emissions and the unit CO_2 emissions per thousand kg of wood-chipping residue keep steady; the CO_2 emissions of waste-wood products are optimized but the unit CO_2 emissions per thousand kg increased by 0.0014 thousand kg.

Table 6. The differences between total CO_2 emissions of each node and three key raw materials under the current situation and optimization (Unit: thousand kg).
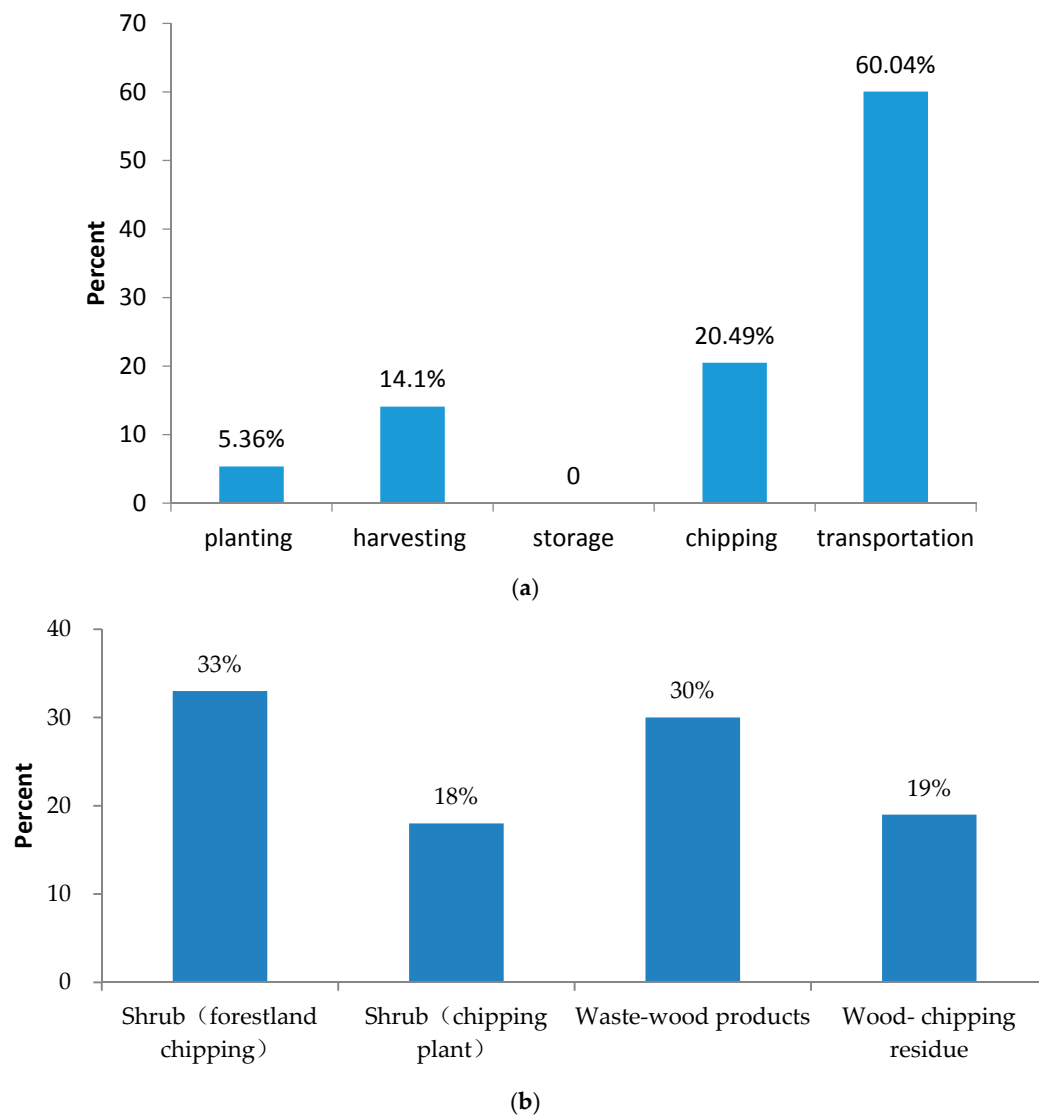
CO_2 Emissions		Shrub (Forest Land)	Shrub (Chipping Plant)	Wood-Chipping Residue	Waste-Wood Products	Total Emissions of Each Node	Differences between Total Emissions of Each Node in Two Situations (b − a)
Planting	a	195.1	109.8	0	0	304.9	−0.1
	b	195.1	109.7	0	0	304.8	
Harvesting	a	594.6	207.8	0	0	802.4	−0.7
	b	594.5	207.2	0	0	801.8	
Storage	a	0.002	0.000	0.001	0.001	0.0	0.0
	b	0.002	0.005	0.005	0.001	0.0	
Chipping	a	410.6	313.9	0	465	1189.5	−24.9
	b	420.6	313.9	0	430.1	1164.6	
Transportation	a	689.5	392.8	1075.2	1300	3457.5	−44.8
	b	689.7	382.4	1075.2	1265.4	3412.7	
Total emissions of raw materials	a	1889.8	1014.3	1075.2	1765.0	5744.4	−60.6
	b	1899.8	1013.3	1075.2	1695.5	5683.8	
Differences between total emissions of materials in two situations(b − a)		10.0	−1.1	0	−69.5	−60.6	–
The unit emissions per thousand kg of raw materials	a	0.0315	0.0338	0.0269	0.0353		–
	b	0.0317	0.0300	0.0269	0.0367		–
Differences between the unit emissions per thousand kg of raw materials in two situations (b − a)		0.0002	−0.0038	0	0.0014	–	–

Notes: "a" represents the current condition; "b" represents the optimization; the data is from the case study questionnaire.

The percentage of optimal CO_2 emissions for each node and three key raw materials is presented in Figure 4a,b. In Figure 4a, transportation accounts for 60.04% of CO_2 emissions, which is a significant portion; chipping accounts for 20.49% of CO_2 emissions; the third largest is the CO_2 emissions of harvesting, accounting for 14.10%. In Figure 4b, the largest percentage of sandy shrub stubble residue (chipped in the forestland) accounts for 33% of CO_2 emissions and the smallest percentage of sandy shrub stubble residue (chipped in the chipping plant) accounts for 18% of CO_2 emissions.

Transportation and chipping have the greatest overall impact in the supply chain. We therefore selected these as critical nodes for the sensitivity analysis. In transportation, differentiation for the path of sandy shrub residue can be reflected by the farmer's average transportation distance. The parameter of transportation distance is 119.71 km in the optimal model. When the optimal supply of three key raw materials remains unchangeable, the transportation distance varies by ±30%. The results of the sensitivity analysis on transportation distance show that (1) when the transportation distance decreased by 30%, the supply cost and the CO_2 emissions are $7333.7 thousand and 5356.9 thousand kg, respectively; (2) when the transportation distance increased by 30%, the supply cost and the CO_2 emissions are $7569.2 thousand and 6304.7 thousand kg, respectively (Table 7).

In chipping, the unit chipping costs have a significant impact in the supply chain. When the optimal supply of three key raw materials remains unchangeable, the transportation distance varies by ±14.7%. The results of the sensitivity analysis show that (1) when the unit chipping cost decreases by 14.7%, the supply cost and the CO_2 emissions are $7180.7 thousand and 5729.2 thousand kg, respectively; (2) when the unit chipping cost increases by 14.7%, the supply cost and the CO_2 emissions are $7721.2 thousand and 5698.2 kg, respectively (Table 8).

(**a**)

(**b**)

Figure 4. Percentage of the optimal CO_2 emissions of each node (**a**) and three key raw materials (**b**).

Table 7. Sensitivity of the optimal solution to the transportation distance.

Rate	Transportation Distance (km)	Supply Cost (Thousand $)	CO_2 Emissions (Thousand kg)
−30%	84.13	7333.7	5356.9
−20%	95.77	7372.1	5463.9
−10%	107.74	7411.5	5573.8
0%	119.71	7450.9	5683.8
10%	131.68	7490.4	5793.7
20%	143.66	7529.8	5903.7
30%	155.60	7569.2	6304.7

Table 8. Sensitivity of the optimal solution to the unit chipping cost.

Rate	Unit Chipping Cost (Thousand $)	Supply Cost (Thousand $)	CO_2 Emissions (Thousand kg)
−14.7%	0.00872	7180.7	5729.2
−10%	0.00920	7267.2	5712.2
0.0%	0.01022	7450.9	5683.8
10%	0.01124	7634.6	5692.8
14.7%	0.01172	7721.2	5698.2

4. Discussion

The major raw material for the company was sandy shrub stubble residue (52.8% of all raw materials) and the biggest concern during the supply chain was high supply cost (50.3% of the total supply cost). That supply cost was dependent largely on the raw material's own characteristics: (1) raw material in Inner Mongolia possessed the following characteristics: broad dispersion, low density, high moisture content [37,45]; (2) uneven seasonal availability [40]. The sandy shrub stubble residue could be transformed into bioenergy to promote the development of a residue-recycling economy. However, the unit cost of the sandy shrub stubble residue chipped in the forestland was $0.01394 thousand less than that of the sandy shrub stubble residue chipped in the chipping plant after optimization. Although the chipping plant can achieve intensive chipping and improve efficiency, the construction of a chipping plant required heavy investment in terms of funds, equipment and labor. It was possible to increase the supply amount of chipped sandy shrub residue in the forestland (33% of the total supply), as shown in [32]. The price of a household shrub chipper was relatively high, so if the households have not specifically been engaged in raw material collection work, they would generally not be willing to buy a chipper which was why they would rather sell the non-chipped sandy shrub stubble residue to the chipping plant. On the other hand, the CO_2 emissions of the sandy shrub stubble residue chipped in the chipping plant was 0.0002 thousand kg less than that of the sandy shrub stubble residue chipped in the forestland. The increased CO_2 emissions of non-chipped residue during transportation were much smaller than the decrease in CO_2 emissions in the chipping plant. Therefore, it is necessary to construct a chipping plant in an area that is rich in sandy shrub stubble residue.

The second raw material was the waste-wood products (25.69% of the total raw material) and it served the second-recycling use for bioenergy. Its supply should be decreased compared to the current situation because of its high acquisition cost. After optimization, the supply cost and the CO_2 emissions were optimized, but the unit supply cost and the unit CO_2 emissions were increased. The third raw material was the wood-chipping residue (22.22%) and its optimal supply remained unchangeable compared to the current situation. Therefore, its supply cost and the CO_2 emissions should be kept steady after optimization.

Not only did the enterprise optimize its supply chain, but it should also fulfil its social responsibility to lower CO_2 emissions during the usage of forest biomass as much as possible. It was indicated that the transportation and chipping node had the greatest impact on the supply chain. The transportation node had the highest share of the total cost (38.83%) and CO_2 emissions (60.04%). Similar to [45], the transportation to the terminal which served an important role in the woody biomass supply chain accounted for 23% and 31% of the total cost and total emissions, respectively. The unit transportation distance was significant regardless of road condition, particularly for low-density sandy shrub residue. This is mainly due to high fossil fuel consumption from the forestland to the terminal. In [46], the effect of unit transportation distance became evident when cumulated biomass and round wood were transported by the same trucks and over the same road and the impact of unit transportation distance on the cumulated biomass was larger than round wood. In this paper, all nodes of the supply chain were simultaneously economically and environmentally optimized with a reduction of $98.4 thousand and 60.6 thousand kg, respectively, to helpfully build a complete low-cost and low-carbon supply chain model. However, the CO_2 emissions of the harvesting, skidding and transportation nodes were merely calculated in [38] which showed that chain-sawing, cableway skidding and truck transportation of raw material was the optimal mix to reduce emissions; this was echoed in [39] which analyzed the CO_2 emissions of the woody biomass supply chain from the perspective of direct emissions and indirect emissions.

In the optimal model, the farmer's transportation distance was 119.71 km, and the unit chipping cost was $0.0102 thousand. After the sensitivity analysis, the farmer's transportation distance could be 84.13 km and the unit chipping cost could be $0.0102 thousand, so the optimal solution remained unchangeable. For the farmer's transportation distance, the variation of supply cost and CO_2 emissions correlated positively with the transportation distance; when the transportation distance decreased

by 30%, correspondingly the supply cost decreased by 1.5% and the CO_2 decreased by 5.7%. For the unit chipping cost, the variation of supply cost and CO_2 emissions correlated negatively with the unit chipping cost; when the unit chipping cost decreased by 14.7%, the supply cost decreased by 3.6% while the CO_2 emissions increased by 0.8%. A similar sensitivity analysis was conducted on the profitability of the biomass supply chain in [16] which examined the optimal solution to the variation in the demand and price of products, as well as the availability and the cost of forest residue. This paper differed from those aforementioned studies in that only the transportation distance and unit chipping cost were selected to conduct the sensitivity analysis based on the largest percentage of supply cost and CO_2 emissions. Therefore, we may add other parameters into the sensitivity analysis to find out how the optimal results will change.

5. Conclusions

This study presented a multi-objective linear programming model and sensitivity analysis to optimize the supply chain of forest biomass power generation. The purpose was to investigate the trade-offs between economic and ecological benefits within the biomass supply chain of the Mao Wu Su biomass Thermoelectric Company. The optimal results show that the amount of sandy shrub residue should be increased and the amount of the waste-wood-products should be decreased; there is still a lot of room for optimization of the transportation path of sandy shrub residue; the cost and the CO_2 emissions of transportation and chipping account for a large percentage of the overall supply chain. Finally, a sensitivity analysis was introduced to determine that the farmer's average transportation distance and the farmer's unit chipping cost are significant parameters in the transportation and chipping nodes. The findings on these two nodes for the Mao Wu Su biomass Thermoelectric Company are applicable to other companies with similar forest biomass supply chains.

In order to achieve a lower-cost supply chain and a CO_2 emissions reduction, the following suggestions are put forward for the Mao Wu Su biomass Thermoelectric Company: (1) develop long-term cooperation with farmers to ensure a stable flow of sandy shrub residue for residue-recycling. The results show that the sandy shrub residue should be increased by 3750 thousand kg. Farmers are of great importance for the supply of raw material for biomass production. Long-term cooperation with farmers will help to ensure a stable flow and increase the income and the enthusiasm of farmers to harvest the sandy shrub stubble and improve the quality of raw materials. Therefore, the enterprise could strengthen the importance of the farmer's participation in the forest biomass power industry through energy forest construction projects and by signing a long-term raw material supply contract with farmers and increasing subsidies for the main farmers; (2) buy chain-saws for regularly used farmers to improve efficiency. The farmers who are very much involved in the supply of sandy shrub stubble residue are generally over 55 years of age. Generally, they use a hoe to harvest shrub which is inefficient and laborious. On the other hand, most farming families are poor and generally cannot buy their own chain-saws. The price of a chain-saw is $0.188 thousand. Farmers may find this price unaffordable, so borrowing from enterprises can help to improve efficiency; (3) build several chipping plants (middlemen) in areas that are rich in sandy shrub to shorten the required transportation distance and chipping cost. Based on the sensitivity analysis, the transportation distance of 87.13 km and chipping cost of $0.01022 thousand are optimal parameters that should be established as soon as possible. The existing chipping equipment is limited in technology and popularity and a chipping plant (middlemen) needs to be introduced to reduce the cost of raw materials. Middlemen should be encouraged to participate in the forest biomass power supply chain and make full use of the role of the market mechanism, i.e., the price of raw material changes with the market to guarantee farmers' income. However, the construction of a chipping plant requires investment of a certain amount of capital so the number of middlemen should be considered carefully in the future.

Growth of the Mao Wu Su biomass Thermoelectric Company is contributing to the prevention of desertification and protection against the harsh ecosystem in semi-arid areas; it also motivates local farmers to plant much sandy shrub, thus promoting residue-resources recycling for bioenergy.

In addition, the development of the enterprise helps to promote economic development and provides jobs for farmers. This case can set an example for other countries to follow, i.e., a bio-enterprise optimizes its supply chain for low-carbon development. The effective use of sandy shrub stubble residue will contribute towards the sustainable development of these regions, thus alleviating the energy crisis and future global warming. Future work should involve the addition of labor employment and the number of chipping plants (middleman) to the study, as well as analyzing the amount of subsidies provided and how these subsidies can support the forest biomass power generation industry.

Author Contributions: Min Zhang and Feng Mi conducted the background research, built the entire framework of the article and edited the content. Guangyu Wang provided additional guidance and suggestions. Min Zhang, Yi Gao and Zhenqi Wang gathered the statistical data and calculated the results of the article. All authors have read and approved the final manuscript.

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

Appendix A

Name	Explanation
M_i	Raw material type $i \in \{\text{sandy shrub stubble residue}, \text{wood} - \text{chipping residue and waste} - \text{wood products}\}$
K_k	Raw material transportation form $k \in \{\text{chipped}, \text{nochipped}\}$
T_j	Transportation path, $j \in \{\text{forestland} \quad -\text{skidding area}, \text{skidding point} - \text{storage point}, \text{storage point} -\text{chipping plant}, \text{chipping plant} - \text{power plant}, \text{forestland} -\text{storage point}, \text{forestland} - \text{chipping plant}, \text{forestland} -\text{power plant}, \text{storage point} - \text{power plant}, \text{storage point} -\text{power plant}, \text{skidding point} - \text{chipping plant}\}$
U_u	Planting equipment, $u \in \{\text{no}, \text{land preparation machine}, \text{tap machine}, \text{weeding machine}\}$
V_v	Harvesting equipment $v \in \{\text{no}, \text{small hand} - \text{held harvesters}, \text{medium} - \text{sized harvester}\}$
W_w	Skidding equipment, $w \in \{\text{no}, \text{handcart}, \text{gathering manchine}, \text{firewood collecting machine}, \text{tractor}\}$
X_x	Chipping equipment, $x \in \{\text{no}, \text{chipping machine}, \text{crusher}, \text{chopper}\}$
Y_y	Transportation equipment, $y \in \{\text{human} - \text{load}, \text{agricultural tricycles}, \text{truck}\}$
D_d D_s D_c	Skidding point, $d \in \{\text{no}, \text{forest} - \text{road}, \text{roadside}, \text{chipping plant}\}$ Storage point, $s \in \{\text{no}, \text{site1}, \text{site2}, \ldots, \text{site } n\}, n \in Z$ Chipping point, $c \in \{\text{no}, \text{site 1}, \text{site2}, \ldots, \text{site } m\}, m \in Z$

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