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Research article

Effects of population density of a village and town system on the transportation cost for a biomass combined heat and power plant

Yifei Zhang[a,*], Chunpeng Qin[b], Yi Liu[c]

[a] *School of Architecture, Harbin Institute of Technology; Heilongjiang Cold Region Landscape Science Key Laboratory, Room 328, No.66 Xidazhi Street, Nangang District, Harbin, Heilongjiang Province, 150001, China*
[b] *School of Architecture, Harbin Institute of Technology, Harbin, 150001, China*
[c] *The 2nd Affiliated Hospital of Harbin Medical University, Harbin, 150001, China*

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ABSTRACT

Combined heat and power (CHP) generation can meet winter heating demands. Therefore, biomass CHP plants are more suitable for the development of biomass energy in village and town systems in cold regions. Transportation cost is one of the factors that determine operating costs. In this study, potential biomass energy is estimated based on the distribution of various types of crops. The locations and service areas of biomass CHP plants are determined using geographic information system analysis tools based on population distribution and energy demand data. Equations that contain multiple interference factors are used to calculate the raw material supply area and transportation cost for a biomass CHP plant to generate an optimal transportation route within a region. The analysis results show that biomass CHP plants are only suitable for village and town systems with a relatively low population density (*PD*). The curve of the supply area versus the *PD* of the village and town system (PD_{VTS}) has an inverse-S shape. The transportation cost increases exponentially as the PD_{VTS} increases. Biomass CHP plants can achieve higher efficiency in transportation costs when built in areas with a $PD_{VTS} \leq 65$ people/km^2.

1. Introduction

Agriculture provides humans with food. Compared to biomass from forests, agricultural biomass is a stable and reliable source with an enormous potential as a biomass carrier (Apfelbacher et al., 2014). Building a biomass combined heat and power (CHP) plant is a relatively efficient way of using agricultural biomass. Hence, numerous efficiency analysis studies concerning biomass CHP plants have been conducted. Transportation cost is one of the key factors that affect the efficiency of biomass CHP plants (Mirkouei et al., 2017).

Golecha et al. (Golecha and Gan, 2015) built an estimation formula and model that consider biomass yield density and road network transport radius and used them to analyse the transportation cost of biomass CHP plants. However, this study failed to take into account the effects of biomass type, differences in the calorific values of straw and the population density (*PD*) of the village and town system (PD_{VTS}) in question. Daianova et al. (2012) studied the cost of fuel consumed by fleets of vehicles that transported raw materials to biomass CHP plants within Sweden and concluded that ethanol production cost, gasoline price and straw processing cost were the three most significant factors that affected fuel cost. However, this study did not consider factors such as highway tolls, differences in road conditions and design vehicle speed. Kurka et al. (2012) estimated the transportation cost and carbon dioxide emissions for 10 medium-sized biomass CHP plants using geographic information system (GIS) tools and concluded that a scattered distribution of biomass CHP plants is more beneficial when both conventional and renewable energies are available. However, the thermal power plants selected for the analysis model by Kurka et al. had similar total powers. Consequently, when used to analyse situations in which the differences in *PD* are relatively significant, this model will generate estimation errors. Riha et al. (Riha and Tichy, 2015) built a model based on the road transportation perspective for estimating transportation cost on urban and rural roads. However, their study did not set additional parameters for modes of transportation specific to biomass CHP plants. Liu et al. (2014) examined the logistical cost involved in pre-processing biomass and concluded that crushing, packing and curing are suitable pre-processing methods when the transportation distance is less than 26 km, between 26 and 80 km, and greater than 80 km, respectively. However, they did not conduct a detailed investigation of situations in which the transportation distance is less than 26 km. Chen et al. (Cheng et al., 2013) collected 172 straw samples of four types of crops and measured their caloric values. The climate in

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[*] Corresponding author.
E-mail address: 29598757@qq.com (Y. Zhang).

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the area where Chen et al. conducted their study differs from that in the area examined in this study. As a result, there is a difference in the caloric value of straw in these two areas.

In summary, research on the transportation cost for biomass CHP plants has focused on areas of biomass yield density, road network radius, transportation fuel consumption and biomass pre-processing. However, a study on the relationship between PD_{VTS} and the transportation cost for biomass CHP plants is unavailable. Hence, with this relationship as its focus, this study is devoted to describing the variation pattern of the transportation cost for biomass CHP plants with PD_{VTS} to provide data that support the selection of locations for biomass CHP plants.

2. Methods for calculating the supply area and transportation cost and key variables

PD_{VTS} will have an impact on a series of indices related to biomass CHP plants, including total output power, service area, supply area and transportation cost. Our preliminary study has found that for a biomass CHP plant, its total power is determined by the distribution of energy demands in the area and its service area is determined by the heat transfer threshold (Zhang and Kang, 2017). The supply area and transportation cost are further analysed in this study. Determination of the supply area is a precondition for estimating transportation cost. Thus, in this study, after selecting a case study, the supply area is analysed and then the transportation cost is calculated.

The village and town systems shown in Fig. 1 were eventually selected as the case study through screening using several universal conditions: high agricultural yield, complete road network and uneven population distribution. Situated on the Sanjiang Plain in north-eastern Heilongjiang Province, China, and spanning a distance of 57.87 km from east to west and 46.62 km from south to north, this area encompasses an area of 1586.16 km^2 and has a population of 98,492 people. The towns of Shangjieji, Chang'an and Jinshan each have a relatively large population, and each of the remaining 144 villages has a relatively small population (Fujin bureau of statistics, 2016a); therefore, there is a relatively large regional difference in *PD*. Fig. 2 shows the *PD*s obtained by inputting the locations of the towns and villages and their population data into ArcGIS for analysis.

2.1. Method for calculating the supply area for a biomass CHP plant

The calorific value of straw, cultivation area and distribution area differ significantly for different types of crops. These differences will affect the supply area for a biomass CHP plant. Fig. 3 shows the distribution map of crop cultivation areas plotted based on the cultivated crop type and distribution data acquired from local governments. Based on a summary of literature related to straw yield (Zhu et al., 2012; Xie et al., 2010), a relatively widely accepted equation for calculating straw yield is used in this study:

$$P = FI \tag{1}$$

where P is the straw yield; F is the crop yield per unit area; and I is the straw–grain ratio. The quantity of straw that can be obtained from the study area can be calculated based on the statistical agricultural product yield data (National bureau of statistics of the People's Republic of China, 2016; Heilongjiang's bureau of statistics, 2016; Fujin bureau of statistics, 2016b) and the straw-grain ratios. In this study, existing mature equations are optimized, expanded and used to calculate the potential energy corresponding to a farmland area based on the quantity and calorific values of straw. Then, the raw material supply area for a biomass CHP plant is estimated, as shown in equation (3).

$$RN\,(E + T) = KC\,(H_rP_rL_r + H_bP_bL_b + H_cP_cL_c + H_wP_wL_w + H_pP_pL_p + H_oP_oL_o) \tag{2}$$

where R is the peak modulation coefficient of the raw biomass material inventory; N is the number of people served by the biomass CHP plant; E is the annual average power consumption per person; T is the annual average heat consumption per person; K is the biomass combustion efficiency; C is the straw collection coefficient; H_r, H_b, H_c, H_w, H_p and H_o are the caloric values of straw from rice, soybean, maize, wheat, potato and other grain crops, respectively; P_r, P_b, P_c, P_w, P_p and P_o are the straw yields of rice, soybean, maize, wheat, potato and other grain crops per unit area, respectively; L_r, L_b, L_c, L_w, L_p and L_o are the cultivation areas of rice, soybean, maize, wheat, potato and other grain crops, respectively.

By combining and reorganizing equations (1) and (2), equations (3) and (4) are obtained:

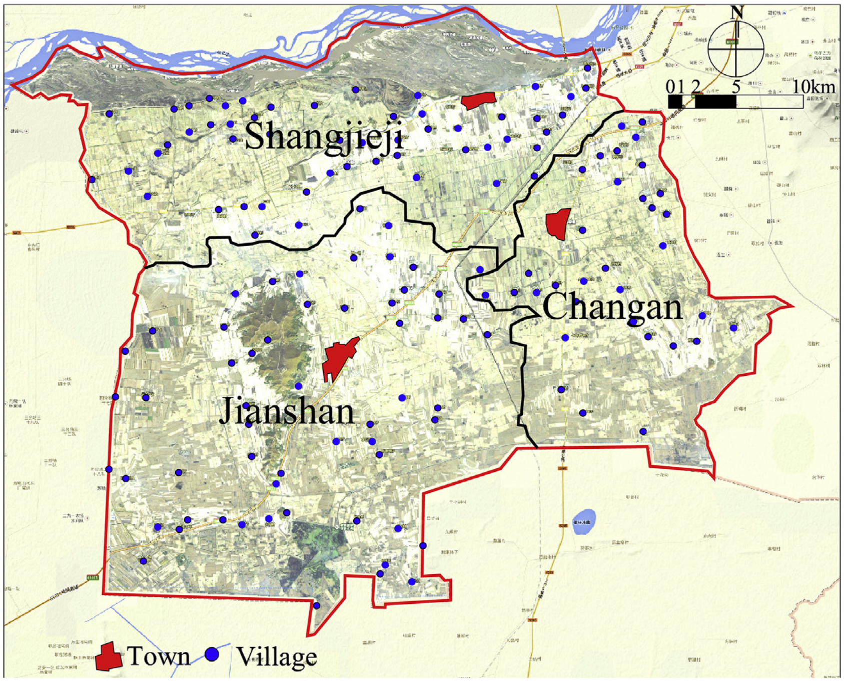

Fig. 1. Relative locations of the villages and towns.