Journal of Environmental Management 202 (2017) 21–28

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Effects of the distribution density of a biomass combined heat and power plant network on heat utilisation efficiency in village–town systems

Yifei Zhang [a, *], Jian Kang [a, b]

[a] School of Architecture, Harbin Institute of Technology, 150001, China
[b] School of Architecture, University of Sheffield, Sheffield S10 2TN, UK

A R T I C L E   I N F O

Article history:
Received 23 April 2017
Received in revised form
19 June 2017
Accepted 8 July 2017

Keywords:
Biomass CHP plant
Distribution density
Heat utilisation efficiency
Village–town system
Fujin

A B S T R A C T

The building of biomass combined heat and power (CHP) plants is an effective means of developing biomass energy because they can satisfy demands for winter heating and electricity consumption. The purpose of this study was to analyse the effect of the distribution density of a biomass CHP plant network on heat utilisation efficiency in a village–town system. The distribution density is determined based on the heat transmission threshold, and the heat utilisation efficiency is determined based on the heat demand distribution, heat output efficiency, and heat transmission loss. The objective of this study was to ascertain the optimal value for the heat transmission threshold using a multi-scheme comparison based on an analysis of these factors. To this end, a model of a biomass CHP plant network was built using geographic information system tools to simulate and generate three planning schemes with different heat transmission thresholds (6, 8, and 10 km) according to the heat demand distribution. The heat utilisation efficiencies of these planning schemes were then compared by calculating the gross power, heat output efficiency, and heat transmission loss of the biomass CHP plant for each scenario. This multi-scheme comparison yielded the following results: when the heat transmission threshold was low, the distribution density of the biomass CHP plant network was high and the biomass CHP plants tended to be relatively small. In contrast, when the heat transmission threshold was high, the distribution density of the network was low and the biomass CHP plants tended to be relatively large. When the heat transmission threshold was 8 km, the distribution density of the biomass CHP plant network was optimised for efficient heat utilisation. To promote the development of renewable energy sources, a planning scheme for a biomass CHP plant network that maximises heat utilisation efficiency can be obtained using the optimal heat transmission threshold and the nonlinearity coefficient for local roads.

1. Introduction

Biomass is a unique renewable energy source because it can be stored easily (Hepbasli, 2008). For this reason, researchers worldwide have aimed to develop more efficient ways to utilise biomass energy, with the goal of reducing the consumption of non-renewable energy sources and the associated environmental pollution (Tasneem and Abbasi, 2010). One of the objectives of this research is to improve the utilisation efficiency of biomass energy in the context of village–town system planning.

Scarlat et al. (2015a) and Peter (2002) concluded that the energy conversion efficiencies of straw-fired cogeneration and liquid fuel technologies are approximately 20–40% and 40–50%, respectively. Guo et al. (2015) argued that liquid fuel production is inefficient at low temperatures, and straw-fired cogeneration technology has become the first choice to achieve winter heating goals in cold regions. Scarlat et al. (2015b) and Göran (2000) compared the energy utilisation efficiencies of straw-fired cogeneration technology and solid fuel production, and found that the energy utilisation efficiencies of these two methods differed slightly. As the production cost of solid fuel is relatively high, it is more economical to build biomass combined heat and power (CHP) plants using straw-fired cogeneration technology. Based on a combined study of landscape and energy planning, Thomas et al. (2013) presented a method for predicting the gross power of biomass power plants according to the

---

* Corresponding author.
E-mail addresses: 29598757@qq.com (Y. Zhang), j.kang@sheffield.ac.uk (J. Kang).

http://dx.doi.org/10.1016/j.jenvman.2017.07.019

heat demand distribution, which involves analysing the population distribution of villages and towns. Xun et al. (2008) used geographic information system (GIS) tools to analyse transportation costs for a biomass carrier from the perspective of village–town planning, and determined the economically optimal distribution density of biomass power plants. However, since the biomass CHP power plants in this model cannot meet winter heating goals, this model cannot be applied to cold regions. Dornburg and Faaij (2001) suggested that the gross power of a biomass CHP plant is directly proportional to the energy conversion efficiency; the energy conversion efficiency reached 35% when the gross power of a biomass CHP plant reached 350 MWh. However, they did not consider the relationship between heat transmission loss and heat transmission distance. An investigation by Lu and Xi (2011) into the relationship between heat transmission loss and heat pipe length from a town planning perspective showed that the heat loss ratio of a heating network was directly proportional to the heat transmission distance when the latter was limited to 20 km.

These results illustrate that, based on development costs and heat output efficiency, building biomass CHP plants is an efficient way to develop biomass energy in village–town systems in cold regions. In addition, research into the heat demand distribution and heat transmission loss shows that the distribution density of biomass CHP plants affects construction costs. Based on these results, this study addresses the following question: can the distribution density of a biomass CHP plant network affect heat utilisation efficiency? This question involves investigating the ecological and economic concerns of village–town systems, a topic which has not previously been studied in depth.

The relationship between the distribution density of biomass CHP plants and their heat energy utilisation efficiency is not well studied, so investigating this relationship is the goal of the research presented here. Biomass CHP technology analyses involve heat utilisation efficiency, electricity utilisation efficiency, and many other factors, but this study focused on analysing heat utilisation efficiency because this is crucial to the energy saving required for winter heating in village–town systems in cold regions. Therefore, the purpose of this study was to evaluate the effect of the distribution density of a biomass CHP plant network on heat utilisation efficiency from the perspective of village–town system planning. Since heat utilisation efficiency is determined by the heat demand distribution, heat output efficiency, and heat transmission loss, these factors form the focus of this research. Based on theoretical models, GIS tools were used to perform overlay or network analyses of factors including the village–town distribution, population density, and road networks. Several different biomass CHP plant network planning schemes with various heat transmission threshold values (between 6 and 10 km) were simulated and generated, and a multi-scheme comparison was conducted to determine the optimal heat transmission threshold for maximising the heat utilisation efficiency. Studying this topic using GIS tools, for a series of simulation analyses with data that are readily available from local governments, represents a considerable cost saving compared to studies that use expensive remote sensing (RS) data or collect data from field surveys.

2. Methods: biomass CHP plant network model and analysis of a typical case

The heat transmission loss of a heating network increases as the transmission distance increases. Therefore, there is a threshold for the transmission distance from a biomass CHP plant to the end user: this distance cannot be increased indefinitely. This threshold differs depending on the country because of variations in municipal planning standards. The heat transmission threshold was the most important research target in this study.

2.1. Range of heat transmission threshold values

Due to its close relationship with heat transmission loss, heat transmission distance should be considered when establishing a biomass CHP plant network; its value can affect the service area and construction costs of biomass CHP plants (Amit et al., 2003; Biberacher et al., 2008; Biberacher and Gadocha, 2009; Blaschke et al., 2008; Prinz et al., 2009; Moser et al., 2009). According to conventional heating network design specifications in China, the optimal range of the heat transmission distance from plant to end user is 6–8 km, and the maximum value is 10 km (Zhang et al., 2008). Thomas et al. (2013) engaged 21 experts to evaluate a series of threshold values in terms of energy transmission, and the results demonstrated that the maximum heat transmission distance should be 10 km. Although these results broadly agree, a further question arises: given the heat transmission distance range of 6–10 km, what value within this range optimizes the heat utilization efficiency of a biomass CHP plant network? To answer this question, this study investigated the optimal value for the heat transmission threshold through a series of quantitative analyses. Owing to extremely high road construction costs, it is economical to build biomass CHP plants and install a heating network using existing roads, bearing in mind the required range for the heat transmission threshold.

2.2. Basic and improved model forms

The relationship between the locations of the biomass CHP plants and the radii of villages and towns can be deduced based on the heat transmission threshold (T). Because the roads connecting villages and towns tend to form irregularly shaped networks, a road nonlinearity coefficient (Wang et al., 1998) (N) was incorporated, and the average service radius of the biomass CHP plants was set as T/N. Here, it was assumed that all the biomass CHP plants were regularly distributed on a plain; future research will investigate complex mountainous terrains. It is well known that a cellular structure is the best topological structure to cover a two-dimensional plane, so this structure was used as the basis of the biomass CHP plant network in this model, as shown in Fig. 1. According to the known angles and side lengths of the equilateral triangles, the straight-line distance between two biomass CHP plants can be calculated as $T/N.2\cot(30^\circ)$.

Various zigzag forms exist in real road networks; therefore, the average service radius (T/N) in the above model will vary within a certain range, and the degree of variation can be determined based on the distribution density of the villages and towns (Ma and Zhang, 2016).

In addition to the heat transmission threshold, the distribution status and populations of the villages and towns can affect the form of the biomass CHP plant network.

The distribution of villages and towns was the most crucial factor in estimating the heat demand distribution. If no villages or towns exist in a certain region, it is economical to remove all biomass CHP plants in this region from the regularly spaced network. The borders of the biomass CHP plant service areas adjacent to such a region transform from a hexagonal to a circular form. If the distribution density of villages and towns is relatively low in a certain region, the construction costs of a regularly distributed biomass CHP plant network would be excessively high. In this case, it is economical to adjust the positions of some of the plants so that the resulting irregularly distributed network, with fewer biomass CHP plants, can serve the same number of villages and towns. When the distribution density of villages and towns is relatively high, the service area borders of the biomass CHP plants tend to form hexagonal shapes, whereas they tend to be circular when the distribution density of villages and towns is relatively low. Based on these rules, an