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Research article

Combined biomass network design: A new integrated approach based on ArcGIS

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ABSTRACT

In light of contemporary energy and environmental objectives, a pivotal transformation of the energy system, encompassing biomass energy, is imperative. A notable challenge in biomass energy facility layout planning is the trade-off between high-efficiency production and the associated investment costs. To harmonize energy efficiency with economy viability, a hybrid layout with the simultaneous construction of centralized and decentralized biomass energy facilities has emerged as a crucial strategic solution. However, the delineation methods for these two layouts lack explicit data support. This study established a population density threshold (PDT) suitable for selecting the distributed layout and employed population density as the criterion for delineating the two layouts. Taking Fuxin City as an example, hybrid layout planning schemes were generated under different PDTs, and a cost and energy benefit analysis framework was developed for these schemes. The results indicated that the scheme with a PDT of 145 person/km^2 exhibited the highest energy and economic comprehensive benefits. Compared to a single layout, the planning strategy proposed in this study could achieve nearly the same energy surplus level while saving an investment cost ranging from 2403.9 million CNY to 25,000.23 million CNY. The findings are applicable to other regions with similar conditions, and the analysis framework proposed in this study can be utilized in formulating biomass development strategies for other countries and regions.

1. Introduction

Due to its transportability and storability, biomass energy is one of the important renewable energy sources for many regions [1]. The biggest challenge in biomass energy spatial planning is optimizing the layout of biomass energy facilities to reduce investment costs as much as possible and ensure energy efficiency [2].

Biomass energy facilities have two layout modes: 1) centralized – single large, and 2) distributed – several small. The centralized layout has high energy efficiency but high transportation costs. The distributed layout has low transportation costs but low energy efficiency [3]. As it is difficult to balance the high transportation cost and energy efficiency, the debate on distributed layout and

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centralized layout has never been conclusively ended [4].

In the existing research, there are many studies on the optimization of a single layout mode, especially the centralized layout. The optimization of centralized layout mainly involves the siting or site suitability assessment of energy facilities, see Table 1 for details. In this regard, ArcGIS is the leading tool. The site selection objectives mainly focus on reducing investment costs, improving energy efficiency and reducing carbon emissions. In contrast, distributed research focuses more on technical aspects rather than spatial layout. This is because distributed facilities are usually household-scale and do not involve location issues.

However, due to the uneven population distribution, it is unrealistic to adopt a single layout method for the entire area. In order to reduce the total investment cost and improve energy utilization, it is necessary to adopt a combined layout. Therefore, how to determine the selection boundaries of these two layouts has become an important research topic. However, most research in this area focuses on small-scale, technology-level studies, such as technology selection at the village or power plant scale. There is less analysis of the trade-offs of layout patterns. In the existing study, three sizes of factories: micro, small and medium-sized when determining factory location have been considered [6]. A study investigated the effects of harvest region shape, biomass yield, and plant location on optimal biofuel facility size [12]. But both studies focus on centralized layouts, differing only in collection radius and scale. In addition, most studies remain at the text analysis stage and lack data support. For example, some studies analyzed the characteristics of centralized layout and distributed layout, but only proposed a strategy framework. Some studies analyzed the social, economic and environmental impacts of different layout modes, but they were limited to making policy recommendations [13,14].

Delving deeper, in the comparative analysis of centralized and distributed layouts, the primary considerations can be bifurcated into two key dimensions: technology-economy and environmental performance. Technology-economy performance refers to technical parameters and investment costs, including energy efficiency, equipment costs, transportation cost, etc. Environmental performance refers to pollutant emissions during the life cycle. A study quantitatively analyzed Germany's distributed and centralized renewable energy development. This study concluded that the distributed mode was more suitable for renewable energy power generation, and both centralized and distributed development should be promoted in China [15]. However, this study did not provide a method for determining the development mode [16]. evaluated five rural distributed and centralized biomass technologies in China from the environment, society, and technology perspectives and argued that the optimal solutions are centralized gasifier systems and distributed biogas systems. The study only discussed the best energy system and did not consider the layout of energy facilities [17]. compared the distributed and centralized energy scenarios based on biomass and argued that distributed cogeneration is a more effective decarbonization strategy for the energy sector, considering the bioenergy production increase. However, the study did not consider the combination of distributed and centralized layouts nor calculate the investment costs of different energy scenarios.

Prior studies have determined the suitability of centralized and distributed systems for certain specific conditions. The comparative studies on centralized and distributed systems are generally carried out from three perspectives: environmental impact, economic benefits, and social preferences. The research results are usually a certain optimal energy system at small scales, such as villages, power generation facilities, and airports. Investment cost was the most important factor.

However, in the above studies, no matter the comparative study of these two systems or the practical study of the mixed renewable energy systems, there is a lack of a detailed discussion on the selection criteria of these two systems under the combined planning scenario of centralized and distributed systems. In addition, the existing research objects are usually small, mostly villages, residences, and single buildings, which makes it difficult to form a proposal for the unified planning of biomass energy facilities at the city and county levels.

Based on the identified research gaps, this study leverages population density as a critical determinant to demarcate centralized and distributed layouts, facilitating the generation of combined layout solutions at varying population density threshold (PDT). Each combined layout scheme incorporates both centralized biomass thermal power plants and distributed biomass boilers. Subsequently, the optimal PDT is ascertained through the evaluation of these schemes. The specific objectives are to：

(1) Develop biomass energy facility layout plans for each predefined PDT.
(2) Assess the energy self-sufficiency and investment costs associated with each layout scheme.
(3) Identify the optimal PDT, thereby establishing data standards for choosing between centralized and distributed layouts.

2. Methods

The conceptual model of the overall methodology is shown in Fig. 1, including four steps. At the first step，we create spatial unit-based layout plans using clusters at various population density threshold (PDT). At the second step, we calculate the biomass resource

Table 1
A summary of research on centralized layout optimization.

Reference	Method	Research scale	Factors to consider	Number of plants
[5]	Fuzzy SCPPL model	Province	Cost and carbon emission	Multiple
[6]	ArcGIS	State	Cost	Multiple
[7]	ArcGIS based multi-criteria analysis	State	Transportation cost	Single/multiple
[8]	ArcGIS based multi-criteria decision making	State	Carbon emission	Multiple
[9]	Mathematical model	Plant	Transportation cost and carbon emission	Single
[10]	ArcGIS	Province	Cost	Multiple
[11]	Mathematical model	City	Transportation cost	Multiple

of each villages and towns, considering land use and geographical location of villages and towns. At the third step, these resources are spatially distributed in alignment with the energy requirements of villages and towns, leading to the formation of combined layout schemes under different PDTs. The final step involves program evaluation to ascertain the optimal PDT.

Population density critically influences the feasibility of constructing centralized energy facilities. In this context, we introduce the population density threshold (PDT) as a pivotal parameter in our study. The PDT serves as a decision factor for choosing between distributed and centralized layout schemes. Specifically, a distributed layout is recommended for clusters where the population density is below the predetermined PDT. Conversely, a centralized layout is preferable for clusters exceeding this threshold. Thus, by establishing the PDT, we provide a strategic framework to guide the selection between distributed and centralized energy facility layouts.

Fuxin City, located in Liaoning Province, China, with a population of 1.843 million, was selected as the research case in this study. According to prior research results of our research team [18], Fuxin has a high degree of energy self-sufficiency (78 %) with coordinated utilization of solar and biomass energy. The urban population of Fuxin City is mainly concentrated in the villages in the southwest but distributed evenly (Fig. 2), which makes it an ideal condition for studying population density and construction mode.

This study has selected Fuxin City in Liaoning province China, as the case study. The choice of Fuxin City is justified for two reasons. First, Fuxin boasts a remarkable potential for biomass resources. If the city's biomass can be fully developed, it can theoretically meet 78 % of the daily energy needs of local residents [18]. Second, Fuxin serves as a consistent case study, aligning with our prior research in the field of biomass energy facility layout planning. This continuity enables us to draw meaningful comparisons and build upon the knowledge gained from previous investigations.

Fuxin City is located in Liaoning Province, China. The distribution of villages and towns in Fuxin City is both uniform and well-dispersed throughout the city (Fig. 2a). However, the population is primarily concentrated in the southwestern urban area, with a total population of approximately 1.843 million (Fig. 2b). This unique population distribution pattern provides an ideal research environment for evaluating the relationship between population density and construction patterns.

2.1. Determination of the construction mode

The integrated planning of biomass energy facilities refers to the combination of centralized and distributed layout modes. In this study, the centralized layout is based on the biomass combined heat and power (CHP) plant, and the distributed layout is based on the household biomass boilers. The selection of the above energy facilities involves careful consideration of their technical maturity, commercialization, investment cost, and environmental impact.

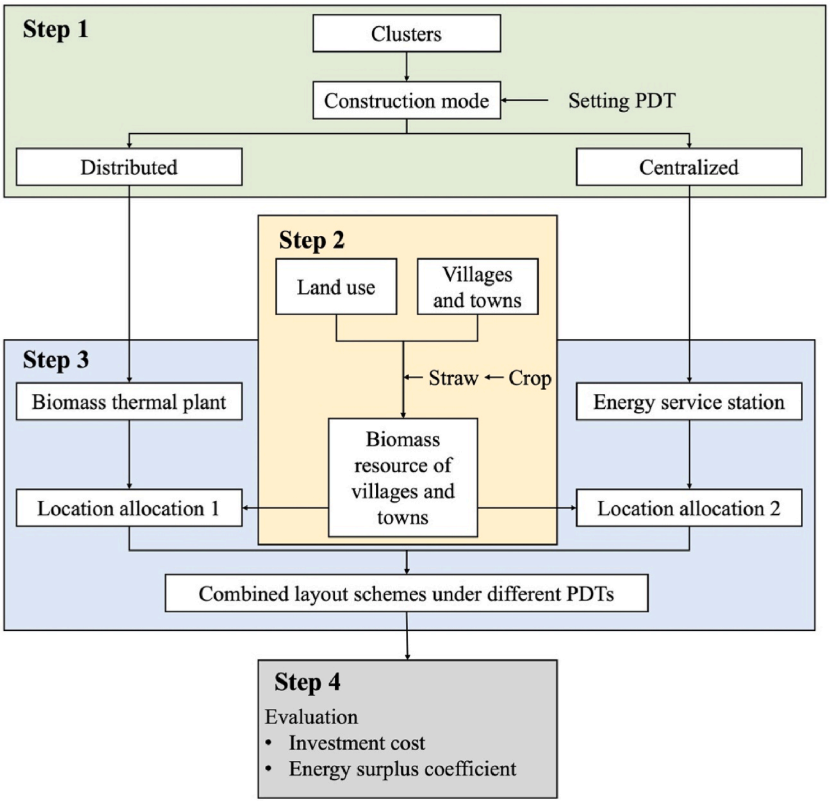

Fig. 1. The conceptual model of the overall methodology.

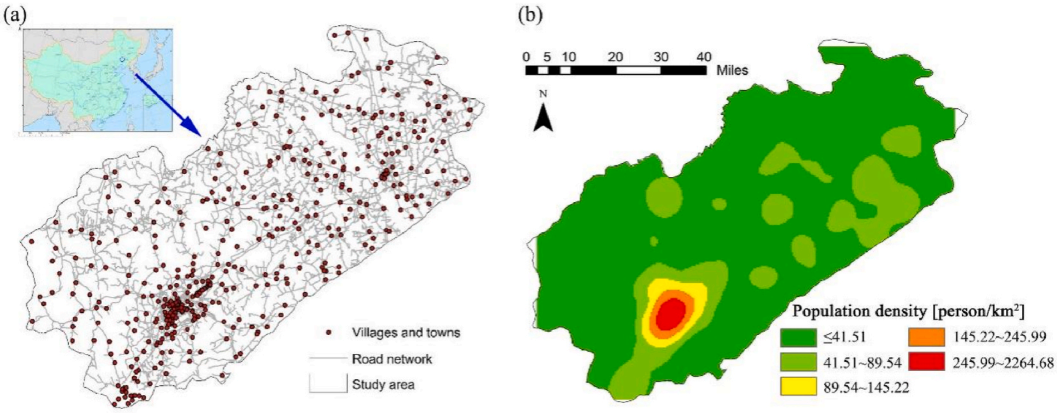

Fig. 2. (a) Villages and towns of the study area; (b) Population density distribution.

This section aims to determine the division indicators and methods of centralized and distributed layouts in the combined layout.

Considering the distribution of cities and villages and the uneven population distribution, this study used population density as the indicator to divide centralized and distributed layouts to determine the suitable layout mode for areas with different population densities. In the combined layout, the population density threshold (PDT) for the selection of distributed layout was first set. Areas with a population density higher than this value would adopt centralized construction; otherwise, distributed construction would be adopted.

2.1.1. Generation of clusters

The study's premise is to determine the range for calculating the population density, defined as the cluster area. The population density calculated in the following sections refers to the population density of the cluster area.

Biomass thermal power plants are subject to distance limitations for energy transmission, which inherently define their service scope [19]. Each plant serves a designated area, with the local residents forming the primary beneficiaries of its energy supply [20]. In our study, the service area of each thermal power plant is employed as the unit for calculating population density. Within this framework, a 'cluster' denotes the specific service area of an individual thermal power plant. According to Ref. [21], the optimal service radius for biomass thermal power plants is typically 10 km. Consequently, we have defined each cluster area as a 20km × 20 km rectangle.

The cluster area was generated by ArcGIS's "Create Fishing Net" tool. The population of the cluster area is the sum of the population of all villages and towns in the cluster area. The population of villages and towns comes from the statistical yearbook. The population density of the cluster area is calculated in Equation (1):

$$D_i = \sum_{n \in i} P_n \Big/ 400 \tag{1}$$

where, D_i is the population density of cluster i, person/km^2; i is the number of the cluster; P_n is the population of the village or town n, person; n is the number of villages and towns; 400 is the area of the cluster, km^2.

The energy demand in the cluster area is calculated in Equation (2):

$$EN_i = (p \times 0.0036 + h) \times \frac{\sum_{n \in i} P_n}{P_t} \tag{2}$$

Where, EN_i is the energy demand of the cluster area i, GJ; p is the total power consumption in the study area, kWh; h is the total heat consumption in the study area, GJ; P_t is the total population of the study area, person; 0.0036 is the conversion factor of kWh and GJ.

2.1.2. Setting of PDT

The population density of the cluster area in the study area was calculated and classified according to the "natural breaks classification" method, with the generated break as the critical value of centralized and distributed construction of each scheme. Where the population density of the cluster area was higher than the set PDT, the centralized construction mode was adopted; otherwise, the distributed construction mode was adopted.

2.1.3. Determination method of construction mode

Although small and medium/large cogenerations are centralized construction, there is still a large gap in power generation costs. Therefore, when determining the construction mode of the cluster area, the scale of cogeneration was also classified.

This study determined the construction mode according to the population density of the cluster area. The distributed construction mode was adopted when the population density was higher than the set PDT. Small cogeneration was adopted when the population density was higher than the set PDT, and the corresponding energy demand was lower than the minimum capacity of medium/large cogeneration (10 MW). Otherwise, medium/large-scale cogeneration was adopted.

2.2. Biomass resources of villages and towns

Calculating biomass resources in each village and town is the premise of the unified allocation of biomass resources. First, according to the land use map of the study area, farmland distribution was obtained, and biomass resource points were generated. Then the total biomass resources in the study area were allocated to all resource points to obtain the resource amount of each resource point. Finally, the biomass resource points and villages and towns were connected spatially. The resources of biomass resource points were gathered to the nearest village or town of each resource point to obtain the biomass resource amount of a certain village or town. The calculation formula of the resources of biomass resource points and village/town are shown in Equations (3) and (4):

$$b_m = \left(\sum_a Y_a \eta_a \alpha_a SC_a \right) \times \beta \times CV \times AL_m \times 10^{-8} \Big/ AL \tag{3}$$

Where, Y_a is the crop yield, t; a is the number of crops; η_a is the grass-grain ratio; α_a is the collectible utilization coefficient of crop straw; SC_a is the standard coal conversion coefficient of crop straw; β is the potential source utilization coefficient of crop straw; CV is the lower heating value of coal, KJ/kg; AL_m is the area of farmland covered by the resource point, km^2; 10^{-8} is the product of kg-t and KJ-10000GJ conversion factors; AL is the total agricultural land in the study area, km^2.

$$b_n = \sum_{m \in n} b_m \tag{4}$$

Where, b_n is the biomass resources of village/town n, GJ; b_m is the biomass resources of the resource point, GJ; m is the number of the resource point.

2.3. Spatial planning of biomass energy facility layout

2.3.1. Site selection of thermal power plants

The cluster areas of 20 km × 20 km were generated according to a thermal power plant's heat transfer threshold of 10 km. A thermal power plant was set up in each cluster area. The geometric center of the cluster was generated, and the "near analysis" was performed on the geometric center. The purpose of this step was to ensure that the thermal power plant was located on the road network. The geometric center was selected as the site location of the thermal power plant.

2.3.2. Site selection of energy service stations

The energy service station is a biomass straw processing plant. Biomass raw materials are transported from villages and towns to energy service stations, processed into straw block fuel, and then transported back to villages and towns. Considering the factors such as transportation costs and the prior research findings, this study adopted the mode of "one factory every two villages" for energy service stations [22].

2.3.3. Transportation of biomass raw materials

One of the core research objectives of this study was to determine the unified allocation method of biomass raw materials with both distributed and centralized construction schemes.

The unified allocation of biomass raw materials requires that the balance between biomass resources and the energy demand of thermal power plants should be kept as much as possible to ensure the lowest transportation cost with a specific transport distance threshold. In line with the existing literature [23], the transportation distance threshold was set at 60 km in this study to ensure the overall high-level utilization of raw materials while reasonably controlling the transportation cost.

In this study, the transportation planning of biomass raw materials was realized by "creating a new location allocation layer and maximizing the capacity-limited coverage."

The first step was to set up request points and facility points. The facility points represented the transporting destinations for biomass raw materials, composed of two parts: the thermal power plants in the cluster area with centralized construction and the villages and towns in the cluster area with distributed construction. The energy demand of the facility point is its capacity.

The request point represents the supply point of biomass raw materials: villages and towns with biomass resource potential greater than 0. When we execute the "Location Allocation" tool, we select the "maximizing capacity-limited coverage" method. The purpose is to transport biomass resources from "request points" to "facility points", but each "facility" has a fixed energy demand, so the amount of biomass resources transported to a facility cannot exceed the facility's energy demand. "Capacity of facility point" refers to the energy demand of the facility point (Unit: J). "Capacity of request point" refers to the amount of biomass resources at the request point, and the unit is also J.

However, there is a problem with this tool: the capacity of the request point cannot be set, and the default is 1. In order to solve this problem, we expanded the number of request points according to the resource amount of the request point. For example, if a request point has 10J resources, we manually add 9 points at the same location. In this way, they can together constitute 10J resources.

The second step was to set the attributes of the location assignment layer. In this step, “impedance” is a key parameter that needs to be set, which can be understood as the “difficulty” of going from one request point to one facility point on the map. In this study, the impedance was the length of the road, representing the transportation distance of biomass raw materials. The driving direction was from the request point to the facility point. Impedance interruption represented the threshold of transportation distance, which was set as 60 km. The number of facility points selected was the number of all facility points in the scheme. The default capacity was 1. Finally, the cumulative attribute was set to the length so that the transportation distance from each request point to the facility point could be directly obtained and the transportation costs could be calculated.

The third step was to run the current analysis, export the attribute table of the line layer generated by the analysis to Excel, and complete the subsequent calculations in Excel.

This method can not only complete the unified distribution of biomass raw materials under the combined centralized and distributed layout but also simplify the calculation of biomass transportation. This is because each point represents the same amount of biomass resources after expanding the number of villages and towns based on the amount of resources. The attribute table of the generated line layer can be directly summarized and calculated to obtain the total amount of biological resources transported to each facility point.

2.4. Investment cost of the scheme

The construction scheme includes centralized and distributed construction; thus, the investment costs of these two parts need to be calculated separately. The literature review shows that the scheme costs include investment and operation costs [24]. The investment costs generally include the generator set of the thermal power plant, plant construction, and heat transfer and transmission costs. The operation costs generally include power generation, transportation, biomass raw material storage, and equipment maintenance costs.

The costs involved in this study are shown in Table 2. This study focused on determining the appropriate construction mode for different population densities. The storage cost of biomass raw materials/straw block fuel does not affect the research results. Therefore, it was not considered in this study.

2.4.1. Transportation cost

In this study, the transportation cost of biomass raw materials in the construction scheme refers to the transportation cost of biomass raw materials from the request point to the facility point and the transportation cost of straw block fuel from the energy service station back to the request point.

It is essential to note that the transportation cost in this study did not include the cost of transportation from fields to villages and towns. The rationale behind this exclusion is that this cost associated with both centralized and distributed construction models are identical [25]. Consequently, this cost does not influence the decision-making process between centralized and distributed construction models. In our calculations of the total transportation costs for different schemes, this cost is thus treated as a constant and is not separately computed. While this may result in a minor underestimation of the total transportation costs, it does not affect the resutlts of our study.

Since this study used the number of request points to represent the resource potential, obtaining the unit resource represented by each request point was necessary before calculating the transportation cost. The unit resource was calculated by the greatest common divisor of the total potential of biomass resources and the energy supply of thermal power plants.

The transportation cost of the construction scheme is calculated according to Equation (5):

$$C_t = \sum_q DIS_q \times t_0 \times c_1 + \sum_r DIS_r \times t_r' \times c_2 \tag{5}$$

Where, C_t is the transportation cost of the construction scheme, yuan; DIS_q is the transportation distance from request point q to the corresponding facility point, km; q is the serial number of the request point; c_1 is the unit transportation cost of biomass raw materials, yuan/km; t_0 is the unit resource represented by a request point, t; DIS_r is the transportation distance of straw block fuel from energy service stations to villages and towns, km; t_r' is the weight of straw block fuel, t; r is the serial number of straw block fuel to be

Table 2
The investments in this study.

Construction mode	Investment
Centralized construction layout	Project cost of thermal power plant Transportation cost of biomass raw materials Power generation cost of thermal power plant Maintenance cost of thermal power plant Heat transfer and transmission cost
Distribution construction layout	Project cost of energy service station Transportation cost of biomass raw materials Transportation cost of straw block fuel Biomass boiler and maintenance cost

transported; c_2 is the unit transportation cost of straw block fuel, yuan/km.

2.4.2. Project investment cost of the thermal power plant

This includes project investment in thermal power plant equipment, infrastructure, and plant. According to the scale of the thermal power plant, the calculation formula of the thermal power plant project investment is shown in Equation (6):

$$C_e = e_s \times u_s + e_b \times u_b \tag{6}$$

Where, C_e is the project investment in a thermal power plant, yuan; e_s is the project investment of each small thermal power plant, yuan; e_b is the project investment of each medium/large thermal power plant, yuan; u_s is the number of small thermal power plants; u_b is the number of medium/large thermal power plants.

2.4.3. Power generation cost of the thermal power plant

The power generation cost of the thermal power plant is calculated according to the energy supply. As the number of villages and towns expands, the energy supply of each thermal power plant is the number of request points transported to the thermal power plant. The power generation cost of the thermal power plant is calculated according to Equation (7):

$$C_p = \begin{cases} U_1 \times E \times 277.78, E < E_0 \; minimum\ power\ generation \\ U_2 \times E \times 277.78, E \geq E_0 \; minimum\ power\ generation \end{cases} \tag{7}$$

Where, C_p is the power generation cost of the thermal power plant, yuan; E is the energy supply of the thermal power plant, GJ; U_1 is the unit power generation cost of small cogeneration, yuan/kWh; U_2 is the unit power generation cost of medium/large cogeneration, yuan/kWh; E_0 is the minimum annual power generation required for medium/large cogeneration, kWh; 277.78 is the conversion factor between GJ and kWh.

2.4.4. Maintenance cost of thermal power plant

The maintenance cost of the thermal power plant is calculated according to Equation (8):

$$C_m = \begin{cases} \gamma \times E \times 277.78, E < E_0 \; minimum\ power\ generation \\ \beta \times C_p, E \geq E_0 \; minimum\ power\ generation \end{cases} \tag{8}$$

Where, C_m is the maintenance cost of the thermal power plant, yuan; β is the proportion of maintenance cost in power generation cost of medium/large cogeneration, % (2 %); γ is the maintenance cost of unit power generation of small cogeneration, yuan/kWh (0.07).

2.4.5. Heat transfer and transmission costs of the thermal power plant

Centralized construction also involves additional heat transfer and transmission costs, which were not the focus of this study. Thus, we calculated the proportion of this part of the cost to the total cost of power generation according to Equation (9):

$$C_h = PR \times C_p \tag{9}$$

Where, C_h is the heat transfer and transmission cost of the thermal power plant, yuan; PR is the proportion of heat transfer and transmission cost in total power generation cost, %; C_p is the power generation cost of the thermal power plant, yuan.

2.4.6. Cost of energy service station

The cost of an energy service station includes the acquisition cost of equipment, infrastructure cost, and plant construction cost. The cost of energy service station is calculated according to Equation (10):

$$C_s = \sum_b (Num_b \times c_a + c_b) \tag{10}$$

Where, C_s is the cost of the energy service station, yuan; b is the number of the energy service station; Num_b is the number of equipment to be purchased for the energy service station; c_a is the cost of straw processing equipment, yuan; c_b is the infrastructure cost and plant construction cost, yuan.

2.4.7. Equipment cost of distributed construction

This study used household biomass boilers, widely used in the study area. The equipment cost for distributed construction is calculated according to Equation (11):

$$C_{bp} = P_n \times \left(c_b + c_{hs} + c_p\right) / ph \tag{11}$$

Where, C_{bp} is the equipment cost of distributed construction, yuan; P_n is the population of villages and towns n, person; ph is the average population per household, person/household; c_b is the price of a household biomass boiler, yuan; c_{hs} is the price of the heat sink, yuan; c_p is the price of a water supply pipeline, yuan.

2.4.8. Total investment cost of the scheme

The total cost of the construction scheme consists of the above costs and some fixed costs, as shown in Equation (12). Fixed cost refers to the cost that does not change with the construction method set in this study, including the cost of straw processing.

$$C = C_e + C_t + C_p + C_m + C_h + C_s + C_{bp} + T \times c_{st} \tag{12}$$

Where C is the total cost of the construction scheme, yuan; T is the total amount of straw processing, t; c_{st} is the cost of straw processing, yuan/t.

2.5. Energy surplus coefficient of the scheme

The energy surplus coefficient refers to the extent to which biomass energy demand in the study area is met. In different schemes, the proportions of centralized and distributed construction were different; thus, the corresponding energy surplus coefficients may differ. According to the research method adopted in this study, the number of lines obtained after the "location allocation with capacity limit" represented the number of request points with a destination. Then, the amount of resources used for energy can be obtained by multiplying the number of lines and the unit amount of resources at the request point, as shown in Equation (13).

$$\varphi = N_q \times t_0 / (p + h) \tag{13}$$

where φ is the energy surplus coefficient of the construction scheme, %; N_q is the number of lines after the solving of "location allocation with capacity limit".

This study also calculated the energy surplus coefficients of the cluster areas in each scheme, as shown in Equation (14).

$$\varphi_i = \left(\sum_{n \in i} N_q^n \times t_0 + N_q^i \times t_0 \right) \Big/ EN_i \tag{14}$$

where, φ_i is the energy surplus coefficient of cluster i, %; N_q^n is the number of lines allocated to villages and towns belonging to cluster area i after the solution of "location allocation with capacity limit"; N_q^i is the number of lines allocated to thermal power plants in cluster area i in the "location allocation with capacity limit" solution.

2.6. Parameters and sources

2.6.1. Study area parameters and their sources

The study area's total electricity and heat consumptions are 634.88 million kWh and 2.281 million GJ, respectively [26]. Its population is 1.843 million, the detailed population information is shown in the Supplementary Material [27].

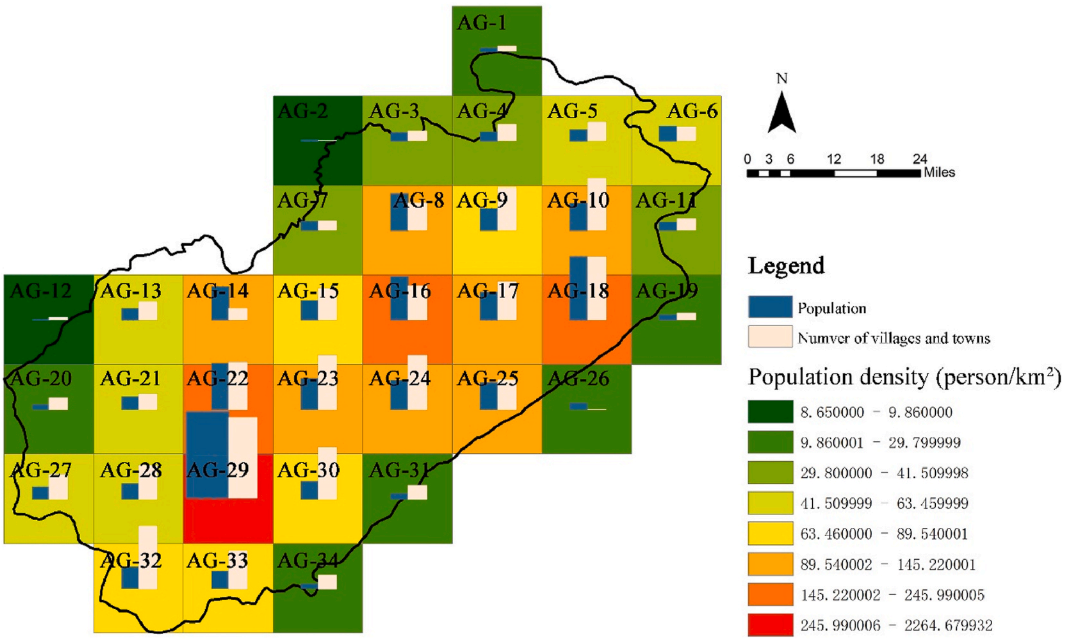

Fig. 3. The cluster area.

2.6.2. Biomass raw material parameters and their sources

The main crop types and yields in the study area were determined according to the statistical yearbook [27]. The crop-related data are shown in the Supplementary Material. The grass-to-grain ratio and the collectible utilization coefficient were derived from relevant literature [28]. The possible energy utilization coefficient of straw was determined as 0.444 [18].

2.6.3. Cost parameters and sources

According to our calculation, the unit resource represented by each request point was 0.08 GJ. The detailed data are shown in the Supplementary Material. The cost of straw processing includes processing oil consumption and equipment maintenance costs, and the straw is broken by the cheaper motor crusher.

3. Results

3.1 Schemes with different PDTs.

Each population density threshold (PDT) corresponds to a planning scheme. According to section 2, each scheme includes: (1) the construction mode of each cluster (centralized/distributed); (2) the number and location of biomass energy facilities; (3) the unified deployment and transportation route of biomass raw materials; (3) evaluation results of energy surplus coefficient and investment cost.

The clusters and the construction schemes are shown in Figs. 3 and 4. With a larger PDT, the clusters with centralized layouts

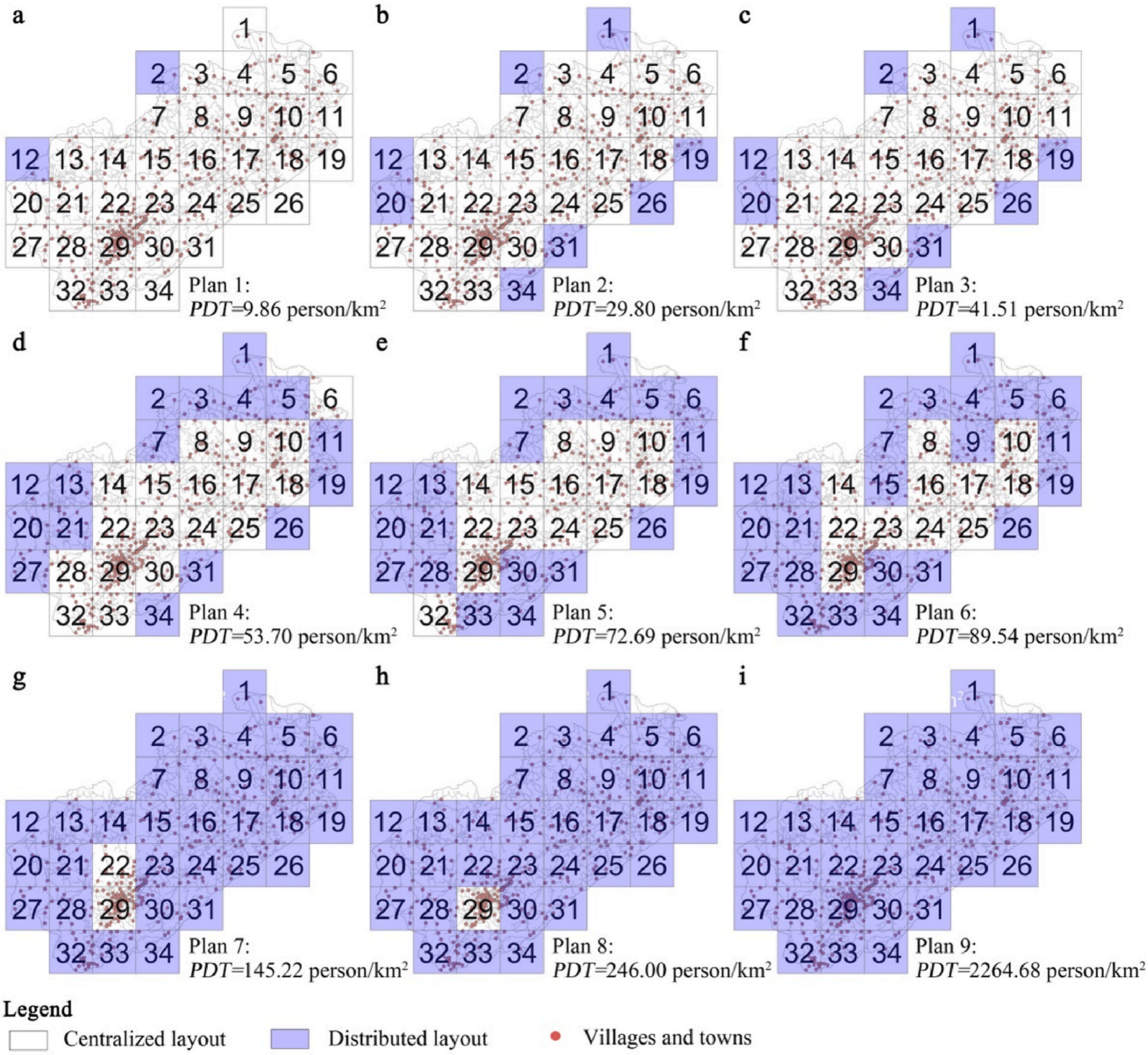

Fig. 4. The higher the population density threshold (PDT), the fewer centralized layouts and the more distributed layouts.

decreased, and those with distributed layouts increased. Plans 1–4 were mainly centralized layouts and Plans 5–9 were mainly distributed layouts.

All cluster areas were numbered. It can be seen that the highest population density was in cluster area 29 (shown in the Supplementary Material), which adopted the centralized layout in the eight schemes.

3.1. Spatial planning results of the scheme

The location assignment layers with different PDTs generated by ArcGIS are shown in Fig. 5. The request points were biomass resource points. Each point represented the biomass resource amount per unit capacity. The facility points were thermal power plants, villages, and towns using distributed construction.

In different schemes, the number and location of request points remained unchanged, totaling 22,261. As the PDT increased, the number of facilities went up. This was because there were more villages and towns with the distributed construction mode. The line represents the correspondence between request points and facility points.

As the PDT increased, there were more facility points, and the line's destination became much more complex. However, in all schemes, it can still be found that, within the allowable range of impedance, most of the destinations of the lines were still the most densely populated areas in the southwest, that is, the No. 29 cluster area. This was because the population here was the largest, and the

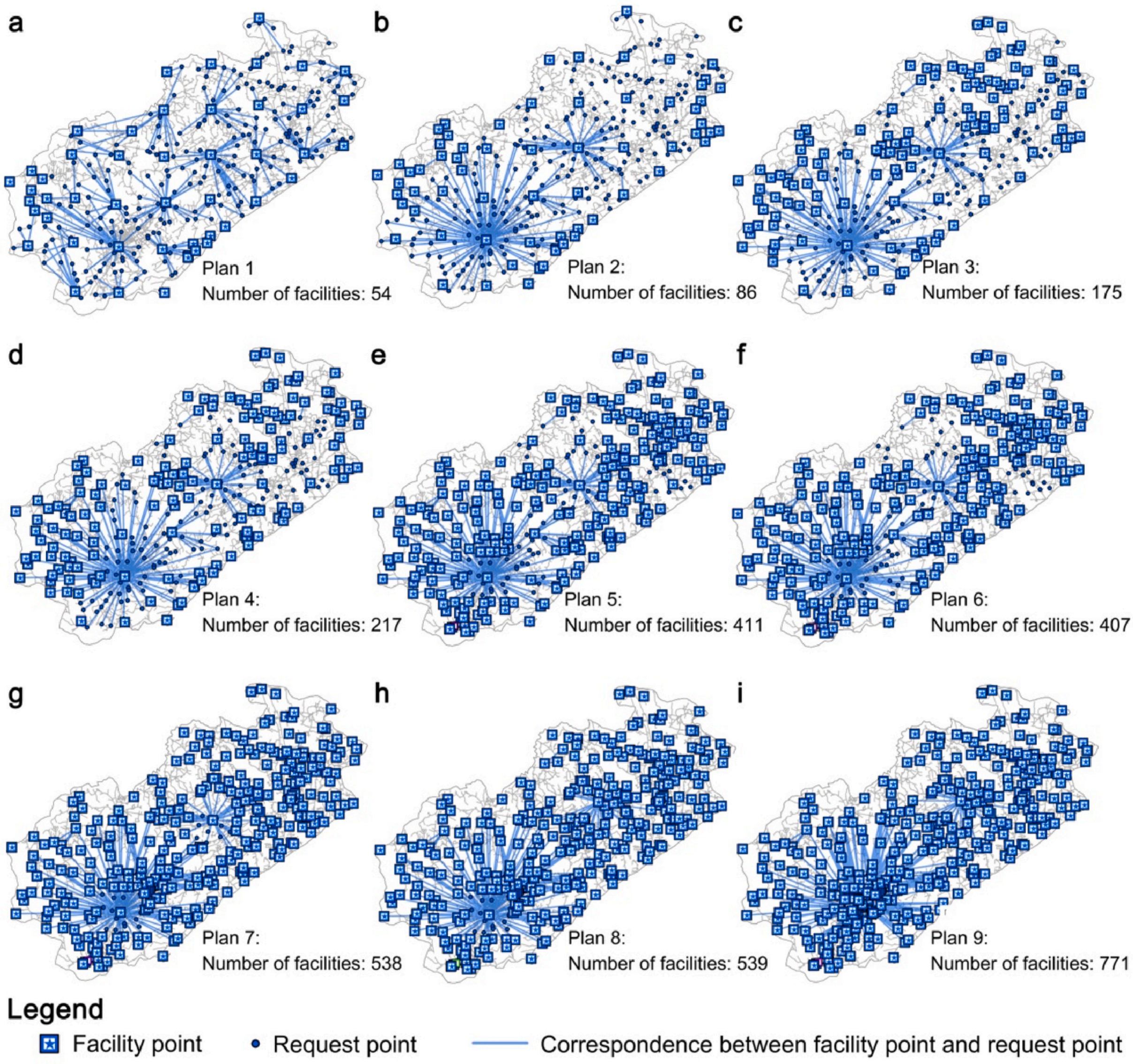

Fig. 5. Location allocation of 9 plans with different population density thresholds (PDTs).

energy demand was the largest.

With the increase of PDT, the number of facility points increased gradually (Fig. 6). This was because the facility points included two parts. The first was the thermal power plant in the cluster area of the centralized layout, and the second was the village points in the cluster area of the distributed layout. As the conditions for the centralized layout rose higher, the number of clusters that did not meet the conditions for centralized construction increased, and the number of villages and towns with the distributed layout increased (Fig. 6). From Fig. 6, most of the facilities in the scheme were villages or towns, instead of thermal power plants. Although the number of villages and towns was large, their energy demand was far lower than that of thermal power plants. This was because the energy demand of thermal power plants was the sum of the energy demand of villages and towns in the cluster area.

3.2. Energy supply analysis of the scheme

There was no significant difference in the energy surplus coefficient of each scheme. The highest value of Plan 9 (42.40 %) was only 4.01 % higher than the lowest value of Plan 6 (38.39 %). This revealed that when analyzing the advantages and disadvantages of schemes, we can focus on comparing their investment costs.

We also calculated the centralized/distributed energy supply ratio (shown in the Supplementary Material). For Plan 8, where only one cluster area adopted the centralized energy supply, the centralized energy supply ratio was as high as 58.04 %. This indicated that a centralized energy supply was the main way as long as there was a thermal power plant. This was due to the large population density of the cluster area of centralized construction, which was also the main energy demand area of the study area.

The energy surplus coefficient of each cluster is shown in Fig. 7. As the color became darker, the degree of energy self-sufficiency was higher. The energy surplus coefficient was different in different schemes for the same cluster area. The degree of energy self-sufficiency of cluster No. 29 was not ideal in all schemes because it was at the center of the study area and had a large population. Some cluster areas could also achieve energy self-sufficiency in all schemes, such as clusters 7 and 8.

Fig. 8 is a stacked bar chart of all costs included in the investment cost of the scheme. The total cost of Plan 1 was the highest, which was 3320.42 million yuan. The total cost of Plan 7 was the lowest, 665.23 million yuan. The total cost of Plan 7 was only 20.03 % of Plan 1, while their energy surplus coefficients were only 0.02 % different.

3.3. Cost analysis of the scheme

In the centralized layout schemes (Plans 1–4), the project cost of the thermal power plant was the main component. With the reduction of the number of thermal power plants, the proportion of these costs in the total cost gradually decreased. The second was the power generation cost of the thermal power plant, which had no significant difference in the different schemes. This was because the energy demand was constant.

Despite the distributed layout, the thermal power plant project cost of Plan 5 and Plan 6 still accounted for the main part. However, starting from Plan 7, the cost of biomass boilers and their maintenance began to increase. In Plan 9, which was entirely distributed, the proportion of biomass boiler and maintenance costs were extremely high.

From the cost composition of different layout schemes, the combined layout is more reasonable and can effectively reduce the investment cost of a single layout mode. According to the change of centralized and distributed proportions (Fig. 8), the irrationality of a purely centralized layout or purely distributed layout lies in the expensive energy facility cost. The construction cost of the thermal power plant is high, and the thermal power plant project investment in the purely centralized layout accounts for 94.73 % of the total investment. However, the number of biomass boilers in the purely distributed layout is related to the number of households. It is exceptionally high, which also leads to high equipment acquisition costs. In addition, the 'Plain maintenance costs' is not explicitly depicted due to its significantly lower magnitude in comparison to other costs. This omission does not imply that the cost is zero. Instead, it reflects its relative insignificance in the overall cost structure. Therefore, combining centralized and distributed layouts is the best choice for biomass energy facility planning.

The centralized and distributed construction costs in the total cost of the scheme are classified and calculated (Fig. 9). It can be found that with more distributed construction, the cost of distributed construction increased slowly at first and then increased sharply

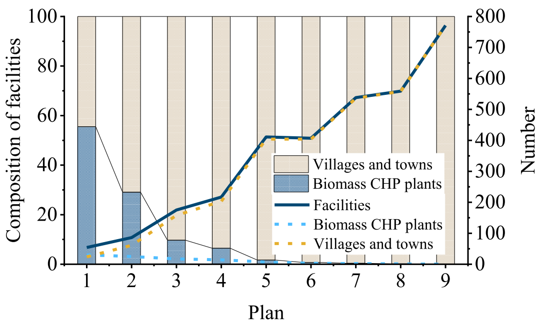

Fig. 6. Composition of facilities.

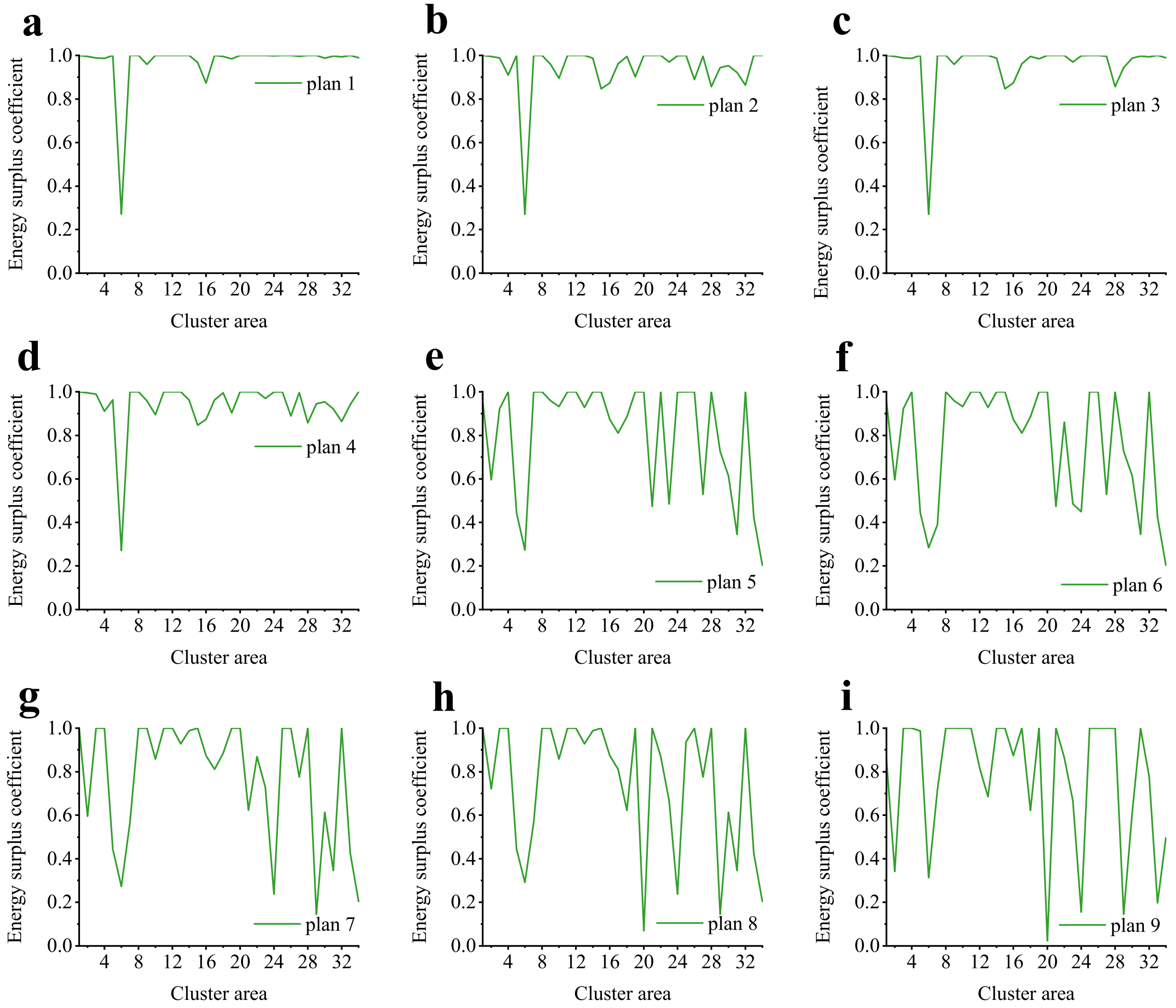

Fig. 7. Energy surplus coefficient of the cluster areas of the 9 plans.

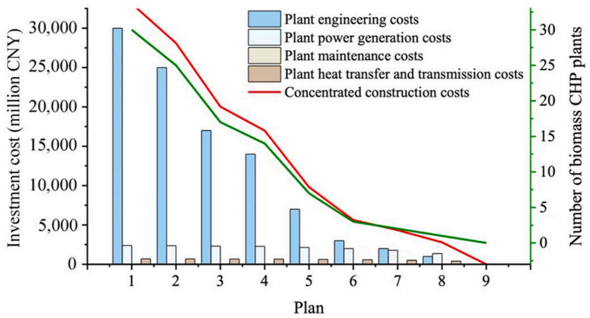

Fig. 8. Composition of the total investment of the nine plans.

after Plan 7. This was due to the soaring cost of biomass boilers caused by the population explosion.

The huge difference in the total cost of these schemes confirms the necessity of reasonably planning the combined centralized/distributed construction scheme to reduce the investment cost. Determining the population density boundary of centralized/distributed construction can provide essential data support for the planning schemes.

The determination of the optimal PDT represents a nuanced balance between energy efficiency and economic viability. Our objective is to minimize investment costs while maintaining a high energy surplus coefficient. As delineated in Section 3.3, the variation in total energy surplus coefficients across the proposed schemes is marginal, with a maximum range of only 4.01 %. Consequently, the pivotal factor in identifying the optimal PDT is the comparative analysis of investment costs. Plan 7, as illustrated in Fig. 9, emerges as the most cost-effective (Fig. 9), corresponding to a PDT of 145.22 persons/km^2. This finding substantiates the rationale for setting the distributed/centralized construction boundary near 145 persons/km^2. Under this threshold, a distributed layout is favored, while a centralized layout is preferable above it. Adopting this PDT enables the most economical allocation of resources, without compromising the efficiency of biomass raw material utilization and energy self-sufficiency.

4. Discussion

The planning method and analysis based on the combined layout showed different combinations of a single large facility and multiple small facilities. It was found that the combined layout can effectively reduce investment costs compared with the single centralized/distributed layout. Moreover, the cost reduction capability was related to the location and proportion of the centralized/distributed layout. This was because the combined layout can apply the centralized and distributed layout to the most appropriate location to maximize strengths and circumvent weaknesses. Although the energy efficiency of the centralized system was higher than that of the distributed system [29], the transportation distance of the distributed system was shorter, which meant lower transportation cost, energy consumption, and carbon emission intensity [30]. The saved fuel consumption for raw material transportation can offset the lower energy efficiency of the distributed system to a certain extent.

The determination of delineation methods for centralized and decentralized layouts poses the most challenging issue in biomass energy facility spatial planning. Most prior relevant studies were qualitative analyses; thus, it was difficult to find solid data support. For example, previous research studied when to choose a centralized/distributed bioenergy system and believed that specific analysis should be made for each region according to the situation [13]. However, the economic and environmental performance data used in this study were obtained through interviews, and only qualitative analysis was conducted. This study's principal innovation lies in establishing a quantitative population density threshold (PDT) for selecting distributed layouts in biomass energy facility planning. Unlike previous approaches that predominantly relied on qualitative analysis, this research provides definitive, data-driven boundaries between distributed and centralized layout choices. This quantitative framework offers clear, empirical guidance for strategic decision-making in biomass energy facility layout planning.

Moreover, this study established a general rule for the hybrid layout of biomass energy facilities, which applies to the layout planning of biomass energy systems in regions with similar conditions worldwide. The "similar conditions" mentioned earlier encompass two key criteria: Firstly, the biomass resource potential should be comparable to, or exceed, that of this study's case. Secondly, the resource-to-population proximity should not be excessively distant. Areas with insufficient biomass potential do not merit development, irrespective of their population density. On the other hand, regions where biomass resources are located far from populated areas incur higher transport costs, necessitating a distributed layout. In such scenarios, the PDT for a distributed layout is expected to exceed 145 person/km^2.

This study also has certain limitations. First, when comparing the centralized and distributed systems, differences in social preferences, such as farmers' satisfaction, family members' workload (whether to save cooking time and raw materials), and system maintenance, have not been considered for the time being [31]. The reason for this is that the focus of this study was to quantitatively analyze the benefits of the layout from the perspectives of energy and economy, maximize the energy surplus coefficient, and minimize the investment cost from the perspective of spatial layout. Moreover, the above factors did not affect the spatial layout of the two systems.

Second, this study identified the population density threshold for choosing centralized and distributed layouts. However, these two layout types can be further categorized. For instance, centralized layout can be classified into large-scale, medium-scale, and small-scale configurations, and this study has not yet pinpointed precise population density limits for these more nuanced subdivisions. Such differentiation remains an area for future investigation, promising to refine our understanding of optimal layout modes in relation to population density.

Third, considering residents' consumption level, this study considered ordinary biomass boilers. Compared with the improved biomass boiler, the boiler discussed was cheap and widely used. However, it also aggravated household pollution. The use of improved biomass boilers can effectively alleviate this problem.

Based on the above limitations, future studies can be carried out in the following directions: (1) quantitative research on how social preferences affect centralized/distributed selection; (2) more technical bases for centralized/distributed layout, such as improved biomass boilers; (3) adjustment of the scale of cogeneration of biomass in the centralized layout to provide a clearer layout strategy.

5. Conclusions

This study conducted an energy-economy comparison of 9 combined layout schemes of biomass energy facilities, which were generated based on different division index values of centralized and distributed layouts. According to the results, the following conclusions can be drawn.

1) The construction of two biomass thermal power plants (Plan 7) in a prefecture-level city was the most cost-effective biomass energy facility layout plan. The investment cost of this layout was 3.56%–79.97 % lower than that of other layouts, while it can reach almost the same level of energy supply (only 0.02 %).

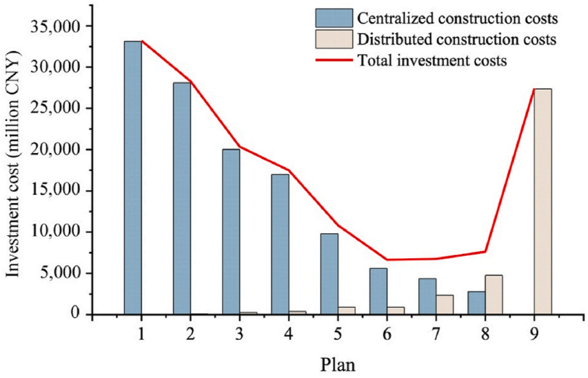

Fig. 9. Distributed and centralized construction costs in the total investment.

2) 145 persons/km^2 was the optimal PDT for the distributed layout. When the population density was lower than 145 person/km^2, distributed construction should be adopted, and the household biomass boiler was a more economical choice. When the population density was higher than 145 person/km^2, biomass boilers were unsuitable. The construction of a thermal power plant can significantly reduce the purchase cost of biomass energy facilities (2403.9 million CNY – 25,000.23 million CNY).
3) Compared with the single layout mode, the combined layout can greatly save investment costs without reducing energy utilization. Compared with the centralized and distributed layout, the optimally combined layout scheme can save 20,660.31 million CNY and 30,429.26 million CNY in the investment cost, respectively.

Data availability statement

The data underlying this article cannot be shared publicly due to privacy reasons.

CRediT authorship contribution statement

Chenshuo Ma: Writing – original draft, Visualization, Software, Methodology. **Yifei Zhang:** Writing – review & editing, Funding acquisition. **Xueqiang Wang:** Writing – review & editing. **Chanyun Li:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e29661.

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