Study on optimal allocation of rural integrated energy system with biogas and photovoltaic

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Abstract. The development of rural energy is directly related to the process of China's energy reform. At present, the energy structure of villages and towns in China is still unreasonable. It is urgent to build a rural energy station integrating the characteristics of rural industrial development to meet the demand of production and living load. In this paper, considering that the rural areas mainly rely on natural production economy and have the advantages of clean energy endowment, through the establishment of a rural comprehensive energy system containing biogas and photovoltaic, the model seeks to maximize the comprehensive benefits including investment cost and expected income, optimize the allocation of energy device capacity, and verify its feasibility with practical cases, so as to provide reference for future rural comprehensive energy planning and green industry Economic upgrading provides theoretical and technical support.

1. Introduction

China's rural areas are vast, with natural and clean energy endowment advantages, mainly including biomass energy, solar energy, wind energy, etc. In recent years, the cost of China's photovoltaic industry has been continuously reduced, and the capacity has increased rapidly[1]. Photovoltaic plays an important role in the future rural energy construction. In addition, most of China's rural areas are dominated by planting and breeding, with rich biomass energy. Straw and livestock manure produced by agriculture, forestry, animal husbandry and sideline fisheries can be used as biogas raw materials. The biomass energy represented by biogas is the key energy to solve the energy consumption conflicts in rural areas and promote the rational utilization of livestock and poultry manure [2-4]. However, in the current rural energy system, the proportion of electricity, natural gas and renewable energy consumption is low, the phenomenon of energy waste is serious, and the quality of energy consumption is poor [5].

At present, there is a certain research foundation for the planning of integrated energy system such as intelligent community and industrial park. For example, the industrial park planning considering the cooperation of photovoltaic cells and hybrid energy storage [6]; the distribution network and gas pipeline planning with CCHP system as the electricity gas coupling hub [7]; the source grid load storage multi link flexible configuration model considering the investment cost and comprehensive benefits of multiple stakeholders [8]; and the capacity optimization configuration model of the combined cooling,
heating and power storage system [9-10]. The research on coupling modeling of rural comprehensive energy is less in the above literature. The next step should be to optimize the interactive network formed by different energy sources in rural energy system, such as electricity, natural gas and renewable energy, in combination with the actual energy endowment and demand in rural areas, so as to promote the green development of rural economy from the integration of agricultural production and living and available clean energy.

Considering that the rural areas mainly rely on natural production economy and have the advantages of clean energy endowment, combined with photovoltaic and biogas, a rural comprehensive energy system including power, natural gas, biomass energy and photovoltaic was established to meet the rural load demand. The model pursues the maximization of comprehensive benefits including investment cost and expected income, optimizes the allocation of energy device capacity, and verifies its feasibility with examples. It provides a theoretical reference for the future rural energy planning to establish a characteristic comprehensive energy system with electricity as the main component and combining with green industry.

2. Rural integrated energy system

On the basis of meeting the basic needs of rural energy, this paper increases the rural renewable energy development characteristic industry in China, and proposes that the rural comprehensive energy system, which is based on the power grid, includes biomass energy, photovoltaic, natural gas, adding cold and hot energy storage links, and integrating government policies, energy endowment and farmers' needs, can be used as a tool for policy planning to solve the rural problems Single energy consumption and low utilization rate. The rural energy system architecture is shown in Figure 1.

Rural comprehensive energy station includes three units: energy supply, energy conversion and energy demand. Natural gas, biogas, photovoltaic and power grid are combined to realize power supply, photovoltaic power generation fills the gap of power supply and demand balance, and surplus power is connected to the grid to increase power generation income; CCHP system is coupled with power grid to supply cooling and heating load; biogas project is combined with breeding and planting industry, livestock manure and straw are used as biogas raw materials, and biogas is used to provide power and heat energy for breeding industry by means of cogeneration Organic fertilizer is provided by crops, and surplus electricity is connected to the Internet, so as to increase rural comprehensive income in many ways.

Figure 1. Structure chart of integrated rural energy station.
3. Optimal allocation method of rural integrated energy system with biogas and photovoltaic

3.1. Objective function

In this paper, the investment cost and expected income of the construction of rural comprehensive energy system are considered, and the purpose is to maximize the comprehensive benefit of annual operation.

$$C_i = \sum_{i=1}^{n} \lambda_i \left(1-\gamma \frac{\lambda_i}{\Lambda_i}\right) (C_{b_{-PV}}+C_{b_{-B}}) - C_{inv} - C_{op} - C_e$$

Where $C_i$ is the annual operation comprehensive benefit, yuan; $C_{b_{-PV}}$ is the net income of village level photovoltaic power station, yuan; $C_{b_{-B}}$ is the net income of biogas recycling agriculture, yuan; $C_{inv}$ is the initial investment cost of the unit, yuan; $C_{op}$ is the annual operation and maintenance cost, yuan; $C_e$ is the annual energy purchase cost, yuan; $\gamma$ is the capital recovery rate, which is 10%; $\lambda_i$ is the present value coefficient of year $i$.

Assuming that the operating life of the photovoltaic power station is 20 years, the net income in the planning period is as follows:

$$C_{b_{-PV}} = \sum_{i=1}^{n} \left( C_{PV_{-g,i}} - C_{PV_{-c,i}} \right)$$

$$= \sum_{i=1}^{n} \left( \sum_{j=1}^{m} P_{PV_{-s,ij}} \times W_e + \sum_{j=1}^{m} P_{PV_{-j}} \times W_e + \sum_{g=1}^{h} \sum_{m=1}^{l} W_e + C_{g} - \sum_{k=1}^{i} M_{k} - 50\% k_{i} \times P_{PV} (1+r_{i}) \right)$$

Where $n$ is the total planning period, which is 20 years; $C_{PV_{-g,i}}, C_{PV_{-c,i}}$ are the total income and total expenditure of photovoltaic power station in the year $i$, yuan. $C_{g}$ is the income from land lease expenses in the year $i$, yuan; $W_e$ is the increase of employment wage in m-th month, yuan; $P_{PV}$ is the configuration capacity of photovoltaic power station, kW; $g$ is the number of employees, $k$ is the proportional coefficient. The annual total income of photovoltaic power station is the sum of electricity sales income, generation subsidy, employment income and land lease cost. $M_{k}$ is the cost of the k-th operation and maintenance in the i year, yuan; $C_{inv}$ is the total investment cost of photovoltaic power station project, which is related to the capacity of photovoltaic power station, yuan; $r_{i}$ is the loan interest in i year; $k_{i}$ is the ratio between the total investment and the capacity of photovoltaic power station.

The calculation period of net income of biogas recycling agriculture is 20 years, and its calculation method of net income is as follows:

$$C_{b_{-B}} = \sum_{i=1}^{n} \left( C_{B_{-g,i}} - C_{B_{-c,i}} \right)$$

$$= \sum_{i=1}^{n} \left( \sum_{j=1}^{m} P_{B_{-s,ij}} \times P_{B_{-j}} \times W_m + \sum_{i=1}^{m} V_B \times (Q_B \times K_i \times C_f) + C_1 + C_2 + C_3 - V_B \times \left( k_2 + \sum_{i=1}^{n} k_3 + k_4 \right) \right)$$

Where $C_{B_{-g,i}}, C_{B_{-c,i}}$ are the total income and total investment of the year, yuan; $W_m$ is the on grid price of biogas power generation, yuan / (kWh); $V_B$ is the capacity of biogas digester, m$^3$; $Q_B$ is the
amount of biogas fertilizer produced per unit volume of biogas, kg; \( K_1 \) is the content of nitrogen, phosphorus and potassium in unit biogas fertilizer, kg; \( C_f \) is the price of nitrogen, phosphorus, potassium fertilizer, here take the same value, yuan / kg; \( C_1 \) is the energy saving income generated by biogas cogeneration, converted into saved standard coal, kg; \( C_2 \) is the additional income of agricultural products brought by the farm, yuan; \( C_3 \) is the income from applying biogas fertilizer to increase crop income, yuan; \( k_2, k_3, k_4 \) are the ratios of biogas digester capacity to initial construction cost, annual daily management and maintenance cost of biogas digester, and replacement cost of aged biogas digester.

\[
C_{\text{inv}} = K_{GT} P_{GT} + K_{GB} P_{GB} + K_{EB} P_{EB} + K_{EC} P_{EC} + K_{AC} P_{AC} 
\]

\[
C_{cp} = K_{GT} \sum_{i=1}^{n} \sum_{j=1}^{24} P_{GT,i,j} + K_{GB} \sum_{i=1}^{n} \sum_{j=1}^{24} H_{GB,i,j} + K_{EB} \sum_{i=1}^{n} \sum_{j=1}^{24} H_{EB,i,j} + K_{EC} \sum_{i=1}^{n} \sum_{j=1}^{24} C_{EC,i,j} + K_{AC} \sum_{i=1}^{n} \sum_{j=1}^{24} C_{AC,i,j} 
\]

\[
C_C = E_G \sum_{i=1}^{n} \sum_{j=1}^{24} P_{G,i,j} + E_G \sum_{i=1}^{n} \sum_{j=1}^{24} (G_{GT,i,j} + G_{GB,i,j}) 
\]

In the formula, \( K_{GT}, K_{GB}, K_{EB}, K_{EC}, K_{AC}, P_{GT}, P_{GB}, P_{EB}, P_{EC}, P_{AC}, K_{GT}, K_{GB}, K_{EB}, K_{EC}, K_{AC} \) respectively refer to investment cost, configuration capacity and operation and maintenance cost of gas turbine, gas-fired boiler, electric boiler, electric refrigerator and absorption chiller; \( E_G \) is the electricity purchase price, yuan /(kW h); \( E_G \) is the price of natural gas, yuan /kWh.

3.2. Constraints

3.2.1. System energy balance constraints.

The energy balance constraint of rural integrated energy system includes electricity, heat and cold.

\[
P_{PV,s,i,j} + P_{B,s,i,j} = P_{PV,i,j} + P_{B,i,j} + P_{G,i,j} - P_{GB,i,j} - P_{EB,i,j} - P_{AC,i,j} - P_{EC,i,j} - P_{L,i,j} 
\]

\[
H_{GB,i,j} + H_{EB,i,j} + H_{EC,i,j} + H_{d,i,j} - H_{ch,i,j} = 0 
\]

\[
C_{AC,i,j} + C_{EC,i,j} + C_{d,i,j} - C_{ch,i,j} = 0 
\]

3.2.2. Equipment operation constraints

\[
\begin{align*}
P_{\text{min}} & \leq P_{GT,i,j} \leq P_{\text{max}} \\
H_{\text{min}} & \leq H_{GB,i,j} \leq H_{\text{max}} \\
C_{\text{min}} & \leq C_{EC,i,j} \leq C_{\text{max}} \\
H_{\text{min}} & \leq H_{EB,i,j} \leq H_{\text{max}} \\
C_{\text{min}} & \leq C_{AC,i,j} \leq C_{\text{max}} \\
0 & \leq P_{G,i,j} \leq P_{\text{max}} 
\end{align*}
\]

Where \( P_{\text{max}}, P_{\text{min}}, H_{\text{max}}, H_{\text{min}}, C_{\text{max}}, C_{\text{min}}, H_{\text{max}}, H_{\text{min}}, C_{\text{max}}, C_{\text{min}} \) are the upper and lower limits of the power of gas turbine, gas boiler, electric refrigerator, electric boiler and absorption refrigerator respectively; \( P_{\text{max}} \) is the upper limit of power purchase from the grid.
4. The example analysis

4.1. The basic data.
In this paper, A rural area C in northern China is selected as the specific research object to verify the validity and practicability of the model. C village is located in the northwest of China with plenty of sunshine. It is mainly engaged in agricultural production, including the cattle farm and the matching crop growing area. According to the biogas production potential, it can be known that cattle manure can produce 35m³ biogas per ton, 246m³ biogas per ton of crop straw, and the daily maximum of biogas is about 2000m³. Biogas is transformed into electricity and heat energy by cogeneration of heat and power. 1m³ biogas can generate electricity of about 1.8kwh by domestic internal combustion generator set of biogas, and heat energy of about 2.4kwh can be recovered by waste heat recovery unit. The total daily electricity consumption of the breeding plant and planting industry in Village C is about 2860.5kwh, and the heat consumption of the farm is 1451.4MJ. Select a typical daily energy load, as shown in Figure 2.

![Figure 2. Typical daily load of rural integrated energy system](image)

4.2. Parameter Settings
In this paper, the construction capacity of rural C photovoltaic power station is set as 300kW, the biogas generation efficiency is 1.5kwh /m³, and the power generation is about 4h per day. The biogas engineering capacity and gas production are determined by the configuration capacity of biogas generator. The relevant parameters of photovoltaic power station, biogas power generation and other energy equipment are shown in Table 1 and Table 2.

| The variable name                                         | Unit       | The set values |
|---------------------------------------------------------|------------|----------------|
| Photovoltaic grid benchmark electricity price           | Yuan/kWh   | 0.85           |
| Photovoltaic subsidized price                           | Yuan/kWh   | 0.42           |
| Number of employees/ Photovoltaic configuration capacity | A/MW       | 0.2            |
| Annual operation and maintenance times                  | time       | 4              |
| Operational costs                                       | 10000 yuan/times | 20          |
| Interest on loans                                       | %          | 3              |
| Total investment/photovoltaic configuration capacity    | 10000 yuan/MW | 70           |
| Feed-in tariff for biogas power generation              | Yuan/kWh   | 0.66           |
| Biogas slurry production                                | Kg/m³      | 5              |
| Renewal production                                      | Kg/m³      | 3.33           |
| Unit yield price of biogas slurry                       | Yuan/t     | 10             |
| Unit yield price of renewal                             | Yuan/t     | 100            |
| Initial input/biogas allocation capacity                | 10000 yuan/m³ | 0.3       |
Annual maintenance cost/biogas allocation capacity: 10000 yuan/m³, 0.27

Aging biogas digester replacement cost/biogas capacity allocation: 10000 yuan/m³, 0.01

### Table 2. Relevant parameters of other equipment

| Device name              | Conversion efficiency | Investment cost per unit capacity (yuan/kW) | Operating cost per unit capacity (yuan/kWh) |
|--------------------------|-----------------------|---------------------------------------------|--------------------------------------------|
| Gas turbine              | Air switch electric0.37 | 790                                         | 0.025                                      |
| Gas boiler               | 0.91                  | 34                                          | 0.02                                       |
| The electric boiler      | 0.98                  | 68                                          | 0.03                                       |
| The electric machine     | 4                     | 110                                         | 0.01                                       |
| Absorption refrigerator  | 1.3                   | 1100                                        | 0.008                                      |

### 4.3. Analysis of optimized configuration results

The configuration capacity of each energy conversion equipment is obtained through the planning of the rural integrated energy system containing biogas and photovoltaic, which is compared with the configuration results of the traditional integrated energy system, as shown in Table 3.

### Table 3. Energy equipment configuration capacity

| Device name              | Integrated rural energy system | Traditional integrated energy system |
|--------------------------|--------------------------------|--------------------------------------|
| Gas turbine(kW)          | 565                            | 998                                  |
| Gas boiler(kW)           | 1475                           | 2031                                 |
| The electric boiler(kW)  | 1531                           | 1866                                 |
| The electric machine(kW) | 1189                           | 1113                                 |
| Absorption refrigerator(kW)| 355                           | 430                                  |

The photovoltaic power station makes full use of local solar energy resources, reduces the purchase of electric energy, thus reducing the collective financial pressure of the village, and achieves annual benefits by selling surplus electricity to the grid. Figure 3 shows the comparison of comprehensive benefit results between the rural integrated energy system combining biogas cycle agriculture and photovoltaic power station and the traditional integrated energy system.

Figure 3. Comparison of benefits between rural integrated Energy Stations and traditional integrated energy stations.
In conclusion, biogas cycle agriculture achieves self-supply of electric energy and thermal energy through co-generation of biogas heat and power, and excess electricity can be sold online. Besides meeting farmers' load demand and maintaining electric energy balance, photovoltaic power stations also bring certain economic benefits. At the same time, by indirectly reducing the configured capacity of gas turbines and other devices, the cost is reduced. Compared with the traditional integrated energy system, the comprehensive benefit of the rural integrated energy system proposed in this paper is increased by 90.02,000 yuan.

5. Conclusion
In this paper, taking villages and towns as the Research scenario, considering the rural resource endowment and natural production of planting and breeding industry, combined with photovoltaic power station and biogas, a rural comprehensive energy system including power, natural gas, biomass energy and photovoltaic was established. The capacity of energy devices was optimized and its feasibility was verified by an example. Numerical examples show that the proposed rural integrated energy system can achieve the purpose of improving comprehensive benefits, reducing energy consumption, saving energy purchased from commodities, and optimizing the rural energy structure.

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