Optimal operation of biomass integrated energy system in villages and towns

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Abstract. In order to improve the efficiency of energy utilization, improve the energy structure of villages and towns, and promote the efficient application of biomass energy in villages and towns, an integrated energy system (IES) with biomass energy as the core is constructed, and a two-stage optimization method of IES considering the loss of heat supply network is proposed. In the first stage, considering the loss of heat supply network and taking the minimum total heat supply as the objective, the outlet temperature of multi heating equipment is optimized. Then, the output mechanism of biomass cogeneration is analyzed and its output model is established. Considering the whole process of biomass transportation, storage and treatment, the energy supply cost model is established. In the second stage, the output operation optimization of each equipment of IES is carried out with the goal of maximum daily income. The results show that the model is effective, the complexity of the problem is reduced by two-stage optimization, the biomass utilization efficiency is improved by cogeneration, and better benefits can be obtained by constructing biomass energy IES.

1. Introduction
With the advancement of China's energy structure reform, the proportion of renewable energy in primary energy will gradually increase, which is expected to exceed 60% in 2050. In order to further improve the consumption and utilization efficiency of distributed renewable energy, all countries are striving to develop integrated energy systems. The main energy sources are distributed gas and renewable energy such as wind, light and geothermal. Biomass energy is a kind of energy which can develop friendly with the environment, has huge reserves and has not been fully utilized. It has been widely concerned by all countries in the world and has developed rapidly in recent ten years. Therefore, we should make full use of the abundant biomass energy in rural areas of China and build a comprehensive rural energy supply system relying on biomass cogeneration, which can promote the implementation of the beautiful rural plan and increase rural income. It is of great significance to promote industrial adjustment.

In recent years, some achievements have been made in the research and application of biomass combined heat and power (CHP). Reference [1] studied the cogeneration of furfural residue, xylose residue and agricultural straw as raw materials, compared and analyzed the standard coal consumption, annual average total thermal efficiency and cost saving, and showed that under the same production electric load, local utilization of biomass cogeneration can reduce coal consumption and save single energy cost; literature [2] takes into account the environmental cost, and the biomass cogeneration and combustion with forest as the main source Through full cost economic comparison including initial
equipment investment, operating expenses and environmental value, it is found that the environmental benefits of biomass are significant, and the total cost is lower than that of coal-fired cogeneration. According to the quantitative analysis of CO₂ emissions in the whole life cycle of biomass from planting to power generation in literature [3], the results show that the total CO₂ emission of biomass is far less than that of coal-fired, and the higher the CO₂ emission price is, the higher the CO₂ emission price is, the better the benefit of material cogeneration is. References [4,5] show that the efficiency of energy utilization can be improved by replacing the working fluid water in the rankine cycle with organic matter. The existing studies have verified that biomass cogeneration has good economic and environmental benefits, but there are few studies on its power generation characteristics and modelling, which is the basis of integrated energy system operation and optimization planning.

To sum up, this paper constructs a rural electricity heat integrated energy system with biomass energy, photovoltaic and other renewable energy as the core, establishes the output model and cost model of biomass cogeneration, and optimizes the output of each equipment based on the maximum daily income of IES.

2. Rural integrated energy system model

2.1. Integrated energy system structure
According to the characteristics of rural resources, biomass, photovoltaic, geothermal and power grid are used as the energy input of energy center to establish an integrated energy system. Meanwhile, in order to further develop the potential of biomass, a waste heat boiler is added behind the incinerator to form cogeneration to improve the utilization efficiency of biomass.

The operation of the system follows the principle of "self-use and surplus on Grid". After the biomass and photovoltaic power generation meets the needs of users, all the remaining electricity will be received by the power grid. If it is insufficient, it will purchase electricity from the power grid, to obtain power supply income, power generation on-line income and power generation subsidy income. At the same time, waste heat boiler, electric boiler and heat pump are used to generate heat to ensure the thermal demand of IES and earn heating income. The whole system is optimized to maximize the daily revenue.

2.2. Unit equipment model

2.2.1. Biomass cogeneration
(2) Biomass CHP power generation model
The CHP output model of biomass can be expressed by the following formula:

\[
P_{chp}(t) = \eta_{e} \frac{m_{b}(t) NCV_{b}}{3.6 \Delta t}
\]

where, \( P_{chp}(t) \) is CHP electric power (MW) at time \( t \); \( \eta_{e} \) is the electrical conversion efficiency (%) of CHP system; \( m_{b}(t) \) is the biological mass of combustion; \( \eta_{b} \) is the combustion conversion efficiency of biomass (%); \( NCV_{b} \) is the net calorific value (MJ/kg) of biomass used.

The calorific value of biomass is divided into total calorific value (GCV) and net calorific value (NCV). The total calorific value is the calorific value obtained when the water generated from biomass combustion is stored in the product in the form of steam. Since the temperature of combustion exhaust is usually quite high, the water is in the state of steam. Therefore, net calorific value is usually used. Net calorific value can be calculated from gross calorific value[6]:

\[
NCV = GCV \left( 1 - \frac{w}{100} \right) - 2444 \times \frac{w}{100} - 2444 \times \frac{h}{100} \times 8.936 \times \left( 1 - \frac{w}{100} \right)
\]
\[ GCV = 0.3491X_C + 1.1783X_H + 0.1005X_A - 0.0151X_N - 0.1034X_O - 0.0211X_{ash} \]  

where \( w \) is the water content of the fuel; \( h \) is the specific gravity of hydrogen in the fuel. \( X_i \) is the specific gravity of carbon (C), hydrogen (H), sulfur (S), nitrogen (N), oxygen (O) and ash in biomass, respectively.

Similarly, the thermal output of biomass CHP system is as follows:

\[ \Phi_s(t) = \alpha_s \frac{\eta_{CHP}(t) NCV_s}{3.6\Delta t} \]  

where, \( \alpha_s \) is the heat conversion efficiency of CHP system.

### 2.2.2. Heat pump and Electric boiler output model

Heat pump (HP) and electric boiler (EB) takes electric power as the energy and converts it into heat energy for residential heating:

\[ \Phi_{HP} = \eta_{HP} P_{HP} \]  
\[ \Phi_{EB} = \eta_{EB} P_{EB} \]

where, \( \Phi_{HP} \), \( P_{HP} \) and \( \eta_{HP} \) are the output thermal power, input electric power and conversion efficiency of heat pump respectively; \( \Phi_{EB} \) and \( \eta_{EB} \) are the output thermal power and conversion efficiency of the electric boiler respectively, and \( P_{EB} \) is the input electric power of the electric boiler.

### 3. Scheduling optimization of electric thermal integrated energy system

#### 3.1. Objective function

According to the principle of "self-use and surplus online", IES can sell the surplus electricity to the power grid and earn some profits. Therefore, the optimization objective of the second stage is no longer to optimize the conventional operation cost, but to optimize the output of each equipment with the maximum daily operating profit under the premise of meeting the constraints.

\[ \text{max } F = \sum_{r=1}^R [R_{CHP}(r) + R_{PV}(r) + R_{s}(r) + R_{eb}(r) - (C_{CHP}(r) + \text{GRID}_F(r))] \]

where \( F \) is the daily profit; \( R(r) \) is the income of CHP, PV, HP and EB in \( t \) period; \( C,(r) \) is the cost of CHP and electricity purchase from power grid in \( t \) period; \( N_r \) is the total dispatching period.

1. Income of biomass CHP: the income of biomass cogeneration is divided into four parts: power supply income to users, revenue from selling electricity to the grid, subsidy income and heating income.

\[ R_{CHP}(r) = \left[ P_{s}^{eff}(r) U_{grid}^{r} + P_{a}^{eff} U_{grid}^{a} + P_{b}(r) U_{subsidy}^{b} \right] \Delta t + \Phi_{b}(r) U_{b} \Delta t \]

where, \( P_{s}^{eff} \) is self-consumption electricity; \( P_{a}^{eff} \) is the selling electricity to the grid; \( U_{grid}^{r} \) is the electricity price; \( U_{grid}^{a} \) is selling price of biomass power generation to power grid; \( U_{subsidy}^{b} \) is subsidy for biomass power generation; \( U_{b} \) is the heat price.

2. Income of PV: the income of PV is divided into three parts: power supply income to users, income from selling electricity to the grid and subsidy income.

\[ R_{PV}(r) = \begin{cases} 
  \left[ P_{s}(r) U_{grid}^{r} + (P_{a}(r) - P_{s}(r)) U_{grid}^{a} + P_{b}(r) U_{subsidy}^{b} \right] \Delta t, P_{a}(r) > 0 \\
  \left[ P_{s}(r) (U_{grid}^{r} + U_{subsidy}^{b}) \right] \Delta t, P_{a}(r) \leq 0
\end{cases} \]
where, $U'_{\text{grid}}$ is the price of photovoltaic power sold to grid; $U'_{\text{subsidy}}$ is subsidy for photovoltaic power generation. $P_s(t)$ is the equivalent load of the supply part after the total electricity consumption is removed from biomass cogeneration, which can be expressed as:

$$P_s(t) = P_{hp}(t) + P_{eb}(t) + P_{l}(t) - P_{self}(t)$$

where, $P_{hp}(t), P_{eb}(t), P_{l}(t)$ and $P_{s}(t)$ are heat pump power, electric boiler power, consumer power load and biomass CHP power.

(3) Income of heat pump and electric boiler: the income of heat pump and electric boiler is mainly heat supply income, which can be expressed by the following formula:

$$R_{hp}(t) = \Phi_{hp}(t)U_{ht}\Delta t$$

$$R_{eb}(t) = \Phi_{eb}(t)U_{ht}\Delta t$$

where, $\Phi_{hp}(t), \Phi_{eb}(t)$ are the heat power of heat pump and electric boiler respectively; $U_{ht}$ is the heat price.

(4) The cost of biomass CHP: the cost of biomass CHP mainly includes raw material cost, processing cost, storage cost and transportation cost.

$$C_{\text{CHP}}(t) = \lambda_1 m_b(t) + \lambda_2 S_b(t) + C_{\text{raw}}(t)$$

where, $\lambda_1$ is the cost coefficient of raw material treatment; $\lambda_2$ is the storage cost coefficient of raw materials; $S_b(t)$ is the total biomass of energy center in time $t$. $S_b(t)$ is related to the residual biological quality of the last period and the biological quality transported in this period.

$$S_b(t) = S_b(t+1) + m_b(t) + m_{\text{raw}}(t+1)$$

where, $m_{\text{raw}}(t+1)$ is the biological mass transported in $t + 1$ period.

$C_{\text{raw}}(t)$ is the cost of raw material transportation, which related to transportation volume and transportation distance. The raw material collection mode adopted in this paper includes purchasing with fuel broker and transporting directly to power plant by farmers. The cost corresponding to different collection modes is different, which can be expressed by the following formula:

$$C_{\text{raw}}(t) = \begin{cases} 
m_{\text{farmer}}(t)U_{\text{farmer}} \\
m_{\text{broker}}(t)U_{\text{broker}} 
\end{cases}$$

where, $U_{\text{farmer}}, U_{\text{broker}}$ are the purchase price of raw materials delivered by farmers and fuel broker; $m_{\text{farmer}}(t)$ and $m_{\text{broker}}(t)$ are the biomass delivered by farmers and fuel distributors in $t$ period.

Among them, $m_{\text{farmer}}(t)$ is related to the farmers' transportation quantity and transportation time. It is assumed that the farmers' transportation time and each transportation volume obey the normal distribution; while the fuel broker's transportation time obeys the uniform distribution, and each transportation volume obeys the normal distribution. Through Monte Carlo simulation, we can get the raw material purchase quantity in each period of the day.

(5) Power purchase cost of power grid: when the self-generating electricity of the integrated energy system is insufficient, it is necessary to purchase electricity from the power grid.

$$C_{\text{grid}}(t) = P_{\text{grid}}(t)U_{\text{grid}}(t)\Delta t$$

where, $P_{\text{grid}}(t)$ is the power purchased from the grid in time $t$; $U_{\text{grid}}(t)$ is the electricity price in time.

3.2. Constraints

(1) Biomass related constraints
The fuel of biomass CHP is limited and cannot exceed the amount of fuel stored.

\[
0 \leq m_s(t) \leq S_s(t) \quad (17)
\]

\[
0 \leq S_s(t) \leq S_s^{\max} \quad (18)
\]

where, \(S_s^{\max}\) is the maximum biomass that can be stored in the energy center.

(2) Power balance

\[
P_e(t) + P_{PV}(t) + P_{grid}(t) = P_L(t) + P_{EB}(t) + P_{HP}(t)
\]

\[
\Phi_L(t) + \Phi_{EB}(t) + \Phi_{HP}(t) = \Phi_{E}(t)
\]

where, \(P_L(t)\) is the power load of the system in t period (MW); \(\Phi_{E}(t)\) is the heat load of period t.

Other conventional constraints include ramp rate constraint and output upper and lower limits.

4. Optimization model solving algorithm

In this paper, the objective function and constraint conditions are linear and contain the constraints of integer variables. The mixed integer linear programming problem is formed. It can be solved by GUROBI solver. In this paper, MATLAB R2014a is used to program, and the GUROBI solver is called by YALMIP to solve the problem.

5. Case study

5.1. System structure and parameters

Taking a certain area in northern as an example. The system equipment capacity is as follows: electric boiler 0.5MW; heat pump 0.4MW; biomass CHP maximum output is 0.5MW; photovoltaic uses a typical daily data, the maximum output is 1.4MW. The model parameters and TOU price are shown in Table 1.

| Parameter | Value | Unit | Meaning |
|-----------|-------|------|---------|
| \(\lambda_1\) | 12 | yuan/t | Cost of biomass raw material treatment |
| \(\lambda_2\) | 16 | yuan/t | Storage cost of biomass raw materials |
| \(U_{farmer}\) | 180 | yuan/t | Purchase price of raw materials transported by farmers |
| \(U_{broker}\) | 200 | yuan/t | Purchase price of raw materials delivered by fuel distributors |
| \(U_{grid}\) | 0.35 | yuan/kW·h | Electricity price sold to the grid (excluding subsidies) |
| \(U_{subsidy\_PV}\) | 0.4 | yuan/kW·h | Subsidy for photovoltaic power generation |
| \(U_{subsidy\_B}\) | 0.4 | yuan/kW·h | Subsidy for biomass power generation |
| \(U_{th}\) | 0.127 | yuan/kW·h | Unit price of heating |

5.2. Analysis of optimization results

The electricity, heat load and photovoltaic power generation of the integrated energy system are shown in figure 1. The optimization results in the second stage are shown in figure 2. By optimizing the output of each equipment in one day, the maximum profit is 5094 yuan. It can be seen from figure 2 that the electricity price in the period 1-5 is the valley time price. At this time, the electric heat generation equipment is mainly used for heating and purchasing electricity from the grid.

During the period 6-7, biomass CHP was used more, which was due to more biomass storage. In order to reduce the storage cost, biomass energy was used for power generation and heat generation. As the heat production efficiency of electric boiler is much smaller than that of heat pump, so the electric boiler will be out of operation in both normal and peak periods.
During the period 7-17, PV generation, due to the low cost of PV, this period is flat and peak electricity prices, so the first use of photovoltaic power for load supply, if there is surplus, then sell to the grid. Heat load continue to be supplied by biomass CHP and heat pump; the corresponding CHP electricity is mainly sold to the grid to earn income. During the period 17-23, PV will no longer generate electricity. At this time, the biomass CHP will supply IES energy, and the insufficient part will be purchased from the grid. Meanwhile, CHP and heat pump will continue to supply heat load. At 24:00, the electricity price valley period will enter, and the electric boiler will be put into operation.

6. Conclusion
According to the characteristics of rural biomass, light and rich land resources, this paper establishes an integrated electric thermal energy system suitable for rural areas. The results show that: (1) the CHP output model and the cost model of biomass transportation and storage can be effectively applied to the operation optimization of integrated energy system. (2) Cogeneration improves the utilization efficiency of biomass, and the construction of biomass energy integrated energy system can obtain better benefits.

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