Techno-economic analysis of 30MW biomass power plant modification for heating supply

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Abstract. Biomass combined heat and power (CHP) generation is the more efficient use of biomass compared to the direct combustion power generation. The techno-economic analysis of 30 MW biomass direct combustion power set’s modification for heat supply is investigated in this work. Three schemes are employed to provide the district heating supply, including low vacuum condenser, steam extraction, and turbine bypass. The low vacuum condenser approach is the most promising based on the techno-economic analysis. The calculated outlet pressure of the steam turbine, the power generation capacity, the heating supply and the maximum heating area are 30KPa, 27MW, 143.58GJ/h, and 900,000 m² respectively. The expected annual income of biomass combined heat and power plants amounts up to 7,422,700 RMB.

Keywords: Biomass combined heat and power, Low vacuum; Steam extraction, Bypass heating.

1 Introduction

Energy transition towards a low-carbon and high-efficiency energy system has been a long-term strategy for China. Biomass plays an important role in energy mix1. Biomass power plants could provide heating and electricity to meet the heating requirement, which is the world's largest thermal power market 2. Biomass power plant modification for heating supply is an important approach to reduce energy consumption, increase energy supply, and improve energy efficiency.

Some efforts of heating modification have been made in coal-fired boilers of thermal power plants. Xu et al. adopted the steam supply method of reheating the cold section of the steam turbine and the exhaust steam extraction of the medium pressure cylinder and configuring the pressure matcher3. Liu et al. proposed to reduce the work share of the high-pressure cylinder, so as to increase the main steam flow of the unit and the heating and pumping capacity of the unit under the same power generation power conditions4. However, the modification of small capacity biomass power plant needs the techno-economic analysis in details.

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2 Case description

A biomass power plant has a 30MW generator set, steam turbine model is N30-8.83 with high temperature, high pressure, single cylinder, single shaft, condensing type, six-stage reheat extraction. The recuperation system consists of 2 high-pressure heaters, 1 shaft seal heater, 1 deaerator, 3 low-pressure heaters and low-heating trap pumps\(^5\). The main parameters of the unit are shown in Table 1, and the pumping parameters at all levels of the recuperation system are shown in Table 2.

### Table 1. Turbine design parameters.

| Parameter | Unit | Numerical value |
|-----------|------|-----------------|
| Rated power | MW | 30 |
| Rated steam inlet | t/h | 114 |
| Rated exhaust pressure | kPa | 4.9 |
| Cooling water temperature | °C | 20 |
| Condenser steam flow | t/h | 79.5 |
| Cooling water volume | t/h | 4500~6500 |
| Rated inlet steam temperature and variation range | °C | 535 ( +5/-10 ) |
| Rated steam inlet pressure and variation range | MPa | 8.83±0.49 |

### Table 2. Steam extraction at all levels in full load operation.

| Parameter | Pressure (MPa) | Temperature (°C) | Flow(t/h) |
|-----------|---------------|-----------------|-----------|
| After adjustment | 4.608 | 459 | 8.909 |
| The first level (to #1 high plus) | 2.93 | 405 | 8.909 |
| Second level (to #2 high plus) | 1.143 | 297 | 1.4 |
| Third pole (to deaerator) | 0.649 | 239 | 4.374 |
| Level 4 (to #4 low plus) | 0.344 | 180 | 4.5 |
| Level 5 (to #5 low plus) | 0.165 | 119 | 5.209 |
| Sixth level (to #6 low plus) | 0.063 | 87 | 8.573 |

3 Modification schemes

3.1 Low vacuum circulating water heating

The principle of this technology is to reduce the vacuum degree of the steam turbine condenser, increase the exhaust steam temperature of the steam turbine, and then increase the return water temperature of the cooling water of the condenser for heating\(^6\). The circulating water of the heating network passes through the condenser for the first heating and absorb the waste heat of exhaust steam. In turn, the heating network heater is used for secondary heating to generate high-temperature hot water\(^7\). Then the generated hot water is sent to the hot water pipe network, through the heat exchange station and circulating water for heat exchange. The process is shown in Fig. 1.\(^8\).

The generating power of the unit after the transformation:

\[
P_l = (h_1 - h_2) \cdot D_1 + (h_2 - h_3) \cdot (D_1 - D_2) + \ldots + (h_n - h_1) \cdot (D_n - D_1) + (h_1 - h_2) \cdot (D_1 - \sum_{i=2}^{n} D_i) + (h_n - h_1) \cdot (D_1 - \sum_{i=2}^{n} D_i) + (h_1 - h_2) \cdot (D_1 - \sum_{i=2}^{n} D_i)
\]

(1)

Where \(h_1\) is the steam turbine inlet steam enthalpy, kJ/kg; \(h_2\)-\(h_n\) is Steam enthalpy of each level of extraction steam, kJ/kg; \(h_n\) is the enthalpy of outlet steam, kJ/kg; \(D_1\) is the main steam flow, kg/h; \(D_1\)-\(D_n\) is the extraction steam volume at each stage, t/h.

Heat energy produced:

\[
Q_l = (h_1 - h_{\text{sat}}) \cdot D_1 \cdot \eta_1 \cdot (1 - \eta_2)
\]

(2)
Fig. 1. Schematic diagram of low vacuum circulating water heating.

Where $h_{njs}$ is the enthalpy of the condensate, kJ/kg; $D_m$ is the outlet steam flow, kg/h; $\eta_1$ is the efficiency of the heat exchanger, %; $\eta_2$ is the pipeline loss, %.

Increased temperature of cooling water:

$$\Delta t = \frac{Q}{C_p D_l}$$

(3)

Where $D_l$ is the cooling water flow, t/h.

Considering various factors, this paper selects five sets of steam turbine outlet steam pressure to calculate the corresponding power generation and heat supply. The heating heat index is usually 60W/m$^2$. The calculation results are presented in table 3.

Table 3. Low vacuum circulating water transformation calculation result.

| Parameter               | Unit | Heating period | Non-heating period |
|-------------------------|------|----------------|--------------------|
| Outlet pressure         | kPa  | 35 30 25 20 15 | 4.9                |
| inlet enthalpy          | kJ/kg| 3476.67 3476.67| 3476.67            |
| Exit enthalpy           | kJ/kg| 2307.93 2287.08| 2262.85 2233.81 2197.35 2065.03 |
| Power generation        | KW   | 26839.32 27268.72| 27767.67 28365.80 29116.68 29294.42 |
| Heat supply             | GJ/h | 145.07 143.58 141.84 139.77 137.16 | ——                |
| Heating area            | $10^4m^2$ | 1.362 90.42 89.33 88.022 86.38 | ——                |
| Return water temperature| ℃    | 61.55 61.43 61.29 61.13 60.92 | ——                |

3.2 Steam extraction

Due to the working nature of the deaerator, power system emits a large amount of high-temperature steam, which not only causes energy waste, but also produces certain pollution to the environment. The so-called retrofit of external heating and hot water supply are to extract a certain amount of steam from the holes reserved for the deaerator for heating. The specific process is shown in Fig. 2.

The generating power of the unit after the transformation:

$$P = (h_i - h_e) \cdot D_i + (h_i - h_e) \cdot (D_i - D_e) + (h_i - h_e) \cdot (D_e - \sum D_j) + (h_i - h_e) \cdot (D_e - \sum D_j) + (h_i - h_e) \cdot (D_i - \sum D_j)$$

(4)

Where $D_a$ is the flow of additional steam extracted from the deaerator, t/h.
Heat energy produced:

\[ Q_s = D_s (h_t - h_{sa}) \cdot \eta \cdot (1 - \eta_s) \]  

(5)

Where \( h_{sa} \) is the steam extraction pressure corresponding to the saturated water enthalpy, kJ/kg;

Various factors are comprehensively considered, and five groups of different extraction steam quantity are selected to calculate the power generation and heat supply. The results are shown in Table 4.

### Table 4. Steam extraction retrofit calculation result.

| Parameter                              | Unit   | Heating period |
|----------------------------------------|--------|----------------|
| Steam extraction                       | t/h    | 55  50  45  40  35 |
| Steam extraction enthalpy              | kJ/k   | 2932.6 2932.6 2932.6 2932.6 2932.6 |
| Extraction steam pressure corresponds to saturated water enthalpy | kJ/k   | 683.99 683.99 683.99 683.99 683.99 |
| g                                      |        | 683.99 683.99 683.99 683.99 683.99 |
| Power generation                       | KW     | 27703. 28124. 28241. 28358. 28475. |
|                                        |        | 06  49  48  47  47 |
| Heat supply                            | GJ/h   | 111.31 101.19 91.07 80.95 70.83 |

### 3.3 Bypass heating retrofit

The heat load is certain when the heat load is fixed, so the unit cannot achieve true thermolytic coupling in the above two cases. Many power plants can only use one unit with heating and the other with peak shaving. Some scholars have proposed the solution to the boiler with heating, that is, the heating load is completely carried by the boiler, and the heating steam and power generation steam are separated at the furnace end, and no longer enters the steam turbine to perform work\(^2\). The specific process is shown in Fig. 3.

The generating power of the unit after the transformation:

\[
P_i = (h_i - h_t) \cdot D_i + (h_i - h_t) \cdot (D_i - D_d) + (h_i - h_t) \cdot (D_d - \sum D) + (h_t - h_d) \cdot (D_d - \sum D) + (h_t - h_d) \cdot (D_d - \sum D) + (h_t - h_d) \cdot (D_d - \sum D) \]  

(6)

Where \( D_i \) is the steam flow used for power generation, t/h.

Heat energy produced:

\[ Q_s = (D_i - D_d) \cdot h_t \cdot \eta \cdot (1 - \eta_s) \]  

(7)
Various factors are comprehensively considered, and five groups of different extraction steam quantity are selected to calculate the power generation and heat supply. The results are shown in Table 5.

Table 5. Bypass reconstruction calculation results.

| Parameter          | Unit | Heating period |
|--------------------|------|----------------|
| Steam extraction   | t/h  | 20 25 30 35 35 |
| Power generation   | KW   | 28294.12 27198.21 26094.85 24775.64 22987.34 |
| Heat supply        | GJ/h | 69.5334 86.91675 104.3001 121.6835 139.0668 |
| Heating area       | 10,000m² | 39.41164 49.26455 59.11747 68.97038 78.82329 |

4 Economic analysis

4.1 Profit analysis

In the heating season of each year, the unit runs at full load for 3000 hours, and the heat supply during the heating period is always. Calculated based on heat price of 31.5 yuan/GJ\(^{13}\), the revenue from the co-sale of heat supply during the heating period each year is:

\[
Y_1 = 31.5 \times 3000Q
\]

Where Q is the steam heat used for heating in the three scheme, kJ/kg. Y is the specific income.

4.2 Power loss

Calculated based on the biomass feed-in subsidy price of 0.75 yuan/kWh\(^{14}\), the heating season (3000h) will reduce the income from external power supply:

\[
Y_2 = 0.75 \times 3000\Delta P
\]

Where \(\Delta P\) is the power generation loss due to heating renovation.

4.3 Net income

From the above, we can know net income is:
\[ Y = Y_1 - Y_2 \]  
(10)

The economic calculation results of the three schemes are shown in Table 6.

Table 6. Economic calculation results of the transformation plan.

| Parameter | Unit | Heating period |
|-----------|------|----------------|
| Low vacuum circulating water heating reform |        |                |
| Heat supply | GJ/h | 145.07 | 143.58 | 141.84 | 139.77 | 137.16 |
| Heating revenue | 10,000RMB | 1370.91 | 1356.81 | 1240.43 | 1220.79 | 1196.14 |
| Retrofit loss | 10,000RMB | 711.15 | 614.54 | 602.27 | 567.69 | 498.74 |
| Net income | 10,000RMB | 659.76 | 742.27 | 638.16 | 653.10 | 697.39 |
| Heat supply | GJ/h | 111.31 | 101.19 | 91.07 | 80.95 | 70.83 |
| heat exchange external heating hot water heating transformation technology |        |                |
| Heating revenue | 10,000RMB | 1051.85 | 956.23 | 860.60 | 764.98 | 669.36 |
| Retrofit loss | 10,000RMB | 516.81 | 421.99 | 395.67 | 369.34 | 343.02 |
| Net income | 10,000RMB | 535.04 | 534.24 | 464.94 | 395.64 | 326.34 |
| Heat supply | GJ/h | 69.53 | 86.92 | 104.30 | 121.68 | 139.07 |
| Bypass heating retrofit |        |                |
| Heating revenue | 10,000RMB | 657.09 | 821.36 | 985.64 | 1149.91 | 1314.18 |
| Retrofit loss | 10,000RMB | 383.82 | 630.40 | 878.66 | 1175.48 | 1577.85 |
| Net income | 10,000RMB | 273.27 | 190.96 | 106.98 | -25.57 | -263.67 |

It can be seen from the table that when the low-vacuum circulating water heating technology is adopted and the outlet pressure of the steam turbine is 30KPa, the maximum net income is RMB 7,422,700. Adopting heat exchange external heating and hot water renovation technology, when the air extraction volume from the deaerator is 55t/h, the maximum net profit is 5,350,400 yuan. By adopting the bypass heating reform technology, when the pumping capacity is 20t/h, the maximum net profit is RMB 2,732,700.

5 Conclusion

When the low vacuum circulating water heating technology is adopted, it is the optimal solution to increase the outlet steam pressure to 30kPa. At this time, the heat supply is 143.58GJ/h, the maximum heating area reaches about 900,000 m², and the annual income is 7,422,700 Yuan. When adopting the heat exchange external heating hot water transformation technology, the pumping steam volume is equal to 55t/h as the optimal solution, the heat supply is 111.31GJ/h, the maximum heating area is about 630,900 m², and the annualized income is 5,350,400 Yuan. Using bypass heating transformation technology, the most suitable solution is to enter the steam turbine when the rated steam intake is 20t/h, the heat supply is 69.53GJ/h, the maximum heating area is about 394,100 m², and the annualized income is 2,732,700 yuan.

Comprehensive comparison of the three transformation schemes, low vacuum circulating water heating transformation technology is more mature, under the premise of meeting the overall performance of the unit, it can reduce the overall energy consumption of the unit and ensure the stable operation of the device, and the operating economy is high, which is the best modification scheme.

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