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 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 m^2 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 mix[1]. 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 matcher[3]. 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 conditions[4]. 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	℃	20
Condenser steam flow	t/h	79.5
Cooling water volume	t/h	4500 ~ 6500
Rated inlet steam temperature and variation range	℃	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 (℃)	Flow(t/h)
After adjustment	4.608	459	
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:

$$P_1 = (h_1 - h_2)\cdot D_t + (h_2 - h_3)\cdot (D_t - D_1) + (h_3 - h_4)\cdot (D_t - \sum_{i=1}^{2} D_i) + (h_4 - h_5)\cdot (D_t - \sum_{i=1}^{3} D_i) + (h_5 - h_6)\cdot (D_t - \sum_{i=1}^{4} D_i) + (h_6 - h_7)\cdot (D_t - \sum_{i=1}^{5} D_i) \quad (1)$$

Where h_1 is the steam turbine inlet steam enthalpy, kJ/kg; h_2-h_6 is Steam enthalpy of each level of extraction steam, kJ/kg; h_7 is the enthalpy of outlet steam, kJ/kg; D_t is the main steam flow, kg/h; D_1-D_5 is the extraction steam volume at each stage, t/h.

Heat energy produced:

$$Q_1 = (h_7 - h_{njs})\cdot D_m \cdot \eta_1 \cdot (1 - \eta_2) \quad (2)$$

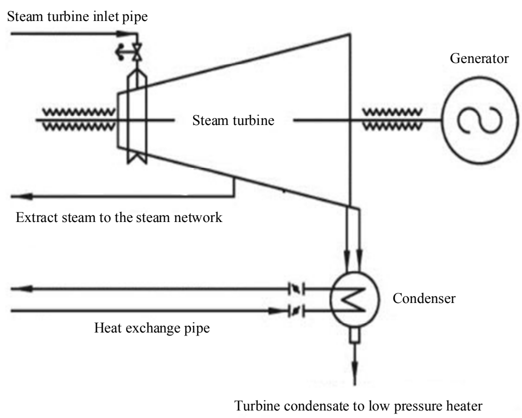

Fig. 1. Schematic diagram of low vacuum circulating water heating.

Where h_{njs} is the enthalpy of the condensate, kJ/kg; D_m is the outlet steam flow, kg/h; η_1 is the efficiency of the heat exchanger, %; η_2 is the pipeline loss, %.

Increased temperature of cooling water:

$$\Delta t = \frac{Q_1}{C_p D_l} \tag{3}$$

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	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	$\times 10^4 m^2$	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[9]. 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[109]. The specific process is shown in Fig. 2.

The generating power of the unit after the transformation:

$$P_2 = (h_1 - h_2)\cdot D_t + (h_2 - h_3)\cdot(D_t - D_1) + (h_3 - h_4)\cdot(D_t - \sum_{i=1}^{2} D_i) + (h_4 - h_5)\cdot(D_t - \sum_{i=1}^{3} D_i - D_a) + (h_5 - h_6)\cdot(D_t - \sum_{i=1}^{4} D_i) + (h_6 - h_7)\cdot(D_t - \sum_{i=1}^{5} D_i) \tag{4}$$

Where D_a is the flow of additional steam extracted from the deaerator, t/h.

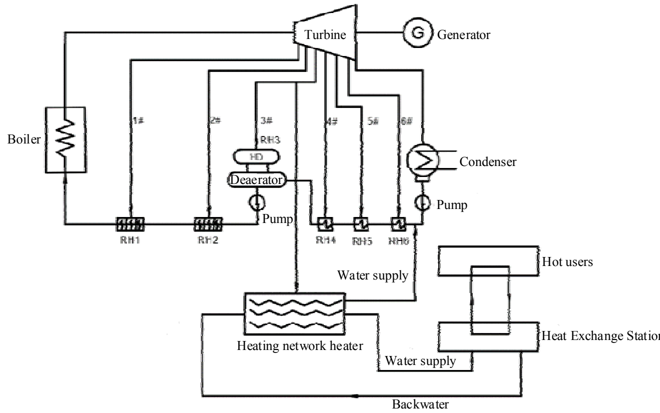

Fig. 2. Schematic diagram of Steam extraction.

Heat energy produced[11]:

$$Q_2 = D_a(h_5 - h_{5a}) \cdot \eta_1 \cdot (1-\eta_2) \tag{5}$$

Where h_{5a} 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/kg	2932.61	2932.61	2932.61	2932.61	2932.61
Extraction steam pressure corresponds to saturated water enthalpy	kJ/kg	683.99	683.99	683.99	683.99	683.99
Power generation	KW	27703.06	28124.49	28241.48	28358.47	28475.47
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[12]. The specific process is shown in Fig. 3.

The generating power of the unit after the transformation:

$$P_3 = (h_1 - h_2)\cdot D_t^{'} + (h_2 - h_3)\cdot(D_t^{'} - D_1) + (h_3 - h_4)\cdot(D_t^{'} - \sum_{i=1}^{2} D_i) + (h_4 - h_5)\cdot(D_t^{'} - \sum_{i=1}^{3} D_i) + (h_5 - h_6)\cdot(D_t^{'} - \sum_{i=1}^{4} D_i) + (h_6 - h_7)\cdot(D_t^{'} - \sum_{i=1}^{5} D_i) \tag{6}$$

Where $D_t^{'}$ is the steam flow used for power generation, t/h.

Heat energy produced:

$$Q_3 = (D_t - D_t^{'})\cdot h_1 \cdot \eta_1 \cdot (1-\eta_2) \tag{7}$$

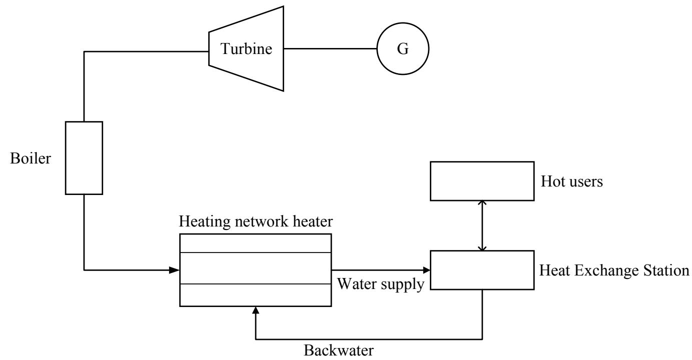

Fig. 3. Schematic diagram of bypass modification.

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	10,000m^2	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:

$$Y_1 = 31.5 \times 3000\mathrm{Q} \tag{8}$$

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:

$$Y_2 = 0.75 \times 3000\Delta \mathrm{P} \tag{9}$$

Where ΔP is the power generation loss due to heating renovation.

4.3 Net income

From the above, we can know net income is:

$$Y = Y_1 - Y_2 \tag{10}$$

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 exchange external heating hot water heating transformation technology	Heat supply	GJ/h	111.31	101.19	91.07	80.95	70.83
	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
Bypass heating retrofit	Heat supply	GJ/h	69.53	86.92	104.30	121.68	139.07
	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 m^2, 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 m^2, 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 m^2, 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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