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Comparison of China’s Biomass Combustion Power Generation with Different Installed Capacities

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Abstract: As a major technical route to utilize biomass energy, biomass combustion power generation (BCPG) has been shown to be of environmental and economic significance. According to the operating experience, the installed capacity has a decisive impact on the operation and economic return of BCPG projects. In China, an installed capacity of either 30 MW or 12 MW is often chosen for constructing a BCPG project. To explore which one is more suitable for China, this paper uses actual operating data to compare the operation performance and techno-economics of two representative BCPG projects with an installed capacity of 30 MW and 12 MW. The results show that the operation situation and electricity production of the 30 MW project are better than those of the 12 MW project. The 30 MW project has a lower biomass consumption than the 12 MW project to produce per unit of electricity. The Internal Rate of Return (IRR) of the 30 MW project is greater than the industry benchmark in China and is almost three times the IRR of the 12 MW project. Therefore, it is recommended to construct BCPG projects with installed capacity of 30 MW in China.

Keywords: biomass; power generation; installed capacity; techno-economic analysis; operating status

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1. Introduction

Countries have been developing renewable energy to substitute traditional fossil fuel energy, which releases heavy carbon emissions and pollution to the environment. Among various renewable energy resources, biomass is a promising one that can be converted into electricity, heat, liquid fuel, gas, hydrogen and chemicals through physical, chemical and biological technologies [1]. In many regions, such as Europe and China, there is growing interest in the use of biomass for energy generation, and the profitability of biomass projects is increasing [2–5]. In the context of achieving carbon neutrality, biomass will play an increasing and irreplaceable role in the energy transition [6]. Taking carbon prices into account, biomass is expected to gradually become more cost competitive than fossil fuels in the future [6–8]. According to the International Renewable Energy Agency, to achieve global net-zero carbon emissions by 2050, global bioenergy consumption in 2050 would have to nearly triple the level of 2018 [9]. In China, the share of biomass in primary energy mix might even reach as high as 10% in 2050 in order to limit climate warming to below 1.5 °C [10].

At present, biomass combustion power generation (BCPG) technology, which originated in Denmark in the 1970s, is a major technical way of utilizing biomass in an industrial scale [11,12]. BCPG technology is a process that burns biomass resources in a combustion boiler, and turns biomass energy into electricity (and heat) [1]. Since the first BCPG plant in Denmark, this technology has been widely utilized in developed countries, such as Holland, Sweden, Finland, the United Kingdom, and the United States of America [13,14]. China is abundant in agricultural and forestry biomass resources. It was reported that China’s biomass resources were approximately 460 million tonnes of coal equivalent per year [15]. China has announced to promote the proportion of non-fossil energy in energy consumption to about 25% by 2030 and strives to realize carbon neutrality before 2060. Subject to the pressure from climate change, energy security, and environmental pollution, China is endeavoring to develop various technologies to utilize biomass. BCPG can not only help to solve the problems of straw stacking and burning in the field, but also reduce the emissions of environmental pollutants, such as CO_2, SO_2, NO_x and PM compared with coal-fired power generation [13,16]. When equipped with carbon capture and storage, BCPG could even generate net-negative carbon emissions, which is indispensable for achieving carbon neutrality [6]. Thus, this technology has been promoted by the Chinese government. Nowadays, the BCPG technology has realized industrial development in China, with over 400 projects being put into commercial operation and total installed capacity of over 13,300 MW by the end of 2020 [17].

Figure 1 illustrates a typical process flow of an agricultural and forestry BCPG project. A BCPG project mainly includes a feedstock logistics system, a consistent and stable feeding system, a boiler combustion and auxiliary system, a turbine generating system, and a transformer and distribution system. In such a project, biomass is sent to the boiler chamber through a special feeding system, then generates heat that is turned into high-temperature and high-pressure steam to drive the turbine and generator to generate power. The flue gas of biomass combustion is treated through ash handling and gas conditioning, and is emitted through the stack after reaching a certain standard (e.g., the emissions limits of boiler air pollutants in the Shandong Province, China, are 10 mg/m^3 for PM, 50 mg/m^3 for SO_2 and 100 mg/m^3 for NO_x). In BCPG projects, the factors that may impact the operation and cost of power generation mainly include the quantity of electricity generated, biomass feedstock collection and processing, feedstock storage and transportation, and operation and maintenance, all of which are closely related to the installed capacity [18]. Therefore, an important question is what kind of installed capacity is suitable for the development of BCPG projects.

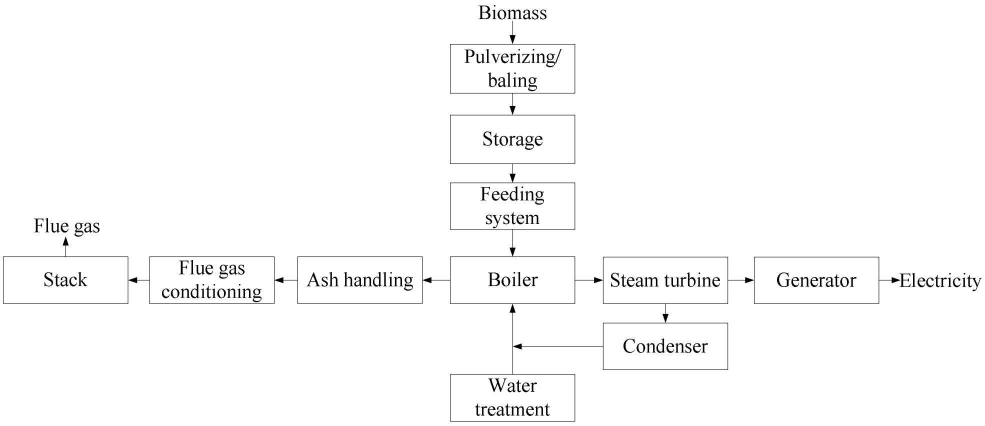

Figure 1. Typical flow for biomass combustion power generation project.

In China, it is debated whether a small installed capacity (typically 12 MW) or a big installed capacity (typically 30 MW) is more suitable for BCPG. Installed capacity directly impacts the production and operation of power plants. An appropriate installed capacity can bring smooth operation and good benefits to a project; in contrary, an unreasonable capacity will lead to a decline in economic benefits or even failure of the project. In the literature, the choice of the installed capacity for China's BCPG has not been analyzed. A techno-economic analysis is necessary for choosing an appropriate installed capacity [18]. Studies on techno-economics of biomass energy utilization have been conducted in developed countries [19–22]. Studies related to the BCPG in China have mainly focused on feasibility analysis [11,23], overall industry assessment [24,25], and policy evaluation [26–29], but few have considered techno-economic analysis. To fill the literature gap, using actual operating data from 1 January to 31 December 2017, this paper conducts a comparative study of two representative BCPG projects in China with different installed capacities—30 MW and 12 MW—to explore which one generates better operation and techno-economic performance.

2. Introduction to the 30 MW and 12 MW BCPG Projects

The two BCPG projects used for this study are both located in the Shandong Province, China, and belong to the National Bio Energy Co., Ltd. The 30 MW project has been in operation since April 2007, and the 12 MW project started running in April 2008. Both have been running safely for over ten years. The two projects share two important similarities: using high-temperature and high-pressure water-cooled vibrating grate boiler as main equipment, and using agricultural and forestry biomass as feedstock. The operating status of the two projects largely reflects the general operating status of all 30 MW and 12 MW projects of the National Bio Energy Co., Ltd. in China, respectively.

The specifications of the high-temperature and high-pressure water-cooled vibrating grate boilers and other key equipment used in the two projects are given in Table 1.

Table 1. Specifications of the equipment used in the selected projects.

Equipment	Designed Parameter	30 MW	12 MW
Boiler	Max. continuous steam capacity	130 t/h	48 t/h
	Steam pressure	9.2 MPa	9.2 MPa
	Steam temperature	540 °C	540 °C
	Boiler efficiency	92%	92%
Steam Turbine	Rated power	30 MW	12 MW
	Rated rotation speed	3000 r/min	3000 r/min
Generator	Rated power	30 MW	12 MW
	Rated voltage	6.3 kV	10.5 kV
	Rated rotation speed	3000 r/min	3000 r/min

3. Operation Performance Analysis

In this section, a comparison of the actual operating status of the two projects is first given based on the data in 2017. For BCPG projects, biomass fuels fed into the boiler affect boiler combustion efficiency and equipment stable operation. The fuels used in both the two projects are mainly agricultural and forestry biomass collected within a radius of 10–15 km around the plants, but they will also be purchased from further places as needed. The designed moisture content of fuel is 15–20% and heating value is 14,630 kJ/kg. However, due to the agriculture plantation features and logistics, the fuel quality usually cannot reach this standard in real operation. As shown in Figure 2, the water content is higher than the standard, but the heating value is lower. In 2017, the average moisture content of the feedstock was 28.3% in the 30 MW project and 27.1% in the 12 MW project; the average heating value of the feedstock was 10,616 kJ/kg in the 30 MW project and 10,202 kJ/kg in the 12 MW project. At the beginning of the development of the industry, it was inferred that a big installed capacity required a large amount of biomass resources, so its fuel quality might be difficult to guarantee. However, actual data show that a small installed capacity does not ensure better fuel quality than a big one.

The original biomass consumption for power generation refers to the quantity of biomass resources consumed to generate per kWh of electricity. In other words, it is the ratio of fuel consumption to electricity production. Under the same combustion conditions, the higher the heating value, the less original biomass resources will be consumed. Figure 3 features that the 30 MW project has a lower biomass consumption than the 12 MW project to produce 1 kWh of electricity. The average original biomass consumption in the 30 MW project was 1184 g/kWh and was 1392 g/kWh in the 12 MW project in 2017.

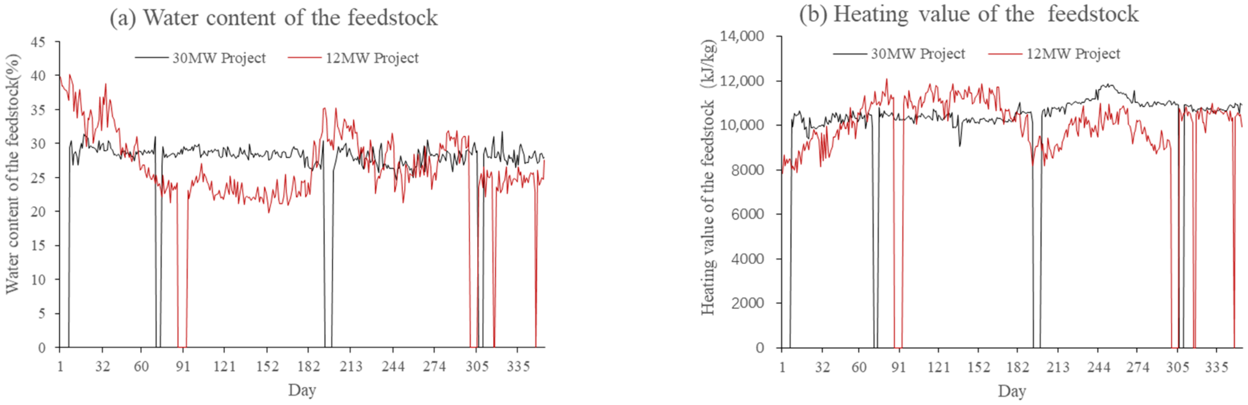

Figure 2. Water content (**a**) and heating value (**b**) of the feedstock.

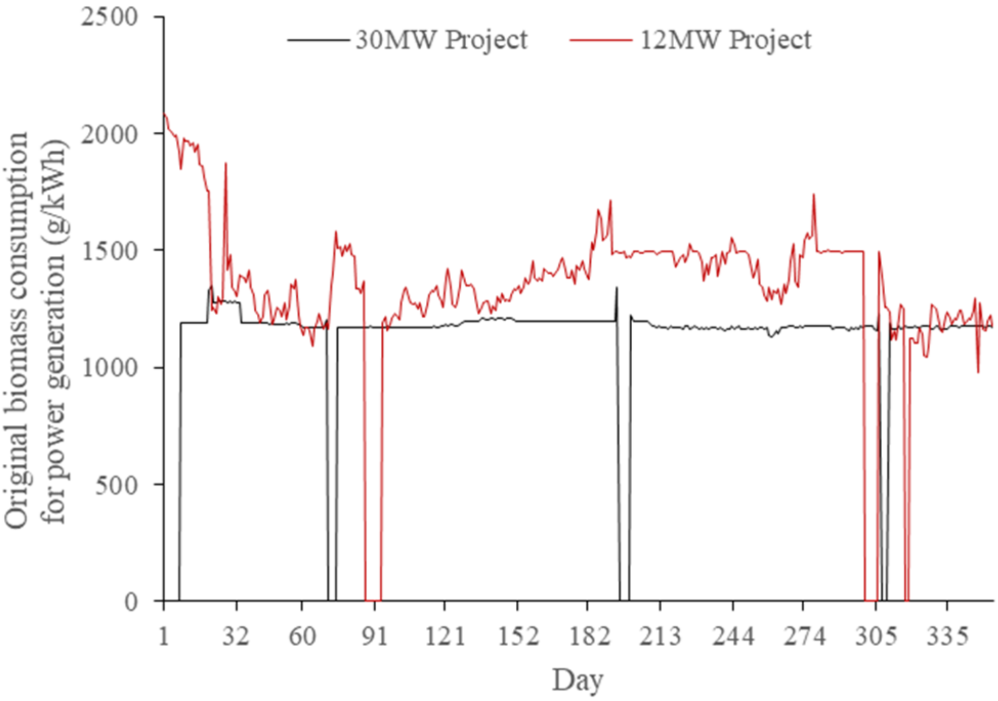

Figure 3. Original biomass consumption for power generation.

The moisture content and heating value of fuel also impact the boiler operation availability and overall thermal efficiency, which further influence the comprehensive profits of plants. As shown in Figure 4a, because the heating value of biomass feedstock is lower than the designed value and the moisture content is higher, the boiler efficiency for both projects in operation is also lower than the designed level of 92%. The boiler efficiency of the 30 MW project is slightly higher than that of the 12 MW project. Influenced by the feedstock, the overall thermal efficiency of two plants is quite different. In 2017, the average thermal efficiency of the 30 MW project was 31.4%, and that of the 12 MW project was 26.5%, as shown in Figure 4b. In addition, we conducted *t*-tests [30,31]. The *p*-values indicate that the differences between the time-series of the two projects are statistically significant at the 1% level.

Table 2 summarizes key operation parameters of the two projects in 2017. In addition to higher electricity production, it is clear that the operating situation of the 30 MW project appears overall better than that of the 12 MW project.

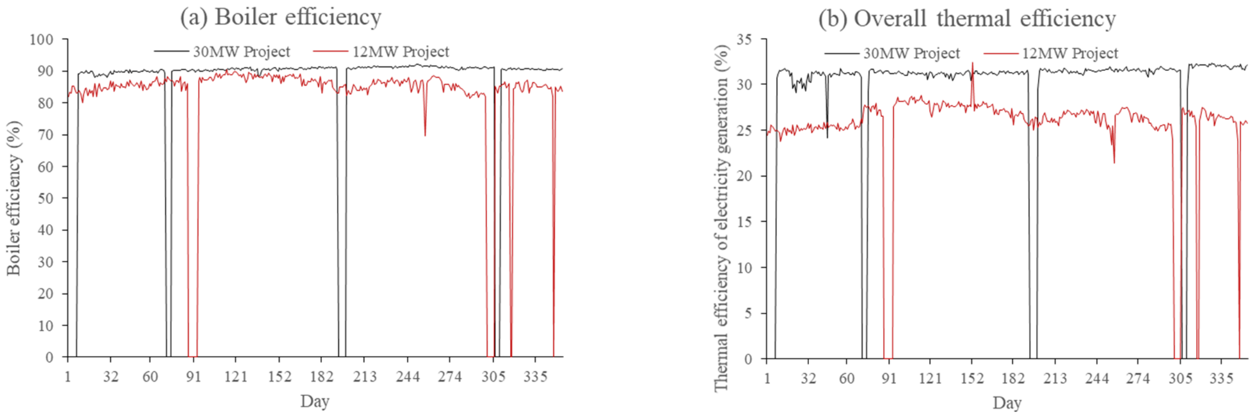

Figure 4. Boiler efficiency (**a**) and overall thermal efficiency (**b**).

Table 2. Overall operation parameters in 2017.

Operation Parameter	30 MW	12 MW
Total power production (million kWh/year)	231.7	93.6
Total power sent into grid (million kWh/year) *	209.3	88.9
Average daily production (10^4 kWh)	65.4	26.4
Equipment utilization period (h/year)	7722	7798
Heating value of feedstock (kJ/kg)	10,616	10,202
Moisture content of feedstock (%)	28.3	27.1
Boiler efficiency (%)	90.6	85.9
Thermal efficiency (%)	31.4	26.5
Original biomass consumption (g/kWh)	1184	1392

* The power plant itself needs to consume electricity for regular operation. The more electricity the plant itself consumes, the less it can sell to the grid. The difference in auxiliary power consumption is due to several factors, such as the management level and energy consumption habits of the power plant.

4. Techno-Economic Analysis

On the basis of actual operation data, in this section, a techno-economic analysis for the two projects is conducted. Table 3 provides the annual revenue and cost of the two projects. We find that the pre-tax net income of 30 MW project was 0.793 million CNY/MW (0.103 CNY/kWh) in 2017, while that of the 12 MW project was 0.716 million CNY/MW (0.092 CNY/kWh). Therefore, the 30 MW project appears more profitable than the 12 MW project.

Table 3. Annual revenue and cost in 2017 *.

Parameter	30 MW	12 MW
Total investment (million CNY)	304	167
Biomass feedstock price (CNY/tonne)	319	249
Biomass feedstock consumption (tonne/year)	274,397	130,228
Cost of feedstock (million CNY/year)	87.5	37.6
Operation cost (million CNY/year)	29.7	16.9
Financial cost (million CNY/year)	15.9	8.8
Total cost (million CNY/year)	133.2	58.1
Output value (million CNY/year) **	157.0	66.6
Pre-tax net income (million CNY/year)	23.8	8.6

* All data are from real construction, production and operation of the two projects. ** The guide feed-in tariff has been 0.75 CNY/kWh in China since July 2010.

The Internal Rate of Return (IRR) [13,32,33] (also see Appendix A) is further calculated for the techno-economic analysis. Financing of 80%, interest of 6.55% (for debt over 5 years), repayment period of 15 years, investment residue of 5%, and income tax of 25% were used for this analysis. The operation period and depreciation period were both 20 years. All these data were adopted from the internal Feasibility Study Report of the National Bio Energy Co., Ltd. in China. Table 4 presents the calculated IRR of the 30 MW and 12 MW BCPG projects. The IRR of the 30 MW project is higher than the benchmark (8%) of this industry in China. However, the IRR of the 12 MW project is lower than the benchmark, only about one third of that of the 30 MW project. Even assuming the same technical performance as the 30 MW project, the IRR of the 12 MW project is estimated at 7.5%, which is still lower than that of the 30 MW project. In addition, we find that the IRR of the 30 MW project is comparable to the IRR of some BCPG projects in other countries. For example, Cardoso et al. [20] mentioned that the IRR of an 11 MW biomass combustion power plant in Portugal was 9.95%; Moon et al. [19] showed that, with renewable portfolio standards, the IRR of biomass direct combustion projects could reach nearly 15% in Korea; Malek et al. [34] showed that the IRR of biomass-based power plants with circulating fluidized bed boiler and steam turbine was average at 12.5% in Malaysia.

Table 4. IRR of the BCPG projects with different installed capacities in China.

Installed Capacity	Project IRR (Benchmark = 8%) *
30 MW	11.7%
12 MW	4.1%

* 8% is set as the benchmark for the IRR of thermal power plants in China's Construction Project Economic Evaluation Methods and Parameters (Third Edition) [35].

5. Conclusions

In China, BCPG projects grow very fast, and 30 MW or 12 MW are often chosen as the installed capacity for a new BCPG project. According to the analysis of the actual operating data, we justified that the operation performance of the 30 MW project is overall better than the 12 MW project. In particular, the profitability of the 30 MW project also appears better than the 12 MW project, based on a techno-economic evaluation.

As BCPG projects have the functions of promoting rural area development and substituting fossil energy to reduce carbon emissions and air pollutants, we should make further efforts to push forward the development of the BCPG industry in China. If feedstock can be supplied, it would be a better option for stakeholders to choose 30 MW as the installed capacity to develop BCPG projects in China. Subject to the feedstock supply, the location of projects should not be very close to each other. To further improve the profitability of BCPG projects, stakeholders could also consider providing heat or other energy services to residents and industrial consumers. Finally, similar studies might also be conducted in other countries to consider which installed capacity is suitable for them.

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Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author. The data are not publicly available due to the policy of the National Bio Energy Co., Ltd., Beijing, China.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Calculation of the Internal Rate of Return

In this analysis, the IRR was determined by Equation (A1), where P_t indicates income (or cash inflow) in year t, C_t indicates cost in year t, T_t indicates tax in year t (C_t + T_t is cash outflow), INV indicates initial investment, and N indicates total period. In other words, the IRR is the discount rate corresponding to a net present value of zero. P_t was calculated as Equation (A2), where pe_t indicates feed-in tariff and $elec_t$ indicates power sent into the grid. C_t was calculated as Equation (A3), where pf_t indicates biomass feedstock price, $fuel_t$ indicates biomass feedstock consumption, oc_t indicates operation cost, and fc_t indicates financial cost (mainly related to debt). T_t was calculated as Equation (A4), where η_t indicates tax rate and D_t indicates asset depreciation. The units for these variables are: P_t, C_t, T_t, D_t, INV, oc_t, fc_t–CNY; pe_t–CNY/kWh; $elec_t$–kWh; pf_t–CNY/tonne; $fuel_t$–tonne.

$$\sum_{t=1}^{N} (P_t - C_t - T_t) \times (1 + IRR)^{-t} - INV = 0 \tag{A1}$$

$$P_t = pe_t \times elec_t \tag{A2}$$

$$C_t = pf_t \times fuel_t + oc_t + fc_t \tag{A3}$$

$$T_t = \eta_t \times (P_t - C_t - D_t) \tag{A4}$$

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