Design and Operation of A 5.5 MW_e Biomass Integrated Gasification Combined Cycle Demonstration Plant

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The design and operation of a 5.5 MW_e biomass integrated gasification combined cycle (IGCC) demonstration plant, which is located in Xinghua, Jiangsu Province of China, are introduced. It is the largest complete biomass gasification power plant that uses rice husk and other agricultural wastes as fuel in Asia. It mainly consists of a 20 MWt atmospheric circulating fluidized-bed gasifier, a gas-purifying system, 10 sets of 450 kW_e gas engines, a waste heat boiler, a 1.5 MW_e steam turbine, a wastewater treatment system, etc. The demonstration plant has been operating since the end of 2005, and its overall efficiency reaches 26−28%. Its capital cost is less than 1200 USD/kW, and its running cost is about 0.079 USD/kWh based on the biomass price of 35.7 USD/ton. There is a 20% increment on capital cost and 35% decrease on the fuel consumption compared to that of a 1 MW system without a combined cycle. Because only part of the project has been performed, many of the tests still remain and, accordingly, must be reported at a later opportunity.

1. Introduction

Biomass is widely available as a resource in China, and its modern use offers a sustainable resource for the future.[1−3] Electricity production from biomass has the potential in alleviating environmental pollution, slowing global warming, and reducing our dependence on the limited fossil fuels.[4] However, biomass is highly dispersed over a wide area, and its energy content is comparatively low, which requires a cost for their collection and transportation.[5] This suggests that the decentralized use, such as mid-scale biomass gasification and power generation (BGPG) technology with the power output of 4−10 MW_e, may be more feasible than large-scale combustion and power generation technology and has the potential to approach the market in developing countries.

There are two main options to produce electricity from biomass: combustion and gasification. The combustion characteristics of biomass are well-understood,[6−8] and the combustion of biomass is fully established and already widely used in biomass applications.[9] In the past few decades, significant efforts have been directed toward the development of biomass gasifiers to replace traditional combustion systems.[4,10]

Since the 1960s, there has been extensive development and deployment of a fixed bed gasifier coupled with generator sets, which have grown in size from 60 to 200 kW_e output in China.[3,11,12] To meet the electricity self-supplying demand of large-scale rice mills, a demonstration project of 1 MW circulating fluidized bed (CFB) BGPG system was set up in the Fujian Province of China by the Guangzhou Institute of Energy Conversion (GIEC), Chinese Academy of Sciences (CAS). The project was funded by the Ministry of Science and Technology of China (MOST) as one of the key projects during the National Ninth Five-Year Plan. It has been successfully operating since August of 1998.[13] Since then, more than 20 commercial power plants have been established in China and several southeast Asian countries based on the experiences obtained from the 1 MW power plant.[14] Many improvements had been made in the 1 MW system as compared to the former

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200 kW system.[13] However, the 1 MW system can only be used as the self-supply power plant by rice and timber mills with cheap biomass resources because its overall efficiency is less than 20%. To promote market competitiveness, capacities and overall efficiencies of the BGPG technology should be further improved.

Biomass integrated gasification combined cycle (IGCC) technology has been reckoned as the most promising way of the BGPG technology in the future.[5,15] IGCC technology based on a high-pressure gasifier, hot-gas-cleaning device, and gas turbine has been developed. It is an advanced power generation technology for large-scale application in the range of 30−50 MW_e with expected efficiencies of more than 40%.[16,17] However, the economic competitiveness of IGCC technology requires so large of plant sizes that this technology is not feasible in all applications using biomass.

The first biomass IGCC plant in the world had been demonstrated at Värnamo in southern Sweden from 1996 until 2000. The plant was based on a pressurized air-blown CFB gasifier and hot-gas cleanup with ceramic filters. The plant produced 6 MW_e and 9 MWth, with an electric efficiency of 32%;[18−20] however, the COE was not competitive for the Swedish electricity market, and the plant operation had been halted.[16] The Italian Thermie Energy Farm (TEF) IGCC demonstration project began in 1997 and was based on a normal air-blown CFB gasifier. It generated 12 MW_e, with a net thermal efficiency of 31.7%.[21,22] The project Arable Biomass Renewable Energy (ARBRE) in the U.K. with a designed capacity of 8 MW_e was based on an atmospheric pressure CFB gasifier. However, the plant had not been tested in an integrated system, and its commissioning was never completed.[23] World wide there are a few examples of similar biomass gasification technologies; the others were developed in the U.S.A., Finland, Brazil, etc.[17] These B/IGCC demonstration plants use a conventional technical route of gasification−gas turbine−steam turbine, while their commercial applications have not been realized thus far because of the difficulty in secured and long-term fuel supplying for large power plants, higher capital and running cost, and some technical problems.

At present, the B/IGCC cannot compete with natural gas combined cycles and low-cost conventional fluidized bed combustion technology. The conventional fluidized bed combustion has become commercially available also in a relatively small scale (10 MW_e), but this technology has a rather low power/heat ratio. Consequently, its potential is limited to applications with district or process heat as the main product. Thus, there is also a real need to develop more efficient methods for small- and medium-scale power production from biomass. One of the alternatives having clearly higher power/heat ratios than can be reached in conventional steam cycles is gasification followed by internal combustion engines.

A project was launched in 2001 with the support of MOST in China, as one of the key projects during the National Tenth Five-Year Plan. The purpose of the project was to demonstrate the technical and economic feasibility of power generation from biomass by using a novel integrated gasification combined cycle concept. The concept, different from the conventional IGCC system developed before,[24] was dedicatedly designed by employing a gas engine instead of gas turbine to meet the situation of China. Its cost performance was expected to achieve a higher level because all of the devices used in the system could be domestically produced, and it was thus technically and economically feasible to be applied in most developing countries.

A demonstration plant with a designed power output of 5.5 MW_e was constructed in Daiyao town, Xinghua city, Jiangsu Province of China by GIEC, CAS.[25] The region is surrounded by 33 000 acres of rice and wheat fields and a great amount of rice mills; therefore, the estimated yield of rice husk is 400 000 tons/year. The abundant biomass resource together with convenient transportation route make the region an ideal location for a biomass project.

The plant is an important step in developing highly efficient and environmentally acceptable technologies based on biomass fuels. The design of the plant started in 2002, and commissioning under part load began at the end of 2005. The running time has been accumulated to more than 8000 h, generating 17 millions kWh of electricity. Its overall efficiency reaches 26−28%. Its capital cost is less than 1200 USD/kW, and its running cost is about 0.079 USD/kWh based on the biomass price of 35.7 USD/ton. Because only part of the project has been performed, many of the tests still remain and, accordingly, must be reported at a later opportunity. This paper introduces the design and operation performances of the 5.5 MW_e IGCC system.

2. Design of the Plant

Figure 1 shows the layout of the 5.5 MW_e biomass IGCC demonstration plant, which mainly comprises a biomass supply system, a 20 MWt atmospheric CFB gasifier, a gas-purifying system, 10 sets of 450 kW_e gas engines, a waste heat boiler, a 1.5 MW_e steam turbine, wastewater treatment and ash discharging systems, etc. The designed technical data of the plant are summarized in Table 1.

Biomass Supply and Transportation System. The local rice husk and cotton stalk available within 30 km are 80 000 and 300 000 tons, respectively. Rice husk is purchased from rice mills through signing long-term contracts with the mills or from individual farmers. In places where cotton stalk is centralized, purchasing and processing depots are set up; the treated cotton stalk is then carried to the plant. Because the seasonal fluctuations of the cotton stalk, storage or special purchasing methods are to be considered. Rice husk is mainly used materials; next is rice and wheat stalk, in case the price of rice husk rises. Table 2 shows proximate and ultimate analysis of the biomass materials used. Rice husk is shipped from

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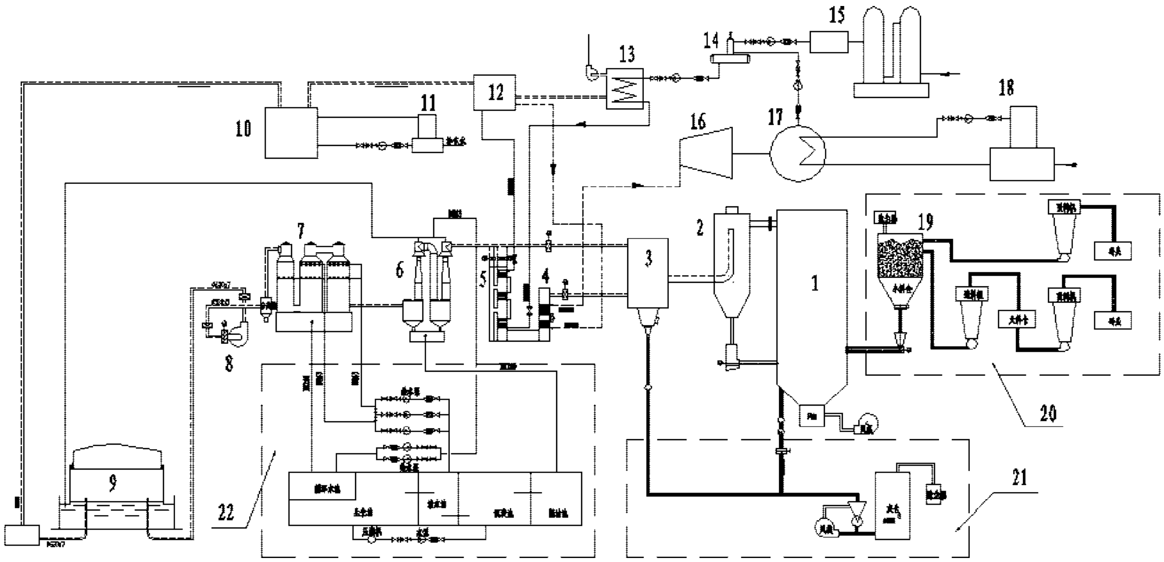

Figure 1. Layout of the 5.5 MW$_e$ biomass integrated gasification combined cycle power generation demonstration plant. 1. gasifier 2. cyclone seperator 3. tar cracker 4. high temperature superheater 5. II-level coal economizer 6. Veturi tube 7. water scrubber 8. Roots fan 9. gas storage tank 10. gas engine sets 11. cooling tower of generating sets 12. waste heat boiler 13. I-level coal economizer 14. de-oxygenator 15. water-softener 16. steam-turbine 17. condenser 18. circulating cooling tower of steam turbine 19. hopper 20. fuel supply system 21. dust discharging system 22. waste water treatment system.

Table 1. Main Technical Data of the 5.5 MW$_e$ Plant

parameters	units	amounts
net power output	MW$_e$	5.5
capacity of gas engines	MW$_e$	4.5
capacity of steam turbines	MW$_e$	1.5
own demand of the plant	%	10
annual running hours	hour	6000
biomass consumption rate	kg kW^{-1} h^{-1}	1.0−1.2 dry biomass
annual biomass consumption	ton	36000
net electricity efficiency	%	26−28

Table 2. Proximate and Ultimate Analysis of the Biomass Materials

biomass		rice husk	stalk
moisture (%)		12.1	14.5
proximate analysis (dry basis)	volatile	68.72	69.01
	fixed carbon	17.37	16.79
	ash	13.9	14.2
ultimate analysis (dry basis)	C	40.73	38.33
	H	4.99	6.17
	O	39.79	40.24
	N	0.41	0.72
	S	0.17	0.34
high heating value (kJ/kg)		15223	14499

the rice mills to the storage workshop of the plant and carried to a small bunker beside the gasifier via air-charging pipes and then is fed by the screw feeder into the gasifier. The feed rate can be adjusted by controlling a speed-regulating motor.

Gasification and Gas-Cleaning System. The biomass gasification and gas-cleaning system is the core of the plant. It mainly includes a gasifier, a cyclone separator, a tar cracker, two venturi tubes, three water scrubbers, an electrostatic tar-catcher, a gas storage tank, etc. The gasifier is of an atmospheric CFB, air-blown type, and consists of the gasifier itself, cyclone separator, and cyclone return screwer. The gasifier and cyclone are totally refractory-lined. The rice husk is pyrolyzed immediately upon entering the gasifier. The gas produced transports the bed material and remaining char toward the cyclone. In the cyclone, most of the solids are separated from the gas and are returned to the bottom of the gasifier through the return screwer. The recirculated solids contain some char, which is burned in the bottom zone, where air is introduced into the gasifier. The combustion maintains the required temperature in the gasifier. The fuel gases are designed to be discharged from the bottom of the cyclone separator to keep a compact layout of the system. Because the ash density is low, a return screw is employed to avoid the controlling difficulties of generally used L-shape valve and loop seal valve. Main dimension parameters and technical indexes of the gasifier are shown in Table 3.

Table 3. Main Dimension Parameters and Technical Indexes of the Gasifier

items	unit	parameters
outer diameter	m	3.0 (bottom)
	m	4.0 (upper)
total height	m	20.0
fuel feeding rate	kg/h	3000−6000
heat output power	MWt	20.0

After the cyclone, a tar cracker loaded with char as the catalyst is mounted to reduce the tar contained in the fuel gases. Theoretically, when some amount of air is introduced into the cracker, both thermal cracking and catalytic cracking happen to decrease the tar content of the gases. The gas exited from the cracker flows to a high-temperature superheater and a II level coal economizer, where one portion of sensible heat of the fuel gases is recovered and the temperature is cooled to 400−500 °C. The cooled gases pass through two parallel venturi tubes and three parallel water scrubbers, where the gas-cleaning process occurs. Ash is discharged from the bottom of the gasifier and from venturi tubes; tar is washed into the wastewater that requires additional treatment in the further step. The gas is cooled to room temperature after the gas-cleaning process, and then it is sent into a gas storage tank by Roots blower.

Gas Engines and Generating Sets. The gas exited from the gas storage tank is burned in the combustion chambers of the gas engines, generating 4 MW of electricity. The gas engine is modified from the model 8300 diesel engine, which is manufactured in Diesel Engine Corporation in China. Its fuel supply system, fuel injectors, and combustors have been redesigned to suit the low calorific value and somewhat dirty fuel gas. Because the maximum capacity of the single engine is 450 kW$_e$, 10 sets of gas engines are installed to achieve the designed power output. The employed gas engines can be fueled by low-quality gases; therefore, the investment cost and technical risk of the power plant decrease greatly as compared to a gas-turbine-based IGCC system. The technical parameters of the gas engines are shown in Table 4.

Table 4. Technical Parameters of Gas Engines

items	parameters
type of gas engines	500GF10
model of gas engines	8250/8300
number of set	12
number of gas cylinder	8
rated power	450 KW_e
rated rotating speed	500 r/m
efficiency of gas engines	30%
generating voltage	400 V
generating frequency	50 HZ
power index	0.85

Table 5. Technical Parameters of the Boiler and Steam Turbine

item	parameter
Waste Heat Boiler	
steam output (t/h)	10.0
superheated steam temperature (°C)	350
superheated steam pressure (MPa)	1.35
water feeding temperature (°C)	60
Steam Turbine	Condensing Turbine
rated power (MW)	1.5
rated inlet steam pressure (MPa)	1.34
rated inlet steam temperature (°C)	310
exhaust steam pressure (MPa)	0.0090

Waste Heat Boiler and Steam-Turbine-Generating System. The hot flue gas from the gas engines is ducted to a waste heat recovery boiler (10 t/h), where steam is generated. The steam is then superheated by the fuel gas and supplied to a steam turbine (1.35 MPa, 350 °C), generating 1.5 MW electricity. The temperature of the discharged gas from the tar cracker and gas engine sets are 800−900 and 500−550 °C, respectively; therefore, the waste heat boiler and steam-turbine-generating system are integrated to form a combined cycle to use this part of sensible heat. Table 5 gives technical data of the boiler and steam engine.

Ash- and Tar-Disposing System. Tar and ash are generated as byproducts in the process of gasification. Dry ash is first discharged from the bottom of the gasifier through an ash-discharging screwer and then is carried to an ash storehouse through pneumatic conveying. The discharged dry ashes can be sold to local steel factories as a kind of thermal insulation material.

The ash and tar contained in the fuel gases will be removed through the water-washing method and the electrostatic tar-catcher. A total of 20 t/h of wastewater are produced in the gas-cleaning process in venturi tubes and water scrubbers and become contaminated with ash, char, tar, and a high level of COD. The contaminated water has to be treated before the water can be returned to the environment. It is thus important to install specialized water treatment equipment to avoid secondary pollution caused by the wastewater.

The treatment process includes four steps as shown in Figure 2. The discharged water from the venturi tubes and the water scrubbers are first sent to the pressure filter, in which ashes contained in the wastewater are filtered and part of the tar will be simultaneously absorbed by the filtered ash. The discharged water is then sent to the aeration tank, in which the color of the liquor changes from tan to black. After the ash and some of the impurities are precipitated in the deposition tank, the water enters the biochemical treatment tank, in which the COD value of the wastewater is reduced from 1000−1500 to 150−200 mg/m^3 by the decomposition effect of aerobic bacteria. After biochemical processing, the treated wastewater can be circularly used. The wet ash filtered in this process can be mixed with coal, producing coalballs, a sort of fuel that is usually used in rural areas.

3. Operating Performance of the Plant

20 MWt Biomass CFB Gasifier and Gas-Cleaning System. It is of great importance to operate the gasifier under suitable conditions. To explore optimized operating conditions, 37 sets of data were collected based on rice husk during the commissioning stage. The operating conditions are feed rate, 3040−5027 kg/h; air rate, 2624−4164 Nm^3/h; ER, 0.22−0.25; and operating temperature, 700−810 °C. Figures 3−5 show the relationships between ER and the gas heating value, gas yield, carbon conversion rate, and gasification efficiency, respectively. It is our intention to study the ability of the plant to operate on different kinds of fuels based on biomass from rice husk to crop stalks.

It is noted that significant variation of the gas quality exists even under conditions of the same load and feedstock, mainly caused by the fluctuation of the raw material; however, the composition of the dry gas and its heating values can be kept at specific ranges, as shown in Table 6.

From Figures 3 to 5, it is found that the maximum gasification efficiency is around 70−75%, with a gas heating value of around 6000 kJ/Nm^3 and gas yield and carbon conversion rate around 1.6−1.7 Nm^3/kg and 90%, respectively. ER should be controlled within a suitable range to obtain the best combination of the reaction temperature and gaseous products.

As is well-known, the production of tar is a strong fraction of temperature. Too small in ER will cause a lower reaction temperature, which results in a high tar production that both reduces the overall efficiency and increases the investment and cost of tar removal; too large in ER will consume the produced gases through the oxidization reaction and decrease the heating value of the gases. The high-temperature limitation is associated with ash and char fusion reactions that result in agglomeration of the silica particles and eventual defluidization of the fluidized bed.[13] The operation on rice husk results in a lower temperature of operation than is possible on wood fuels. Generally, there is an optimized ER range, at which the temperature of the bed should be kept around 800 °C. To maintain stable operation of the gasifier, an automatic control system that can monitor the variation of the fuel characteristics and operation parameters has been considered to install in the further steps.

After half-year operating experiences, the tar cracker proved not to be highly effective, so that it is currently functioning as an inertial separator to enhance the efficiency of ash removing. To meet the demand of the gas engines, an electrostatic tar catcher is mounted to remove the tar contained in the gas before the gas enters the gas storage tank.

Model 8300 Gas Engines Sets. A large engine of say 800−1000 kW would be preferred on cost and operational maintenance grounds, but a tar-tolerant engine in that size is not available. The employed gas engine with 450 kW output is the maximum gas engine suitable for low caloric heating value gases. Results show that the maximum generating efficiency of the engine is 29.7% at 75% of load, a 4% increment as compared to that of 200 kW sets, which was adopted in the above-mentioned 1 MW system, as shown in Table 7.

Waste Heat Recovery Boiler and Steam-Turbine-Generating System. At the commissioning stage under part load, the waste heat used for the boiler was not enough to produce the designed steam to drive the turbines. On the other hand, severe ash deposit on the surface of the superheater was found, which decreased the heat exchange efficiency and resulted in a lower superheated steam temperature. A full load operation will be performed in the further steps.

Comparison of Three BGPG Systems. As compared to the former 200 and 1000 kW BGPG systems, many improvements have been made in the 5.5 MW system, as shown in Table 8. It is found that the gasification efficiency of the 5.5 MW system has been improved obviously. With the adoption of the heat recovery system, the overall efficiency of the present system is 50% higher than that of the 1 MW system and the fuel consumption and electricity cost are reduced greatly.[26]

4. Economic Analysis of the Project

There are two risks on the raw material supply: quantity and price instability. With coal prices increasing, lots of industrial

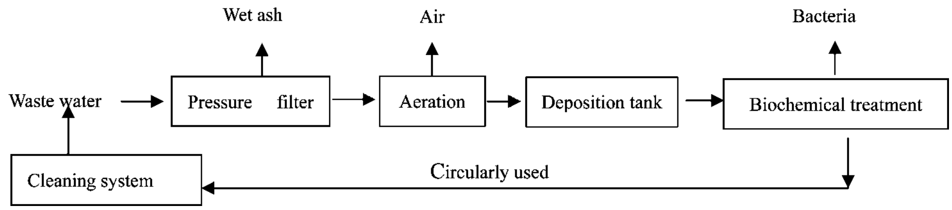

Figure 2. Flowchart of wastewater treatment.

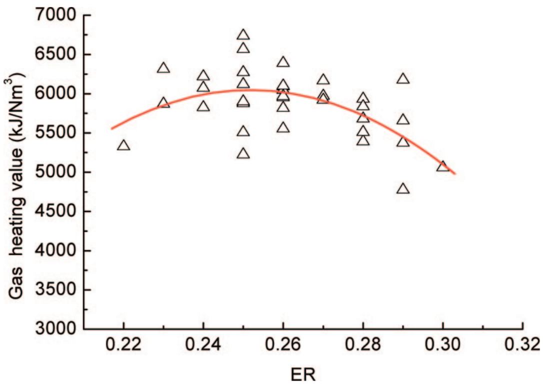

Figure 3. Effect of ER on the gas heating value.

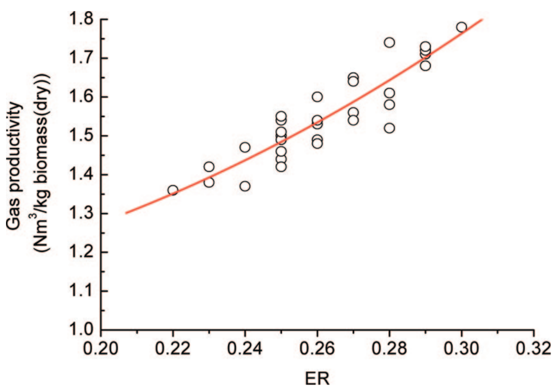

Figure 4. Effect of ER on the gas yield.

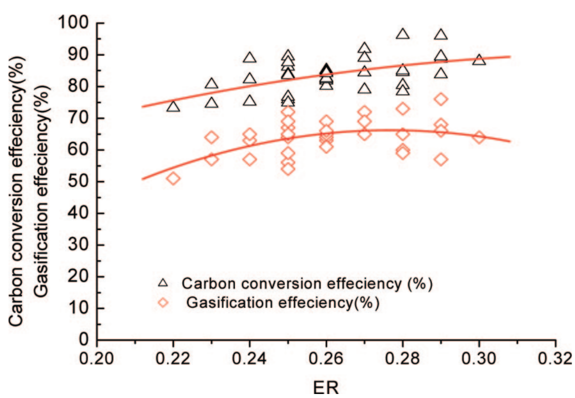

Figure 5. Effect of ER on carbon conversion and gasification efficiencies.

boiler and drying furnaces are fueled with rice husk, resulting in tight supply and a rising price of rice husk. The purchasing price of the raw material at the plant is between 35.7−42.9 USD/ton normally, while it can be increased to more than 42.9 USD/ton during the off-season in some rice mills; the cotton stalk is widely dispersed, but its collection cost is high. The present price of cotton stalk is about 35.7 USD/ton (including crushing treatment).

On the basis of the biomass price of 35.7 USD/ton, the power generating cost of the plant is 0.0790 USD/kWh (including depreciation and interest). As per the local electric grid purchasing price of 0.0793 USD/kWh, balance can be kept with reluctance; however, if the tax of 0.0043 USD/kWh were added, deficit will appear accordingly. According to the current China law on renewable energy, the local electric grid purchasing price should be 0.093 USD/kWh, so that the benefit can be obtained if adopting a preferential electric price, and the internal rate of return (IRR) of the power plant investment can approach 8−9% if the business income tax is exempted; however, the power plant has no profit if the price of raw material is around 42.9 USD/ton and the IRR will be lower than 5%. With a payback period longer than 15 years, the operating risk of the plant becomes very high. Table 9 shows the analysis of the generating cost in the plant.

5. Existing Problems

Although the operation of the demonstration plant has been proven successful after 8000 h test, many problems still exist both in resource availability and technical improvement.

Availability of Biomass Resources. (1) The amount of agricultural stalk fluctuates seasonally; there is still not economic and efficient method to store and keep them. (2) At present, the market of biomass material used for power generating is unstable. The price fluctuates with the demand of market results in the main risks of the economic operation of the power plant.

Technique, Equipments, Operation, and Management. (1) Gasification techniques: existence of the tar produced by the gasification process does not influence the normal operation of the generating equipments but reduces the system efficiency of the plant and increases running cost. Therefore, the gasification technology must be further improved to reduce the formation of tar. (2) Generating equipments: The present engine set is too small; therefore, the amount of installed unit is too many, which makes the management of a large-capacity power plant inconvenient. Developing biomass-fueled gas engines that have a much larger unit capacity should be emphasized. (3) Corollary equipments: the equipments used to bale, porphyrize, and transport agricultural straw are not mature and must be improved during the process of generalization and application of the power plant. (4) Operation and management: management of collecting and supplying of resources must be regulated; the technical standard of the BGPG plant needs to be constituted.

6. Conclusions

A 5.5 MW_e IGCC demonstration plant is introduced relevant to its design and operation at the commissioning stage. The plant was designed on the basis of the gasification−gas engine−steam turbine technical route, forming a novel biomass integrated

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Table 6. Typical Range of the Dry Gas Compositions Used in the Plant

CO	H_2	CH_4	CO_2	C_nH_m	N_2	LHV
15.2−19.2%	6.1−8.9%	3.8−5.7%	12.2−18.4%	0.5−2.3%	46.8−53.3%	4774−6567 kJ/kg

Table 7. Comparison of Power Efficiency between the 8300 and 6250 Gas Engines

relative load of engine sets (%)	8300 (450 kW)	6250 (200 kW)
25	16.9	15.2
50	26.3	22.3
75	29.7	25.6
87.5	29.4	25.9
100	28.7	24.4

Table 8. Comparison of Three BGPG Systems with a Power Output of 200, 1000, and 5500 kW

parameters	200 kW	1000 kW	5500 kW combined cycle
feed rate (kg h^{-1})	400	1500	3000−6000
productivity (kg m^{-2} h^{-1})	127	850	850
efficiency of gasifier (%)	47	65	70−75
gas heating value (kJ Nm^{-3})	3800−4600	4600−6300	4700−6500
overall efficiency (%)	12	18	26−28
rice husk consumption (kg kW^{-1} h^{-1})	2.2	1.7−1.9	1.0−1.2

gasification and combined cycle system. A total of 8000 h of operating experience show that its overall efficiency has been improved from 18% of the 1 MW system to 28%. Its capital and running costs are about 1200 USD/kW and 0.079 USD/kWh, respectively. Its feasibility on technical and economic aspects has been proven according to a preliminary test on the commissioning stage. However, much of the improvement should be considered to increase the efficiency of the system. For instance, to reduce the tar content in the fuel gas and develop a high-temperature gas-cleaning technology; to develop biomass-fueled gas engines that have a much larger unit capacity; or to increase the efficiency of the gas engines by employing pressure boost technology.

Table 9. Analysis of the Generating Cost

item	unit cost (USD/kWh)	remark
fuel cost	0.0464	biomass price: 35.7 USD/ton
repairing cost	0.0050	142 857 USD/year
wage and welfare	0.0057	157 143 USD/year
depreciation	0.0111	300 000 USD/year
management and interest	0.0107	285 714 USD/year
total	0.0790	

The plant is now available for research and development work, which will continue for some years, and during this period, advantages and possible limitations of the new technology will be evaluated. Specific areas of interest, including environmental issues, fuel flexibility, and production costs, will also be focused.

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