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Operating Performance of Full-Scale Agricultural Biogas Plants in Germany and China: Results of a Year-Round Monitoring Program

Lijun Zhou [1,*], Benedikt Hülsemann [1], Zhiyang Cui [2], Wolfgang Merkle [3], Christian Sponagel [4], Yuguang Zhou [2], Jianbin Guo [2], Renjie Dong [2], Joachim Müller [5] and Hans Oechsner [1]

[1] State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim, 70599 Stuttgart, Germany; benedikt.huelsemann@uni-hohenheim.de (B.H.); hans.oechsner@uni-hohenheim.de (H.O.)
[2] College of Engineering, China Agricultural University, Beijing 100083, China; cuizhiyang@inspur.com (Z.C.); zhouyg@cau.edu.cn (Y.Z.); jianbinguo@cau.edu.cn (J.G.); rjdong@cau.edu.cn (R.D.)
[3] Institute for Chemistry and Biotechnology, ZHAW School of Life Sciences and Facility Management, 8820 Wädenswil, Switzerland; wolfgang.merkle@zhaw.ch
[4] Institute of Farm Management (410b), University of Hohenheim, 70599 Stuttgart, Germany; Christian.Sponagel@uni-hohenheim.de
[5] Institute of Agricultural Engineering, University of Hohenheim, 70599 Stuttgart, Germany; joachim.mueller@uni-hohenheim.de
* Correspondence: lijun.zhou@uni-hohenheim.de; Tel.: +49-711-459-23348

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Abstract: Germany (DE) and China (CN) have different political approaches in supporting the biogas sector. Three German and three Chinese large-scale biogas plants (BGPs) were evaluated as part of a year-round monitoring program. Laboratory methods were utilized to analyze the chemical indicators. Results showed a stable anaerobic digestion process without system failures in all BGPs. The methane yield had a range of 0.23–0.35 m^3_{CH4}/kg_{ODM} for DE BGPs and 0.11–0.22 m^3_{CH4}/kg_{ODM} for CN BGPs, due to different substrates and working temperatures. Financial analyses indicated that DE BGPs are viable under their current feed-in tariffs contracts. Their financial internal rate of return (IRR) ranged between 8 and 22%. However, all CN BGPs had negative IRRs, indicating that they are financially unfeasible. Risk analyses illustrated that DE BGPs will face financial nonviability if benefits decrease by 9–33% or costs increase by 10–49%, or if a combined worse case (benefit decrease and cost increase) of 5–20% occurs. Incentives to BGP operations are particularly important in China, where the government should consider switching the construction-based subsidy to a performance-based subsidy system to motivate the operators. BGP monitoring is necessary to understand the performance, in addition to briefing policymakers in case a policy reform is needed.

Keywords: anaerobic digestion; biogas; performance monitoring; financial analysis; policy

1. Introduction

Biogas production is a uniquely flexible form of energy generation. It can be used to generate baseload electricity, meet high demands, provide low-carbon heat, or be upgraded for use as a transport fuel [1]. Since the introduction of a fixed feed-in tariff (FiT) for electricity from biogas plants (BGPs) in 1991, Germany has been continuously developing its biogas technology [2]. The implementation of the German Renewable Energy Sources Act (Act on Granting Priority to Renewable Energy Sources, known by its German acronym "EEG") since 1 April 2000, in which the original legislation guarantees a grid connection for electricity from renewable sources and a governement-set feed-in-tariff for 20 years, has made a great contribution to the biogas sector development. With multiple amendments of the EEG, a tender system in response to market trends was established in the current EEG version from 2017, which will allow the German biogas sector to focus on market-driven electricity production [3–5]. In the case of biomass power plants, the average tendering price reached 14.37 €ct/kWh in 2018 for existing plants [6]. Plants smaller than 75 kW can receive a fixed price up to 23.14 €ct/kWh (biogas from at least 80% manure) under the current EEG 2017.

Up to the end of 2019, there were about 9527 BGPs in Germany, with a total installed electricity capacity of 5.0 GW [7]. In general, the performance-based FiT scheme has led the German BGP operators to focus heavily on the plant operation efficiency to maximize their income and revenue. Renewable resources are widely used as the main substrates for biogas production, accounting for 48.9% of the total substrate input in BGPs in 2016 [8,9]. Livestock excrements (slurry and manure) took second place (44.5%), municipal biowaste ranked third (4.2%), followed by residues from industry, trade, and agriculture (2.4%) [9].

Meanwhile, three nation-wide biogas measurement programs had been conducted to identify the technical, biological, and financial operation efficiency. The first German Biogas Measurement Program (BMP I), conducted from 2001 to 2004, examined operations in each of the 60 BGPs over a one-year period [10]. BMP II was performed from 2006 to 2008 for 61 BGPs put into operation according to the EEG 2004 [11]. The most recent BMP III placed an additional focus on the repowering measures and possibilities of flexible biogas production for a demand-driven energy supply, apart from the operation efficiency of 60 BGPs and the impact of the EEG 2009.

As one of the largest agricultural countries, China has made efforts to develop its biogas sector by implementing a variety of programs, initially as household-based, and gradually switching supports to farm-based BGPs [12,13]. By the end of 2015, investment by the central and local governments supported the completion of 41.6 million rural household biogas digesters and 110,975 biogas projects of various types [14]. During 2000–2017, the central government invested 42 billion Chinese Yuan (CNY) (equivalent to €5.5 billion) in the biogas sector. Furthermore, multilateral and bilateral international development organizations also played a key role in promoting the biogas sector development in China, either through grants or long-term loans [15,16].

In China, most agricultural BGPs used livestock manure as the main substrates. In 2015, there were about 1.06 billion tons of livestock manure available for biogas production, accounting for 75.5% of the total substrates, followed by agricultural straws (12.8%). However, NDRC and MOA (2017) pointed out that nearly 180 million tons of crop straws were not used properly but were burned directly in the field, causing severe air pollution. The intensive livestock farms in China produced about 205,000 tons of manure annually, of which 56% were not properly treated, which can lead to high levels of environmental pollution and a lack of compliance in the livestock sector under the stricter environmental protection regulations. The 13th Five-year Plan for National Rural Biogas Development has set-up targets to increase biogas production capacity by the use of 8.64 million tons of crop straws as substrate to produce 26.5 million tons of digestate by 2020 and subsequently replace 1.14 million tons of chemical fertilizer [14], which means that the biogas sector in China will continue to expand in the coming years.

Unlike the German FiT scheme, the Chinese government tended to invest funds primarily in the forms of subsidies or grants to households or livestock farms for the construction of biogas digesters or plants. As a result, BGPs were operating inefficiently or closed down [12] due to little investment in the final products and maintenance. The Chinese government acknowledged this issue and attempted to gradually switch the policy goal to focus more on quality and less on quantity. Since 2006, the government has issued several regulations to promote the subsidizing of biogas-power projects [17,18]. However, the grid companies are not obligated by law to accept renewable power from biomass, and such biomass power projects require additional government approval before grid connection, further hindering the implementation of such regulations.

Despite the recent impressive expansion in scale, a comprehensive evaluation of the sector's performance in China has not been conducted yet, neither by the government agencies nor research institutes. Significant data gaps exist, particularly in the actual biogas production, rather than the data always reported by official sources about the potential daily production [14,19] or research studies [13,20], as well as the substrate input amount, quantified economic costs, and benefits of biogas digesters, to confirm whether government subsidies are justified. Only a few previous studies have investigated BGPs on a full-scale, although neither chemical indicators nor actual operating data of BGPs have been tested in the laboratory. Han (2011) monitored the monthly operation of three BGPs in Northern China, and found that they have a stable anaerobic digestion process under mesophilic conditions (30–35 °C). However, the financial balance was only calculated for one BGP, which operated at a loss [21]. Liu et al. (2014) conducted a contrastive analysis on the economy of pig farm biogas projects in China and Germany based on a biogas fermentation steady-state model. The results showed poor profitability of Chinese BGPs due to the low electricity tariff [22]. Overall, the BGP operation efficiency in China remains unclear to the public, which on the other hand, makes it difficult to provide sufficient and quantified feedback to the policymakers to improve the policies.

Since October 2017, the authors' team has initiated the first BMP in China with the initial trial conducted on three BGPs based on (1) the substrate applied, (2) operation status, (3) sampling possibility, (4) data availability, and (5) the willingness of BGP operators to cooperate. Three BGPs from the current German BMP III were selected to conduct a general comparison of the BGP operation efficiency. The objectives of this study were: (1) To evaluate how the technical setup, operation conditions, and substrate compositions impact the operation of BGPs; (2) to evaluate the financial viability of these BGPs; (3) to discuss how different Germany (DE) and China (CN) policies have affected the financial sustainability of agricultural BGPs; and (4) to discuss how the DE BGPs can resist the coming auction market pricing.

2. Materials and Methods

2.1. Selection of Full-Scale BGPs in Germany and China

Three Chinese (CN) BGPs were selected in Beijing to conduct a one-year monitoring, within 100 km of the China Agricultural University (Beijing), where the laboratory for the chemical analysis is located. The key selection criteria included (1) willingness of the BGP operators to cooperate; (2) sampling possibilities; and (3) availability of operation data records. Three German (DE) full-scale BGPs under the current BMP III were selected to make general comparisons with CN BGPs in all aspects. They are all located in Baden-Württemberg.

DE1 was built in 2011, commenced operation in 2012, and holds a FiT contract under the EEG 2009 for 20 years. It consists of a 1500 m^3 heated continuous stirred-tank reactor (CSTR) with a mesophilic average working temperature of 42.3 ± 1.9 °C. Cow manure from the packed bedding stalls (CM) and liquid manure from cow (LM) and grass silage (GS) are fed directly to the digester, while the digestate flows into a gas-tight storage tank of 1500 m^3, for subsequent application as fertilizer on-site. The biogas drives a 250 kW combined heat and power (CHP) generator (Motortyp Scania–Schnell, ES 2507; 2G Bio-Energietechnik AG, Heek, Germany). Power is sold to the power grid and heat is partially used for warming up the digesters, and the rest is sold to local residential houses in the surrounding area. Under its EEG-2009 contract, the annual revenue is derived from the basic power tariff, EEG bonus for energy crops, CHP unit and manure, and heating supply. One-year monitoring was conducted in September 2017 to August 2018.

DE2 was built in 2009 and commenced operation in 2011. It holds an FiT contract under EEG 2009 for 20 years. It consists of one 1880 m^3 heated CSTR (average thermophilic working temperature at 49.3 ± 1.0 °C) and one 1880 m^3 complete mixed secondary digester (heated). CM, LM, maize silage (MS), and cereal leftovers (CL) are fed directly to the digester, while the digestate flows into three gas-tight storage tanks of 13,539 m^3 in total, for subsequent fertilizer application on-site. The biogas drives four CHP generators, including three 400 kW generators and one 350 kW generator (E2842 LE322, E3268 LE232, Elektro Hagl KG, Geisenfeld, Germany). Power is sold to the power grid and heat is partially used for heating digesters, and the rest is sold to local residential houses. Under its EEG-2009 contract, the annual revenue is derived from the basic power tariff, EEG bonus for energy crops, CHP unit, manure and power flexibility scheme, and heating supply. One-year monitoring was conducted from September 2016 to August 2017.

DE3 was built in 2013 and commenced operation in the same year. It holds an FiT contract under the EEG 2012 for 20 years. It consists of an 847 m^3 CSTR digester (heated) (mesophilic average working temperature at 41.9 ± 0.2 °C). Chicken solid manure (CSM), CM, LM, MS, and GS are fed directly to the digester, while the digestate flows into a storage tank of 1742 m^3, for subsequent application on-site. The biogas drives one 75 kW CHP generator. Power is sold to the power grid, and heat is completely used for heating the digesters. Given the capacity of this plant (75 kWh CHP unit), the annual revenue only comes from the basic power tariff. One-year monitoring was conducted from September 2017 to August 2018.

In DE BGPs, all initial investments were made by the farmers (in this case, also the BGP operators). Loans obtained from commercial bank(s) to cover the payment had differing loan terms and conditions based on the assessment by each of the banks. During the operation, income was generated from the sale of electricity and heat to repay the principal loan and interest to the bank(s).

CN1 was built in 2007 and commenced operation in the same year. It consists of two 700 m^3 upflow solid reactors (USR) with an average working temperature of 31.3 ± 5.1 °C, a low mesophilic range. Biogas was supplied to seven villages with a total of 1700 households for cooking. CSM was mixed with digestate and/or water for ease of pumping and fed to the digesters (heated by electricity or solar energy), while the digestate flowed into a storage tank of 1500 m^3 for subsequent application on farmland or circulation for feeding. After removing H_2O and H_2S, biogas was compressed through two 22 kW biogas compressors, stored in four 8 bar storage tanks (40 m^3 each), and was then supplied to households. One-year monitoring was conducted from October 2017 to September 2018.

CN2 was built in 2008 and commenced operation in the same year. It was equally financed by the government and the village committee. It consists of four 450 m^3 CSTR digesters (heated by air source heating pumps or electricity or biogas burning) with a mesophilic average working temperature of 38.0 ± 2.2 °C. After mixing with freshwater in the mixing tank (about 60 m^3/d), the substrates, including CSM and CM, were fed directly to the digesters, while the digestate flowed into a storage tank of 1742 m^3, for sequent application on the village-owned farmland and orchards. The biogas was compressed by two 11 kW compressors (42F, AL-160M/4 TF, Nord Drivesystems Nord Co., Ltd., Suzhou, China) and stored in six 8 bar storage tanks with a total capacity of 280 m^3. Biogas was supplied to approximately 2000 households in one village for cooking. Monitoring was conducted from October 2017 to July 2018 as this BGP was closed down afterward due to the natural gas supply to local households.

CN3 was built in 2007 and commenced operation in 2008. It was equally financed by the government and the village committee. It consists of two 160 m^3 USR digesters (heated) with an average working temperature of 32.0 ± 2.2 °C in the low mesophilic range. Pig manure (PM) was fed directly to the digester, while the digestate flowed into the underground storage tank with 450 m^3 (not fully covered, no biogas collection), for sequent application in the vineyard and other agricultural fields (free of charge and delivered to the field for farmers). The biogas was compressed by an 11 kW compressor and stored in one 8 bar storage tank of 30 m^3. Biogas was supplied to 184 households in one village for cooking. One-year monitoring was conducted from October 2017 to September 2018.

In all CN BGPs, the village committee is responsible for the daily operation, as well as managing the income and the assumption of operation costs (including labor and all maintenance cost). Investment from the central government is a type of grant, requiring no repayment. Income is sourced from biogas sold to the local households.

Table 1 presents the details of these BGPs. Figure 1 presents the general BGP schemes of DE BGPs and CN BGPs.

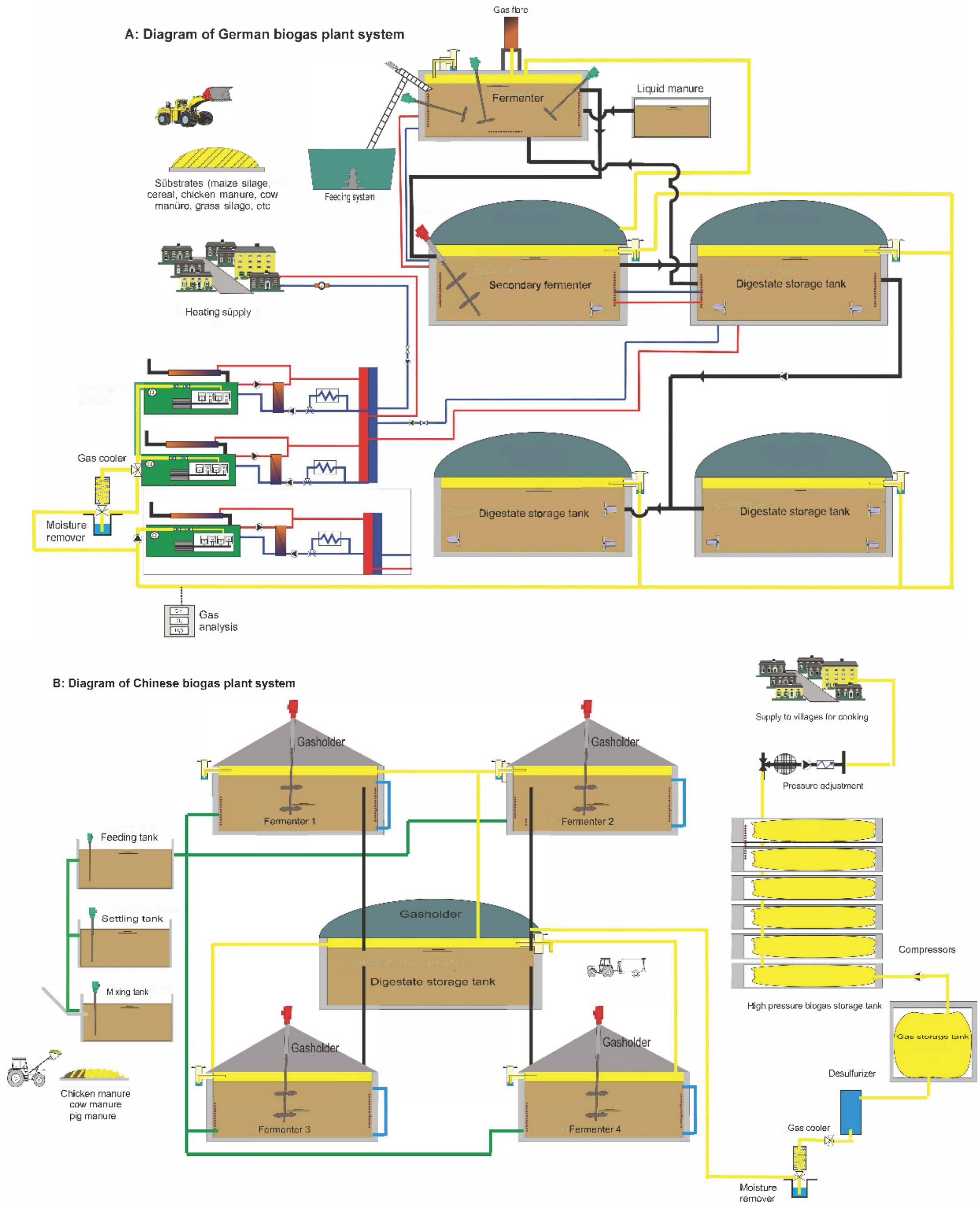

Figure 1. Diagram of the generally selected German (**A**) and Chinese (**B**) biogas plants.

Table 1. Characteristics of the selected German (DE) and Chinese (CN) biogas plants.

Key indicators	DE1	DE2	DE3	CN1	CN2	CN3
Year of construction	2011	2009	2013	2007	2008	2008
Main technology	CSTR	CSTR	CSTR	USR	CSTR	USR
Mixing tank (m^3)		201		40	80	20
Digester (m^3)	1500	1880	847	1400	1800	320
Secondary digester (m^3)	-	1880	-	-	-	-
Digestate storage tank (m^3)	1500	13,539	1742	1500	1000	450 [1]
Biogas compressor (kW)	-	-	-	22	22	7.5
CHP (kW)	250	1550	75	-	-	-
Substrates	CM, LM, GS	CM, LM, MS, GS, CL	CSM, CM, LM, MS, GS	CSM	CSM, CM	PM

[1] open storage tank. CSTR = continuous stirred-tank reactor, USR = upflow solid reactor, CHP = combined heating and power, CM = cow manure, CSM = chicken solid manure, GS = grass silage, LM = liquid manure, MS = maize silage.

2.2. Sampling

For all six BGPs, samples were collected monthly, including the substrates, feeding slurry (FS), fermentation liquid from digesters (FL), fermentation liquid from secondary digesters (SFL), and digestate slurry from storage tanks (DS). Sample collection methods were the same as described in Ruile et al. (2015) and Lansing et al. (2019) [23,24]. In DE BGPs, all samples were transported on ice and stored at −20 °C before the analysis, while in CN BGPs, all samples were cooled down to 4 °C, and analyses were conducted immediately after the collection and transported back to the laboratory. Biogas quality (CH_4 concentration) was measured through an on-site continuous biogas monitoring system for DE1 and DE2, whereas such a system was not installed in DE3, and biogas sampling was impossible during the monitoring period. In CN BGPs, biogas samples were collected monthly and the CH_4 content of the biogas was measured using a methane-sensor (UE20, ONUEE Electronics Co., Ltd., Shenzhen, China). Records of the working temperature for the digesters were obtained from on-site recording.

2.3. Chemical Analyses

2.3.1. German (DE) Laboratory

DE sample analysis was conducted in the laboratory of the State Institute of Agricultural Engineering and Bioenergy at the University of Hohenheim. Dry matter (DM) and organic dry matter (ODM) concentrations for all samples were determined in accordance with DIN EN 12880 and DIN EN 12879 [25,26], by the volatile solids. The pH values of FL and DS were measured using a digital pH meter (pH 330, WTW, Weilheim, Germany). The acid concentration equivalent was determined by GC (GC2010plus, Shimadzu Corp, Kyoto, Japan) with the capillary column WCOT Fused Silica (50 m length, 0.32 mm ID, coating CP-Wax 58 (FFAP)-CB) and an FID detector (280 °C) (both Varian, Palo Alto, CA, USA). Helium was used as the carrier gas. A detailed description of the method can be found in Steinbrenner et al. (2019) [27].

The ratio of volatile organic acids and total inorganic carbon (VOA/TIC) was obtained by determining acetic acid equivalents of the fermentation slurry through an automatic titration system (785 DMP Titrino-Metrohm, Filderstadt, Germany) after sample centrifugation in a refrigerated centrifuge at 5000 rpm (Z323K, Hermle-Labortechnik, Wehingen, Germany). The total ammonium nitrogen (TAN) was analyzed by using the automatic distillation system Gerhardt Vapodest® 50s (Gerhard Analytical System, Königswinter, Germany). The total nitrogen was detected by the method of Kjeldahl (TKN) with Kjeltabs CX, THURBOTHERM and Vapodest® 50s (all Gerhard Analytical System, Königswinter, Germany) [24,28,29].

2.3.2. Chinese (CN) Laboratory

CN sample analysis was conducted in the Key Laboratory for Clean Renewable Energy Utilization Technology at the College of Engineering of the China Agricultural University (Beijing, China). DM, ODM, and TAN for samples were determined based on the American Public Association standard method APHA [30,31]. The pH values of FS, FL, and DS were measured using a digital pH meter (Fiveeasy Plus FE28, Mettler Toledo, Shanghai, China).

The ratio of VOA/TIC was obtained by determining acetic acid equivalents of the fermentation slurry through a manual titrator (Model 923, BRAND GMBH+CO KG, Wertheim, Germany) by the Nordmann method [32].

In the three CN BGPs, operators did not record the mass but the volume of daily substrate input (for the purpose of payment). To estimate the corresponding mass, the density of all substrates was determined by weighing the substrates in a $30 \times 30 \times 25$ cm^3 box, resulting in 1.0, 0.86, and 0.8 t/m^3 for PM, CSM, and CM, respectively.

2.4. On-Site Data Collection

Operation data were collected from the operators of DE and CN BGPs. Data from DE BGPs included the (1) amount of substrates; (2) biogas, electricity, and heat production; (3) electricity and heat sold; (4) working temperature; and (5) financial data for 2016 and 2017. Data from CN BGPs included the (1) volume of substrates (due to lack of weighing system); (2) biogas production in CN1 and CN2; (3) biogas sold to households; (4) working temperature; the (5) financial data for the entire operating period.

2.5. Calculations and Statistical Analysis

The statistical analyses were performed in EXCEL. Data were reported as averages ± standard deviation (SD) wherever possible.

Equations for calculating the hydraulic retention time (HRT), expressed in days; organic loading rate (OLR), expressed in kg$_{ODM}$/m^3/d; and the productivity related to biogas production, expressed in m$^3{}_{CH4}$/m^3/d [33] are as follows:

$$HRT = \frac{V_R}{\dot{V}} \tag{1}$$

$$OLR = \frac{\dot{m} \cdot c}{V_R \cdot 100} \tag{2}$$

$$P_{CH_4} = \frac{\dot{V}_{CH4}}{V_R} \tag{3}$$

$$A_{CH_4} = \frac{\dot{V}_{CH4}}{\dot{m}_{ODM}} \tag{4}$$

where V_R is the digester volume (m^3), $\dot{V}$ is the volume of substrate added daily (m^3/d), $\dot{V}_{CH4}$ is the methane production (m^3/d), $\dot{m}$ is the amount of substrate added per unit of time (kg/d), $\dot{m}_{ODM}$ is the amount of ODM added per unit of time (t/d), and c is the concentration of organic matter (ODM) (% fresh matter (FM)).

2.6. Financial Analysis

Financial analysis has been undertaken individually for all BGPs by applying the discounted cash flow method. The financial analyses focus on the financial viability of the biogas produced for CN BGPs and the electricity and heat for the DE BGPs. The assumptions that were used for the financial analysis include:

- Project costs are expressed in Euro (€), and the average exchange rate in 2017 (€ 1.00 = CNY 7.6293) was used for CN BGPs wherever needed.

- All BGPs were expected to be fully implemented (civil works and equipment supply and installation) in one year following the completion of construction, and the residual value of the investment is zero.
- DE BGPs are assumed to operate for 20 years due to the existing EEG contracts while CN BGPs were operated for 10 years based on the actual operation situation.
- Based on the consultation with operators of DE BGPs, replacement of the CHP unit is required after seven years of operation.
- Operation and maintenance costs have been estimated to cover the costs of fuel and power for the BGPs, salaries and welfare, routine maintenance (including CHP units), and other operating expenses.
- For DE BGPs, the income tax rate is calculated individually for each BGP according to the German Income Tax Act, assuming that the income from the BGP is the total taxable joint income per calendar year 2017 of the operators, and BGPs are sole proprietorships [34].
- The weighted average cost of capital (WACC) used for the financial analysis is estimated based on the actual interest rate that operators paid for loans from commercial bank(s) and the investments that are financed by the operators in DE BGPs, or in CN BGPs, by the village committees and government.
- Revenues are based on prevailing prices in 2017 and are expressed in constant 2017 terms.

In the present work, the future scenario using an average market price cap for biomass (2018 auction price, 14.37 €ct/kWh) [6] is used to explore the financial viability when German renewable energy will face the end of guaranteed pricing. This scenario also applies to newly built BGPs in the future, which are operated similarly as these selected BGPs.

The financial net present value (NPV) is defined as the sum of the present values of the individual (yearly) cash flows. A project is financially feasible when the NPV is positive, and the financial internal rate of return (IRR) must be greater than WACC, which is used as the discount rate to estimate the NPV of the BGP cash flows [35,36]. The higher the NPV, the more profitable the BGP [37]. The IRR of a net cash flow is calculated after tax. Equations for calculating the NPV, IRR, and WACC are expressed as [38]:

$$PV = \sum_{t=0}^{n} a_t S_t \tag{5}$$

$$0 = \sum \frac{S_t}{(1 + IRR)^t} \tag{6}$$

$$WACC = \left[r_{debt} * (1 - tax\ rate) * \frac{Debt}{Debt + Equity} \right] + [r_{equity} * \frac{Equity}{Debt + Equity}] \tag{7}$$

where a_t is the financial discount factor chosen for discounting at time t, S_t is the balance of cash flow at time t (€), r_{debt} is the cost of debt (%) (actual cost collected from the operators), and r_{equity} is the cost of equity (8.1% was used in the calculation for DE BGPs) [39].

2.7. Sensitivity and Risk Analysis

Risks associated with the proposed BGPs may be summarized as follows:

- Costs of operation and maintenance (O and M) will be higher than the current situation due to possible system failure.
- Overall benefits may be lower than expected due to operational issues or simply lower than the expected production of biogas, or in the future after termination of the current EEG FiT.
- In a worst-case scenario, the BGP might experience both of these impacts.

Each of these risks has been analyzed through sensitivity tests on the financial analyses. The tests investigated the impact of:

- 10% increase in O and M costs,
- 10% decrease in benefits, and
- 10% increase in O and M costs combined with a 10% reduction in benefits [35].

Switching values (SV) were calculated according to the ADB Guidelines for the Economic Analysis of Projects [35], which is a parameter to indicate the percentage change required in a variable for the financial/economic viability to change.

3. Results and Discussion

3.1. Substrates and Their Characteristics

3.1.1. Substrates and Their Characteristics in DE BGPs

In DE BGPs, all substrates were transported to plants from the field, and silage was made in the silos for daily feeding. Table 2 summarizes the substrate input and its relevant DM and ODM. Both energy crops and livestock manure were fed as substrates. DE1 fed 44% manure (2996 t/a fresh matter: FM) and 56% energy crops (3755 t/a FM), DE2 fed 50% of each (23,611 t/a FM in total), and DE3 fed 82% manure (3726 t/a FM) and 18% energy crops (806 t/a FM).

Table 2. Annual substrate input and characteristics in German (DE) and Chinese (CN) biogas plants. Results are averages ± SD.

Types	Indicators	DE1	DE2	DE3	CN1	CN2	CN3
CSM	FM (t/a)			411	1101	995	
	DM (%)			53.9 ± 7.5	26.3 ± 0.9	25.7 ± 2.7	
	ODM (% FM)			46.3 ± 6.3	19.3 ± 2.0	19.5 ± 3.0	
CM	FM amount	313	4616	272		1109	
	DM (%)	23.3 ± 3.0	25.9 ± 3.5	24.7 ± 4.6		31.4 ± 2.5	
	ODM (% FM)	18.5 ± 2.1	21.5 ± 2.7	19.0 ± 3.7		23.9 ± 0.8	
PM	FM amount						898
	DM (%)						26.2 ± 2.1
	ODM (% FM)						20.2 ± 1.8
LM	FM amount	2683	7300	3043			
	DM (%)	6.9 ± 1.9	4.5 ± 2.2	10.2 ± 3.4			
	ODM (% FM)	5.2 ± 1.6	3.5 ± 1.9	7.8 ± 2.6			
MS	FM amount		10,468	215			
	DM (%)		37.7 ± 3.2	34.1 ± 2.9			
	ODM (% FM)		36.3 ± 3.2	32.9 ± 2.8			
GS	FM amount	3755		591			
	DM (%)	32.3 ± 4.9		27.1 ± 10.8			
	ODM (% FM)	28.5 ± 4.3		23.5 ± 10.3			
CL	FM amount		627				
	DM (%)		83.3 ± 6.7				
	ODM (% FM)		81.0 ± 6.5				
DS [1]	FM amount				13,140		
	DM (%)				3.1 ± 1.6		
	ODM (% FM)				1.4 ± 0.6		
Total energy crops FM (t/a)		3755	11,695	806			
Total manure FM (t/a)		2996	11,916	3726	14,241	2103	898
Total FM (t/a)		6751	23,611	4532	14,241	2103	898
Total substrate cost (€/a)		0 (Self-supply)	277,843.2	0 (Self-supply)	14,101.6	19,420.7	9475.6

[1] assumption based on the CN1 operator. CSM = chicken solid manure, CM = cow manure, PM = pig manure, LM = liquid manure, MS = maize silage, GS = grass silage, CL= cereal leftover, DM = dry matter, ODM = organic dry matter, DS = digestate slurry.

3.1.2. Substrates and Their Characteristics in CN BGPs

In the CN BGPs, substrates (only manure) were transported to plants each day, but no storage silos were present. CN1 fed CSM (about 1101 t/a) together with digestate for dilution (about 36 m^3/d according to the operator, instead of using fresh water). CN2 fed 995 t/a of CSM and 1109 t/a of CM into four identical digesters. CN3 fed 898 t/a of pig manure.

It was found that the CSM from DE and CN had significantly different compositions. For instance, CSM in CN1 and CN2 had a DM value of 26.3 ± 0.9% and 25.7 ± 2.7%, respectively, and an ODM value of 19.3 ± 2.0% FM and 19.5 ± 3.0% FM, respectively. However, in DE3, CSM had a DM value of 53.9 ± 7.5% and an ODM value of 46.3 ± 6.3% FM. This can be caused by different types of chicken reared, as well as different farming systems used. This result is supported by the research carried out by Jurgutis et al. (2020) for seven CSM samples collected in Lithuania, in which the DM ranged between 27.71 ± 1.13% and 81.80 ± 1.75%, and the ODM ranged between 45.90 ± 2.05% DM and 85.88 ± 0.88% DM [40]. Furthermore, CN BGPs used only livestock manure as substrates while DE BGPs used both livestock manure and energy crops as substrates, which can lead to a significant difference in productivity (Table 3).

Table 3. Outputs and performance of selected German (DE) and Chinese (CN) biogas plants.

Items	DE1	DE2	DE3	CN1	CN2	CN3
Biogas production (m^3/d)	2290	10,458	804	431	581	91
Productivity ($m^3{}_{CH4}/m^3/d$)	0.82	1.41	0.49	0.17	0.18	0.17
Yield ($m^3{}_{CH4}/t_{ODM}$)	354	349	234	222	199	106
Electricity production (kWh/d)	4585	23,695	1757	-	-	-
Heat production (kWh/d)	4461	9228	Not recorded	-	-	-
OLR ($kg_{ODM}/m^3/d$)	2.31	4.05	2.10	0.78	0.91	1.55
HRT (day)-heated system	81	58	72	36	30	16
HRT (day)-gas-tight system	162	267	234	74	47	16

HRT = hydraulic retention time, ODM = organic dry matter, OLR = organic loading rate.

3.2. BGPs Outputs and Performance

3.2.1. Outputs and Performance of DE BGPs

As presented in Table 3, DE1 had a daily OLR of 2.31 $kg_{ODM}/m^3/d$, a HRT in the heated system of 81 days, and a HRT in the entire gas-tight system of 162 days. It produced a total of 835,765 m^3/a biogas, which generated 1,673,661 kWh of electricity and 1,628,128 kWh of heat. This led to a CH_4 productivity of 0.82 $m^3{}_{CH4}/m^3/d$ and a CH_4 yield of 354 $m^3{}_{CH4}/t_{ODM}$.

DE2 had a daily OLR of 4.05 $kg_{ODM}/m^3/d$, a HRT in the heated system of 58 days, and a HRT in the entire gas-tight system of 267 days. It produced a total of 3,817,055 m^3/a biogas, which generated 8,648,634 kWh of electricity and 3,368,255 kWh of heat. This led to a productivity of 1.41 $m^3{}_{CH4}/m^3/d$ and a CH_4 yield of 349 $m^3{}_{CH4}/t_{ODM}$.

DE3 had a daily OLR of 2.10 $kg_{ODM}/m^3/d$, a HRT in the heated system of 72 days, and a HRT in the entire gas-tight system of 234 days. It produced a total of 3,817,055 m^3/a biogas, which generated 293,622 kWh of electricity. Heat was not recorded, as it was only for internal consumption. It had a CH_4 productivity of 0.49 $m^3{}_{CH4}/m^3/d$ and a CH_4 yield of 234 $m^3{}_{CH4}/t_{ODM}$.

For these three DE BGPs, the HRT in the gas-tight system is longer than the period required according to the EEG 2017, which states that the HRT in the entire gas-tight system that is connected to a gas consumption device should last for at least 150 days. This is the case for installations commissioned after 31 December 2016 and digestate storage facilities after 31 December 2011 [4], even though this requirement is not mandatory for these three BGPs. The OLR was between 2.10 and 4.05 $kg_{ODM}/m^3/d$, which is in the middle range of results from other research conducted in more than 140 German BGPs, resulting in a daily OLR between 0.4 and 7.0 $kg_{ODM}/m^3/d$ [10,11,23,24]. Regarding the CH_4 yield, DE1 and DE2 had a similar value. However, as manure was the dominant substrate in DE3, it had a much lower productivity (0.49 $m^3{}_{CH4}/m^3/d$). This result represents the lower end among other similar plants that were monitored under the BMP I, of which eight BGPs applied manure as main substrates (83–88% of the total FM), with an OLR range of 0.8–5.1 $kg_{ODM}/m^3/d$ and a productivity of 0.41–0.89 $m^3{}_{CH4}/m^3/d$ [10]. Such differences could be caused mainly by: (1) The characteristics of the substrates; and (2) working temperatures.

3.2.2. Outputs and Performance of CN BGPs

CN1 had a daily OLR of 0.78 $kg_{ODM}/m^3/d$, a HRT in the heated system of 36 days, and a HRT in the entire gas-tight system of 74 days. Li et al. (2017), in a 10-day monitoring to two BGPs (mono-digestion with CSM) in Penglai City of Shandong Province in China, showed a daily OLR of 0.97 ± 0.4 $kg_{ODM}/m^3/d$, a HRT in the primary digester of 30 days, and a HRT in the entire system of 40 days, for a BGP with a total digester volume of 3300× m^3 and working temperate of 37 ± 2 °C; and a daily OLR of 0.85 ± 0.3 $kg_{ODM}/m^3/d$, a HRT in the primary digester of 45 days, and a HRT in the entire system of 55 days, for another BGP with a total digester volume of 3300×12 m^3 and working temperate of 37 ± 2 °C [41]. In our study, CN1 produced a total of 157,202 m^3/a biogas to supply households. It had a productivity of 0.17 $m^3{}_{CH4}/m^3/d$ and a yield of 222 $m^3{}_{CH4}/t_{ODM}$.

CN2 had a daily OLR of 0.91 $kg_{ODM}/m^3/d$, a HRT in the heated system of 30 days, and a HRT in the entire gas-tight system of 47 days. It produced a total of 212,206 m^3/a biogas to supply the households. It had a productivity of 0.18 $m^3{}_{CH4}/m^3/d$ and a yield of 199 $m^3{}_{CH4}/t_{ODM}$.

CN3 had a daily OLR of 1.55 $kg_{ODM}/m^3/d$ and a HRT of 16 days. It produced a total of 33,333 m^3/a biogas to supply the households. It had a productivity of 0.17 $m^3{}_{CH4}/m^3/d$ and a yield of 106 $m^3{}_{CH4}/t_{ODM}$.

Currently, China has no regulation yet to restrict the HRT in an anaerobic digestion system. Unlike the co-digestion BGPs, a pure livestock manure BGP usually has a much lower HRT, both in DE and CN [41]. There were nine BGPs under the BMP I, applying predominantly livestock manure (>95% of the total FM), which resulted in a HRT range of 17–43 days, a daily OLR range of 1.0–5.6 $kg_{ODM}/m^3/d$, and a productivity of 0.50–1.41 $m^3{}_{CH4}/m^3/d$ [10]. Therefore, the productivity of these three CN BGPs was much lower than the comparable DE BGPs, which may be caused by (1) lower substrate input and mono-digestion; (2) lower working temperature, especially during the wintertime; and (3) sedimentation in digesters caused by improper mixing in CN1 and CN3, which reduced the working volume.

3.3. Digester Temperature

As presented in Figure 2, in the DE BGPs, the monitoring showed a stable working temperature in digesters under thermophilic or mesophilic conditions (42.3 ± 1.9 °C, 49.3 ± 1.0 °C, and 41.9 ± 0.2 °C for DE1, DE2, and DE3, respectively). This is mainly caused by the heat supplied to digesters sourced from the CHP units.

In the CN BGPs, records showed a relatively low working temperature with high variations (31.3 ± 5.1 °C, 38.0 ± 2.2 °C, 32.0 ± 2.2 °C for CN1, CN2, and CN3, respectively). Wandera et al. (2018) in their paper also presented four BGPs in Beijing that had a working temperature of 35 °C [42]. Due to the lack of CHP units in CN BGPs and stricter environmental protection regulations in Beijing (no raw coal burning since 2017), external sources of energy, such as solar energy and electricity (CN1), biogas combustion and/or electricity (CN2), and geothermal pumps and solar energy (CN3), were used to maintain the temperatures in the digesters during winter. However, the use of such energy sources is costly; therefore, operators only supplied heating for a few hours in the wintertime (less than 12 h) to prevent pipelines and digesters from freezing. Consequently, the low working temperature limited the biogas productivity in CN BGPs.

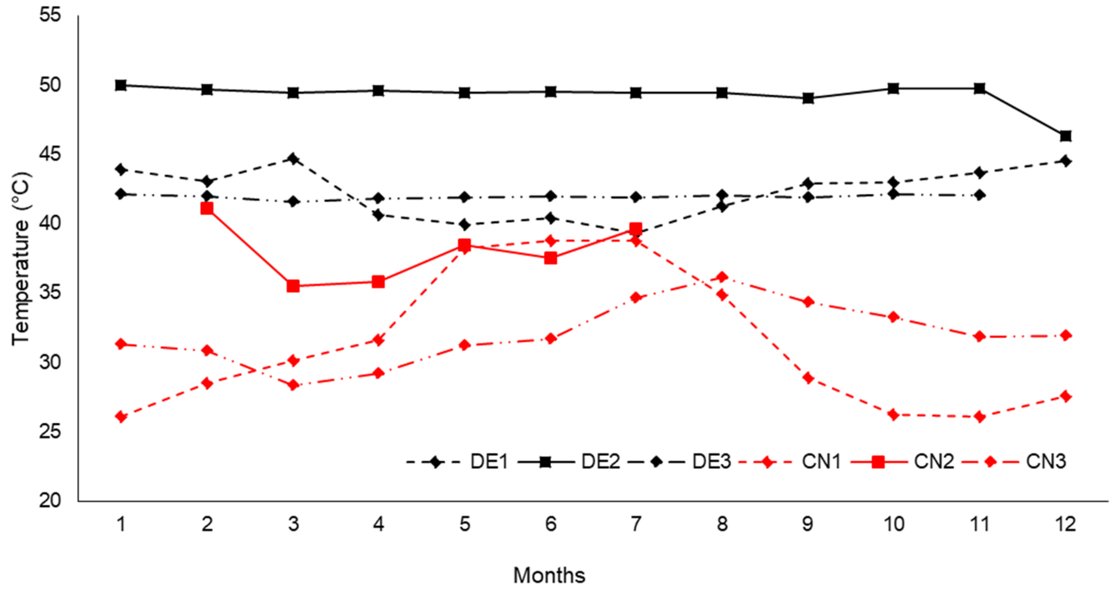

Figure 2. Year-round digester temperature of the selected German (DE) and Chinese (CN) biogas plants.

3.4. Digester Process Stability

3.4.1. pH

During the monitoring period, it was found that in CN2, the pH value of the feeding slurry varied significantly (pH 6.7 ± 0.9) due to a periodic switch of feeding between CSM and CM (normally, 30 days feeding for CSM and 15–20 days feeding for CM). However, this situation was not found in FL and DS, as such liquids were homogenized. The testing showed a stable pH value in the FL and DS for both DE BGPs and CN BGPs.

3.4.2. Total Ammonia Nitrogen (TAN) and Total Kjeldahl Nitrogen (TKN)

It was found that in DE3, the concentration of TAN in the FL reached 5.55 ± 1.55 g/kg. This is likely due to the feeding of CSM, which normally contains a higher concentration of ammonium (NH_3-N) [23], while in CN1, where CSM was fed and DS circulated due to the difficulties of field application, a high TAN concentration resulted with high SD, both in FL and DS, at 6.40 ± 3.48 and 7.70 ± 4.25 g/kg, respectively. It is possible that the high concentration of TAN, reported between 5 and 14 g/kg, could inhibit the anaerobic digestion process [43,44]. However, even though CN2 and CN3 were fed with 100% livestock manure substrates (CSM and CM, PM, respectively), a low TAN concentration was found in both plants at 1.93 ± 0.88 and 1.24 ± 0.31 g/kg, respectively. This situation could have been caused by the (1) dilution of substrates by freshwater, which decreased the TAN concentration; (2) no digestate circulation to the digesters, leading to lower TAN accumulations; or (3) different substrate characteristics.

3.4.3. VOA/TIC Ratio

The annual average VOA/TIC for FL of DE2 (0.35 ± 0.08) indicated a high biomass input in the digester (overloaded ODM), while in the secondary digester, the VOA/TIC was reduced to 0.23 ± 0.02. Hach Lange GmbH (2015) and Lossie and Pütz (2008) reported that a VOA/TIC ratio between 0.3 and 0.4 maximizes biogas production. While the daily feeding was stable, the slightly high VOA/TIC did not lead to high fluctuations in biogas production during the monitoring. All the other DE and CN BGPs had a VOA/TIC ratio less than 0.3, indicating that the anaerobic digestion process was stable [45–47].

3.4.4. Methane (CH_4) Concentration

During the monitoring year, it was found that in DE and CN BGPs, except for DE3 as the measurement was impossible to carry out, the CH_4 concentration in the biogas was stable (Table 4). CH_4 concentrations in CN BGPs were found to be higher than those of DE BGPs, which is strongly related to the substrate compositions (pure livestock manure in CN BGPs but co-digestion of energy crops and livestock in DE BGPs). It is in line with the KTBL standards [48].

Table 4. Process stability indicators of German (DE) and Chinese (CN) biogas plants (BGPs), including the pH value, concentration of total ammonia nitrogen (TAN), total Kjeldahl nitrogen, VOA/TIC ratio, and total volatile acids (VFAs) in fermentation liquid (FL) and digestate slurry (DS). Results are averages ± SD.

Indicators	DE1	DE2	DE3	CN1	CN2	CN3
			pH			
LM/FS [1]	7.5 ± 0.2	7.4 ± 0.2	7.4 ± 0.2	7.8 ± 0.2	6.7 ± 0.9	6.9 ± 0.3
FL	7.7 ± 0.2	7.9 ± 0.9	8.2 ± 0.1	7.9 ± 0.1	7.5 ± 0.2	7.4 ± 0.2
DS	7.7 ± 0.2	8.2 ± 0.3	7.9 ± 0.1	8.3 ± 0.2	8.2 ± 0.3	7.3 ± 0.4
			TAN (g/kg)			
FL	2.82 ± 0.66	4.35 ± 0.60	5.55 ± 1.55	6.40 ± 3.48	1.93 ± 0.88	1.24 ± 0.31
DS	3.14 ± 0.42	4.86 ± 0.47	5.52 ± 1.30	7.70 ± 4.25	1.92 ± 0.92	0.96 ± 0.28
			TKN (g/kg)			
FL	4.85 ± 0.95	6.74 ± 0.75	6.90 ± 1.66			
DS	4.94 ± 0.60	6.85 ± 0.63	6.61 ± 1.27			
			VOA/TIC Ratio			
FL	0.22 ± 0.03	0.35 ± 0.08	0.22 ± 0.04	0.19 ± 0.07	0.24 ± 0.08	0.24 ± 0.05
SFL		0.23 ± 0.02				
			VFAs			
FL	0.18 ± 0.12	2.01 ± 0.93	0.67 ± 0.56			
CH_4 (%)	53.6 ± 1.5	50.8 ± 2.6		56.2 ± 2.6	56.5 ± 1.3	57.9 ± 2.6

[1] LM for DE BGPs, FS for CN BGPs. LM = liquid manure, FS = feeding slurry, DS = digestate slurry, FL = fermentation liquid, SFL = fermentation liquid from the secondary digester, VOA = volatile organic acids, TIC = total inorganic carbon.

3.5. Financial Performances of DE and CN BGPs

3.5.1. Financial Analysis—Current Operation Situation

The financial analysis indicated that all DE BGPs are financially viable with IRRs ranging between 8.4% and 21.5%, greater than its related WACC (Table 5). DE3 shows the highest estimated unit NPV as the fixed price for BGP lies at 75 kW.

Meanwhile, CN BGPs have negative IRRs and NPVs, which means these BGPs are financially inviable during their entire life cycle (about 10 years) due to lower annual revenues than the operation costs. As the local village committees are responsible for the entire operation, other income sources were used to compensate for all the losses incurred by the BGPs.

Table 5. Estimated financial indicators for German (DE) and Chinese (CN) biogas plants (BGPs).

BGPs	Investment Cost € Million	Average Annual Revenue € Million	Average Annual Operation Cost € Million	WACC %	IRR %	NPV € Million	Unit NPV $€/m^3{}_{biogas}/a$
			Current Situation				
DE1	1.60	0.49	0.29	4.52	8.45	0.54	0.65
DE2	4.00	1.89	0.58	3.65	21.54	7.59	1.99
DE3	0.49	0.16	0.05	4.10	17.76	0.68	2.33
CN1	1.19	0.04	0.10	4.29	<0	−1.01	−6.45
CN2	1.31	0.03	0.08	4.29	<0	−1.02	−4.81
CN3	0.22	0.01	0.02	4.29	<0	−0.22	−6.73
			DE BGPs-Future Scenario				
DE1	1.60	0.33	0.29	4.52	<0	−1.30	−1.55
DE2	4.00	1.32	0.58	3.65	11.10	2.82	0.74
DE3	0.49	0.09	0.05	4.10	2.91	−0.05	−0.16

WACC = weighted average cost of capital, IRR = internal rate of return, NPV = net present value.

3.5.2. Financial Analyses—Future Scenario

Under the future scenario (assuming the power price at 14.37 €ct/kWh), DE1 and DE3 will not be financially viable while DE2 can still be robust, which indicates that DE1 and DE3 need to seek more income channels (i.e., sell more heat to local communities) if the power price drops significantly after the termination of their current EEG-2009 contract.

3.6. Sensitivity and Risk Analyses for DE BGPs

Table 6 summarizes the results of the sensitivity tests for the financial analyses. The analyses indicated that DE2 and DE3 are financially viable as the SV, which indicates that the percentage increase in costs or decrease in benefits required for a BGP to be financially inviable is in excess of 10% (for DE3, the SV for a decrease in benefits is in excess of 30%). However, DE1 has an SV less than 10% for both cost increases and benefit decreases. It is important for DE BGPs, especially DE1, to improve their efficiency and/or income sources to tackle the difficulties that they may face, especially after the termination of the current EEG contracts as the electricity price can decrease significantly if it should be tendered in the market. A sensitivity analysis was not conducted for CN BGPs, due to the current negative FIRRs.

Table 6. Summary of sensitivity tests for financial analyses of German (DE) biogas plants.

Scenarios		Indicators	DE1	DE2	DE3
Cost Increase	**10% Increase**	**IRR (%)**	4.46	16.63	14.36
		Unit NPV ($€/m^3$biogas/a)	−0.01	1.52	1.86
	SV (%)		9.85	42.13	49.24
Benefit Decrease	**10% Decrease**	**IRR (%)**	4.03	16.13	14.02
		Unit NPV ($€/m^3$biogas/a)	0.07	1.32	1.62
	SV (%)		8.97	29.64	32.99
Cost Increase + Benefit Decrease	**10% Cost Increase + Benefit Decrease**	**IRR (%)**	−0.34	11.38	10.77
		Unit NPV ($€/m^3$biogas/a)	−0.73	0.85	1.15
	SV (%)		4.69	17.4	19.75

IRR = internal rate of return, NPV = net present value, SV = switching value.

3.7. Recommendations

The year-round measurements showed that it is important to increase income channels and improve operational efficiency. Alternatives include (1) the co-digestion of substrates in BGPs, considering that a large amount of agricultural residues and kitchen wastes remain untreated in China; (2) stable substrate supply to ensure the proper operation of BGPs.

Note that all three CN BGPs faced difficulties of stable substrate supply due to stricter environmental protection requirements in the livestock sector in China, especially around Beijing, where many livestock farms closed down; (3) CHP incorporation for electricity and heat production, instead of direct supply to households for CN BGPs as the rural energy supply is transformed gradually to electricity. In this way, generated heat can be supplied internally to circumvent the high cost of heating the digesters (20–40% of the total operation cost); (4) from the policy makers aspect, a Chinese government subsidy should be granted on a performance basis to encourage the proper operation of the BGPs. In Germany, starting in 2021, many of the BGPs will no longer receive fixed FiT, meaning some of them may shut down if they are not able to find new business models. Biogas operators are encouraged to find more income sources to tackle the financial difficulties, such as the heat supply to local communities or feeding electricity into the grid during high-demand periods to receive the flexibility premium; and finally, (5) establishment of regular BGP performance monitoring with professional advice and support to the BGP operators.

4. Conclusions

Different biogas regulations have led to the application of different substrates and operational and financial services in the selected BGPs. In Germany, the higher use of energy crops and CHP units led to a longer HRT, and higher OLR and CH_4 yield. Financial analyses showed IRRs ranging between 8.4 and 21.5% in DE BGPs under the current EEG contracts. Negative IRRs showed financial nonviability for the CN BGPs. Although all the losses were covered by the village committees, the government and/or operators need to pursue a higher efficiency and find more income sources to sustain the operation of BGPs in China. The sensitivity analysis indicates that DE BGPs have a resilience to 9.0–33.0% of the reduction in benefits, with 4.7–19.8% to fluctuations if costs increase and benefits decrease simultaneously. Proper policies to promote the effective operation of BGPs are important to sustain the development of this sector, from the plant planning, technical designs, operation, and payment methods.

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