Chapter 5
Design and Techno-economic Analysis of a Biogas Plant as an Alternative Heat Source in the Food Processing Industry

Raman Kumawat, Lata Gidwani, and Kunj Bihari Rana

Abstract Biogas has been a vital source of energy for ages. Biogas is the fourth largest contributor to renewable energy and contributes around 11% of India's and 15% of global renewable energy power generation. Recent advancements in technology make it viable to use biogas as an alternative heat source for small and medium-scale industries. This study focuses on designing a biogas plant to meet up the energy requirements of Bikaji Foods International Ltd., a food processing industry located in Bikaner, Rajasthan. The highest livestock population increase rate (31.85%) in the state makes Bikaner a perfect site for the plant setup. The region has a hot desert climate with an average annual temperature of 29 °C. The plant design is based on volumetric analysis which incorporates economical as well as technical aspects. The currently operating coal-powered (Indonesian coal) setup in the industry needs 41,840 MJ of heat energy on a daily basis. This energy requirement can be met up by producing 3,032 m^3 of biogas daily. Replacing the Indonesian coal-powered setup with the biogas one will significantly reduce the plant's operating cost and will also improve the ecosystem and respiration rate in the region. The study resulted in a capital recovery factor (CRF) of 0.11 and a levelized cost of energy (LCOE) of ₹14.72 m^{-3}, at the 10% discount rate. The maximum net present value at a 6% discount rate is ₹433.68 million, whereas the minimum net present value is ₹219.92 million and ₹314.59 million at discount rates of 14% and 10%, respectively. The digestate obtained after the completion of anaerobic digestion can be used as an organic fertilizer.

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5.1 Introduction

The burning of fossil fuels for power generation adversely affects the environment and damages the ozone layer and imbalances the composition of atmospheric gases. Fossil fuels are widely used as a primary heat source in food processing industries. It is harmful to the atmosphere and one of the prime contributors to global warming issues. This can be avoided by meeting the power demand by using renewable energy sources [1]. Food processing industries have fixed energy demand. Thus, biogas-powered setups can easily replace the existing coal-powered setups. It is feasible in a developing nation like India since it already has a large livestock population. It can also increase the decarbonization of the food industry by cutting down carbon emissions significantly. Biogas can be a useful source of energy for such industries. It has enormous benefits such as eco-friendly fuel and generating many types of fertilizers with much transcendence as by-products [2].

Bikaji Foods International Limited, Bikaner, Rajasthan, was established in the year 1986. At present, the industry's thermal facilities have four coal-fired boilers, with an energy output of 12,552 MJ, 12,552 MJ, 8,368 MJ and 8,368 MJ, respectively. Currently, the burner and boiler are sufficient for operating the biogas without major changes in the system. Ghazi University's 126 MW energy demand is approximately equivalent to 23,923 cubic meters of biogas. The total capacity of 16 boilers is 26265 KW which has been used for heating purposes [3]. Techno-economic analysis of 3,101 m^3 per day biogas production, and municipal solid waste-based biogas plant considering geographical conditions, temperature and climate change [4]. Techno-economic analysis of 320.76 KWh per day heat generation from 2713 m^3 volume anaerobic digestion biogas power plant, and payback time of 5.3 years and high NPV indicate good economic results [5].

Biogas is commonly used for household activities such as cooking and lighting in developing countries. On the other hand, developed countries are focusing more on the commercial use of biogas such as for industrial purposes, power generation and transport [6]. Biogas production by anaerobic digestion is a sophisticated process to convert biodegradable matter into biogas in the absence of oxygen. This is a four-step microbiological process that consists of hydrolysis, acidogenesis, acetogenesis and methanogenesis [7]. The general composition of biogas is methane (40–60%), CO_2 (35–55%), moisture (1–5%), H_2S (0.1–3%), N_2 (0–5%), O_2 (<2%), H_2 and N_2(0–500 ppm) [6].

Biogas potential has been dependent on the availability of biomass and livestock in a nation. India has a total installed capacity of 10,577.45 MW bio-power. Rajasthan has an installed capacity of 125.080 MW bio-power. The total estimated potential of a family/small-type biogas plant is 1,025 MW in Rajasthan [8]. According to the 20th livestock census, in the state of Rajasthan, the total number of cattle (indigenous

Table 5.1 Number of equipment in the industry

Fryers	Nos
Bhujia making	50
Rasgulla making	45
Total	95

and exotic) is 13.93 million [9]. The estimated annual available cow dung is 50.844 Million tonnes in Rajasthan.

The study aims to analyze the technical and economic performance of the biogas plant. Technical performance is based on design features, and economic performance is based on the net present value at various discount rates and the payback period of the proposed biogas plant [5].

5.2 Energy Demand of the Industry

An interrogation-based detailed survey of the production hall, frying lines and roasting lines was carried out to estimate the net daily energy demand of Bikaji Foods International Limited, Bikaner. The total number of equipment that uses heat energy in this industry is summarized in Table 5.1. The total heat energy needed for all the operations is estimated to be 41,840,000 kJ per day (data as received from the industry).

5.3 Energy Equivalence (Replacing Coal with Biogas)

This industry is currently based on a coal-powered setup. In this study, a coal-powered setup is being replaced with a biogas-powered one. It will improve the sustainability of the environment and will be economically beneficial to the industry. The heating value of biogas is 23,000 kJ m^{-3} and burner efficiency has been taken as 60% (assumed):

$$\begin{aligned}\text{Equivalation biogas energy (E)} &= \frac{\text{Total energy required}}{\text{Heating value} \times \text{Burner efficiency}}. \\ &= 3031.884\text{–}3032\,\text{m}^3\ \text{per day}\end{aligned} \tag{5.1}$$

5.4 Designing of Biogas Power Plant

Three techniques of biogas production are widely accepted in India. These are balloon type, fixed dome type and floating drum type. The floating drum technology has been selected for designing the large-scale biogas plant. It provides gas at constant pressure and is easy to construct and maintain [10, 11].

The floating drum-type biogas plant consists of a cylindrical well-type digester tank and a moveable gas holder. The moveable gas holder has an external and internal guide frame that provides stability. The digester is made of quarry stone and brick masonry while the gasholder drum is made of steel.

The slurry (cow dung and water) is prepared in the mixing tank and is fed into the digester through the inlet pipe. This slurry remains unused for about 60 days. During this period, anaerobic fermentation converts organic matter into biogas in the absence of oxygen. Generated biogas will be collected in the gas holder, and the drum will start rising. At a certain limit, pressure applied to the slurry increases. This results in the shifting of the digested slurry from the digester to the outlet slurry tank through the outlet pipe (Fig. 5.1).

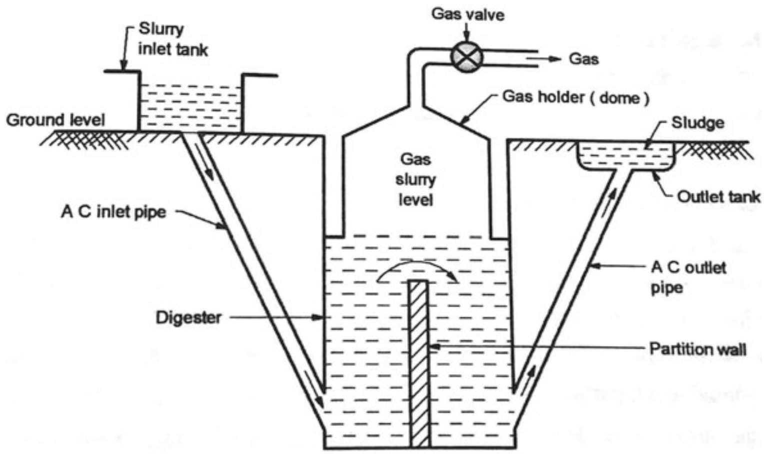

Fig. 5.1 Floating drum-type biogas plant

5.4.1 Mathematical Analysis

5.4.1.1 Designing of Gasholder Drum

The gas holder drum is made up of steel. The thickness of the steel sheet varies between 2–4 mm for the side and 2 mm for the top [12]. Some assumptions are taken into consideration to estimate the volume of the gasholder:

cow dung produced (10 kg per day per cow); collectable cow dung (70%); the weight of dry solid mass in cow dung (18%); production of biogas (0.34 m^3 kg^{-1}); the fraction of gas to be stored in the gas holder (0.6) [13].

At an equilibrium state, the production and consumption of biogas must match. The number of cows required (N) to fulfill the demand for dung for biogas production:

$$\begin{aligned} &0.34 \times 0.18 \times 0.70 \times 10 \times N = 3032 \\ &N \sim 7078 \end{aligned} \tag{5.2}$$

Total available cow dung ($\mathrm{CW_t}$) and total collectable cow dung ($\mathrm{CW_c}$) kg per day are

$$\mathrm{CW_t} = 10 \times N \tag{5.3}$$

$$\mathrm{CW_C} = 10 \times 0.70 \times N \tag{5.4}$$

$$\text{Biogas production(BP)} = 10 \times 0.70 \times 0.18 \times 0.34 \times N \tag{5.5}$$

$$\text{Volume of biogas holder}\left(V_{\mathrm{gh}}\right) = 0.6 \times \mathrm{BP} \tag{5.6}$$

where V_{gh} is the volume of biogas holder in m^3.

5.4.1.2 Designing of Digester

The anaerobic digestion process is completely done in the digester where the microorganisms decompose cow dung into biogas in the absence of oxygen. It should be taken care that there is no gas leakage and no damage due to water. The following assumptions are used for estimating the volume of the digester: the density of slurry (1090 kg m^{-3}); fixed retention time (FRT) (50 days); temperature (35 °C); pH value range (6.6–8.0); collectable cow dung (70%) [13].

For the highest biogas yield, cow dung and water can be mixed in the same ratio of 1:1 [14, 15]:

$$\text{Daily feeding of slurry}\left(m^3\,day^{-1}\right) = \frac{\text{Dung} + \text{Water}}{\text{Density of slurry}} \quad (5.7)$$

$$\text{Volume of slurry in the digester}\,(V_{sd}) = \text{Fixed retention time} \times \text{daily feeding of slurry} \quad (5.8)$$

where V_{sd} is the volume of slurry in the digester in m^3.

Approximately, 90% volume is occupied by the slurry, then the estimated volume of the digester (V_d):

$$V_d\left(m^3\right) = \frac{V_{sd}}{0.9} \quad (5.9)$$

$$\text{Total plant volume}\left(V_{pt}\right) = V_{gh} + V_d \quad (5.10)$$

The site selected for the biogas plant is in the Karni extension, RICCO industrial area Bikaner, Rajasthan. The average annual temperature of the site is 29 °C as shown in Table 5.2. The geographical location of the site lies between 28.01762° North latitude and 73.31495° East longitude. The total number of cows (exotic and indigenous) is 11,94,729 in Bikaner, Rajasthan [9]. The estimated available cow dung is 11,947.30 tonnes per day. There are many gaushalas (cow shelters) located near this site with enough cows [16] (Fig. 5.2 and Table 5.3).

The number of exotic (crossbreed) and indigenous cows are exponentially increasing in the state of Rajasthan. These numbers are highest in Bikaner. The livestock population increase rate in Bikaner from 2012 to 2019 is 31.85%. All the gaushalas (cow shelters) are located close to the site selected for the biogas plant.

Table 5.2 Annual weather temperature report for Bikaner (source: world weather online)

Month	Temperature (°C)
January	17
February	21
March	27
April	32
May	36
June	37
July	31
August	34
September	33
October	31
November	25
December	20
Annual average temperature	29

Fig. 5.2 Satellite view of Bikaji Foods International Limited

Table 5.3 List of gaushalas (cow shelters) located near the site

Gaushalas	Allocated code, no. of cows	Collectable cow Dung per day (kg)
1. Shri Agrasen Jeev Jantu Kalyan Evem Gou Sewa Samiti, Kanasar, Bikaner	GP-08-18, 1666	11,662
2. Shri Karni Gaushala, Deshnok, Bikaner	GP-08-52, 1642	11,494
3. Shri Ganga Jubli Panjarapol Gaushala, Sheetla Gate, Bikaner	GP-08-27, 2286	16,002
4. Shri Murli Manohar Goshala, Bhinasar, Bikaner	GP-08-68, 3584	25,088
Total	9178	64,246

A total of 64,246 kg of cow dung can be obtained from the selected cow shelters per day, but 49,546 kg of cow dung is required per day to meet the energy demand. Adequate cow dung is available to meet the energy demand of the industry under consideration. It is also a good initiative for the use of cow dung waste and a healthy environment. Gaushala owners can use the revenue generated from selling cow dung to look after their cows. Two temperature ranges are highly economical and feasible compared to intermediary ranges for large-scale biogas production.

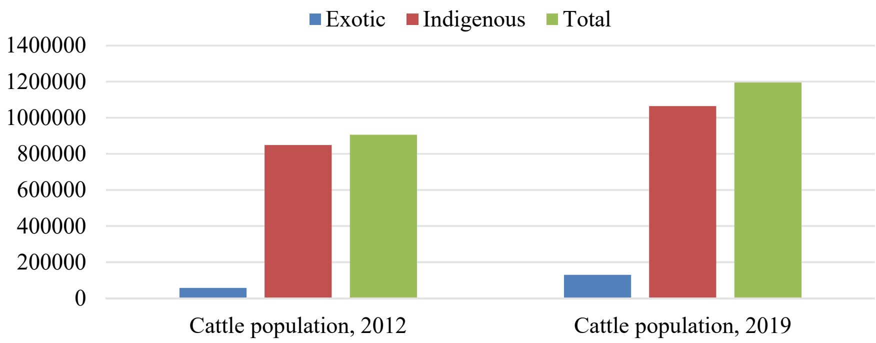

Fig. 5.3 Exotic and indigenous cattle population of Bikaner, Rajasthan

These are optimal mesophilic (30–37 °C) and optimal thermophilic (50–55 °C) for industrial-level biogas production [17, 18] (Fig. 5.3).

Based on the demand price of energy, the estimated required number of cows is 7,078, and 70,780 kg of cow dung is produced ona dailyy basis. The estimated total collectable dung is 49,546 kg per day, which is 70% of the total dung produced. According to this above estimate, the biogas production is 3,032 m^3 per day. The daily feeding of slurry to the digester through the inlet pipe is 91 m^3. The total volume of the biogas plant is 6,876 m^3. The volume of the biogas holder is 1,820 m^3 and that of the digester is 5,056 m^3 as shown in Table 5.4 [22].

The total capital cost of the biogas plant is ₹60 million. In this research, the design of a floating drum-type biogas plant has been prepared. This is manufactured by Dreamtech Machineries. In this system, the construction material of the floating drum is stainless steel or powder-coated mild steel. This is an automatically operated type of plant. The cost of cow dung with transportation is ₹1.5 kg^{-1} so the total cost of cow dung is ₹27.13 million. Operation and maintenance cost is an initial 10% of total capital cost, then the total O&M cost is ₹6 million. If the digester solution is prepared in the ratio of 1:1 of cow dung and water, the annual water cost for this is 0.11 million. Both skilled and unskilled workers are required to operate a biogas

Table 5.4 Biogas plant design (volumetric analysis)

Parameters	Value	Unit
Total available cow dung (CW_t)	70,780	kg
Total collectable cow dung (CW_c)	49,546	kg per day
Biogas production (BP)	3032	m^3 per day
Volume of biogas holder (V_{gh})	1820	m^3
Daily feeding of slurry	91	m^3 per day
Volume of slurry in the digester (V_{sd})	4550	m^3
Volume of the digester (V_d)	5056	m^3
Total plant volume (V_{pt})	6876	m^3

Table 5.5 Cost analysis of biogas plant (annual)

Items	Cost (₹)
Capital cost of biogas plant[a]	60 million
Cow dung cost (with transportation)[b]	27.13 million
Operation and management cost [c]	6 million
Labor cost (unskilled) (Rs. 300 per day)[d]	0.10 million
Labor cost (skilled) (Rs. 500 per day)[d]	0.18 million
Water cost[e]	0.11 million
Total input cost	93.52 million

[a] Ref. [8]
[b] Ref. [19]
[c] Ref. [21]
[d] Based on market survey
[e] Ref. [20]

plant, with a total annual cost of ₹0.28 million. The total cost of the biogas plant based on all the analyses and estimates is ₹93.52 million as shown in Table 5.5. The annual production of biogas is 1,106,680 m^3, which is equivalent to 475,872.40 kg of liquefied petroleum gas (1 cubic meter of biogas is equivalent to 0.43 kg of LPG) [23]. This is equal to about 10,018 commercial 47.50 kg cylinders of LPG. The price of a 47.50 kg commercial LPG cylinder in Bikaner, Rajasthan, is ₹5091.50 in February 2022. Thus, the annual amount of LPG is ₹52,010,315.94.

The biogas-digested slurry is the most effective organic fertilizer for the healthy growth of crops and increases the fertility of the soil [24]. The average composition of biogas digesting solution is 1.5% nitrogen, 1.1% phosphorus and 1% potassium, and is also rich in nutrients. An average of 30% slurry is considered digested slurry as on average 1 kg of cow dung produces 0.30 kg of slurry [25]. It will generate a 14,864 kg per day amount of digested slurry and the annual income from the digested slurry is ₹27.13 million, if sold at a rate of ₹5 kg^{-1}.

5.5 Economic Analysis

5.5.1 Capacity Recovery Factor

The capacity recovery factor is defined in terms of the discount rate and the duration of the plant's life cycle:

$$\text{Capacity recovery factor (CRF)} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{5.11}$$

i = Discount rate; n = Useful life of biogas plant.

Table 5.6 Capacity recovery factor and levelized cost of energy for the different discount rates and different plant life[a]

Discount rate (%)	6	8	10	12	14
Plant life (years)	CRF				
25	0.08	0.09	0.11	0.12	0.14
20	0.09	0.10	0.11	0.13	0.15
15	0.10	0.12	0.13	0.14	0.16
	LCOE (₹/m^3)				
25	12.18	13.02	14.71	15.56	17.25
20	13.03	14.72	13.87	16.41	18.09
15	13.87	15.56	16.41	17.25	18.94

[a] Ref. [26, 27]

The capacity recovery factor for a 20 year life of the biogas power plant at a 10% discount rate is 0.11 as shown in Table 5.6.

5.5.2 *Levelized Cost of Energy*

$$\text{Levelized cost of energy (LCOE)} = \frac{(\text{CC}_\text{p} \times \text{CRF}) + \text{O\&M}}{\text{EG}_\text{p}} \quad (5.12)$$

CC_p = overall cost of biogas plant, CRF = capacity recovery factor,

O&M = operation & management cost, and EG_p = annual energy generated by biogas power plant.

The levelized cost of energy is equal to the average price that consumers must pay in order to pay properly with a rate of return equal to the investor discount rate for capital, operation and management and fuel costs [28]. The levelized cost of energy for this biogas power plant is ₹14.72 m^{-3} at a discount rate of 10%. LCOE (₹/m^3) has been evaluated at different capacity recovery factors and different discount rates for better economic analysis of the biogas plant as shown in Table 5.7.

5.5.3 *Net Present Value (NPV)*

Net present value is the sum of the requisite annual cash flow in the current currency [29]:

$$\text{NPV} = -\text{C}_0 + \sum_{k=0}^{n} \frac{\text{CF}_k}{(1+i)^k} \quad (5.13)$$

Table 5.7 Economics parameters for biogas power plant

Particular	Value
Discount rate (i)	6%, 8%, 10%, 12%, 14%
Inflation rate (j)	6%
Effective discount rate (i_e)[a]	0%, 0.29%, 0.57%, 0.85%, 1.14%
Plant's life (years)	20
Biogas price per m^3 (₹)[b]	24
Total Input cost (₹)	93.52 million

[a] Effective discount rate $(i_e) = \frac{i-j}{1+j}$

[b] Ref. [30].

$$CF_k = P_k - V_k - LC \tag{5.14}$$

C_0 = Investment cost, K = Plant's life, CF_k = Annual cash flow,

P_k = Income from biogas power plant, and V_k = Operation & management cost.

LC = Labor cost.

5.6 Results and Discussion

A biogas power plant designed for the Bikaji food industry has been analyzed. This type of energy source is not only used to reduce the use of fossil fuels, but it is also a big step toward the sustainability of the environment. In this study, an attempt to identify the energy needs of the Bikaji foods industry has been done by using a biogas-powered plant. All the technical and financial aspects have been analyzed. The total estimated energy required for Bikaji Foods International Ltd. for all operations is 41,840 MJ per day. The estimated equivalation energy (coal replaced with biogas) is 3,032 m^3 per day. Cow dung required for a 6,876 m^3 volume biogas power plant to meet the energy demand and to make digester slurry was 49,546 kg per day. The total number of cows that can meet the demand for cow dung is 7,078.

The capital cost of the biogas power plant is ₹60 million. The total annual fixed and variable input cost was ₹93.52 million. The total annual income from the biogas power plant is ₹53.69 million which includes income generated from both slurry and biogas. The capacity recovery factor is 0.11 and the levelized cost of energy is ₹14.72 m^{-3} at the discount rate of 10% considering the plant's life of 20 years. The country's inflation rate is 6%, which is an important factor in the project's financial vitality. The results of the financial analysis of the biogas power plant are shown in Table 5.8. The net present value of the biogas plant is ₹433.68 million at a 6% discount rate, the net present value at a 10% discount rate is ₹314.59 million, and the net present value at a 14% discount rate is ₹219.92 million considering the plant

Table 5.8 Financial analysis of biogas power plant

Discount rate (i)	Net present value	Payback period
6%	433.68 million	2 years
8%	388.81 million	
10%	314.59 million	
12%	250.30 million	
14%	219.92 million	
Effective discount rate (i_e)		
0.29%	825.37 million	2 years
0.57%	750.44 million	
0.85%	719.44 million	
1.14%	million	

life of 20 years. The payback period of the plant is 2 years. The net present value at the 0.29% effective discount rate is ₹825.37 million, the net present value at the 0.57% effective discount rate is ₹750.44 million, and the net present value at the 1.14% effective discount rate is ₹698.28 million. The payback period is the same as the discount rate.

5.7 Conclusion

The food processing industry is one of the emerging sectors in India. The food processing sector of India is one of the largest in the world. The share of agriculture and allied sectors to the total economy is 20.2%. It provides 11.6% of total employment. It contributes to 10.4% of India's exports. This sector is expected to grow as big as $535 billion by 2025–26. In anaerobic digestion systems, carbon dioxide removed from raw biogas reduces carbon emissions. It contributes to greenhouse gas mitigation and is environmentally friendly.

This plant setup currently uses coal as a fuel for heating purposes. For climate and environmental sustainability, we can switch the energy source from conventional to non-conventional. This research paper sums up the technical and financial vitality of a 6,876 m^3 volume biogas power plant which meets the energy demand of Bikaji Foods International Limited at 41,840 MJ per day. To meet the energy demand, a biogas plant with a total volume of 6,876 m^3 has been designed. The volume of the floating drum is 1,820 m^3 and the digester volume is 5,056 m^3.

A financial analysis of biogas plants with different discount rates and different effective discount rates has been done. The most efficient discount rate for the proposed plant is 10% and the effective discount rate is 0.57%. The net present value at a 10% discount rate is ₹314.59 million. The country's inflation rate is currently 6%. The payback period of the biogas power plant at a discount rate of 10% is 2 years.

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