ENERGY ENGINEERING

Bridging the Energy Gap: Performance Benchmarking and Optimisation Potential of Biogas Recovery at a Sewage Treatment Plant in Delhi, India

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Published November 2026

Abstract

Anaerobic digestion of sewage sludge offers a dual opportunity for energy recovery and greenhouse gas (GHG) mitigation, yet large sewage treatment plants (STPs) in India often operate well below their energy recovery potential. This study evaluates biogas generation and energy recovery at a 564 MLD municipal STP in Delhi, India, which employs Anaerobic-Anoxic-Oxic biological treatment with anaerobic sludge digestion and gas-engine based combined heat and power (CHP) generation. Thirteen months of operational data (October 2025 to October 2026), supported by a site visit, were analysed. Biogas production averaged 16,524 Nm^3/day, ranging from 14,442 Nm^3/day (July 2026, monsoon minimum) to 18,269 Nm^3/day (November 2025), with a coefficient of variation of 7.39%, indicating stable digester performance. Biogas-derived electricity averaged 35,062 kWh/month and met 33.0% of plant electricity demand (Energy Self-Sufficiency Index, ESI = 0.330), against a best-practice benchmark of 0.80. ESI showed clear seasonal behaviour, from 0.269 in July to 0.403 in November, linked to monsoon dilution of organic loading. A comparison of theoretical and recorded energy output indicates a large recovery gap, attributed to flaring, engine downtime and biogas quality variation. Current biogas use saves about Rs. 33.66 lakh per year and avoids about 301 tCO_2e/year; raising ESI to 0.50 through optimisation would save an additional Rs. 20 lakh per year and increase avoided emissions to about 503 tCO_2e/year. Five optimisation measures are prioritised, and a replicable benchmarking framework for large Indian STPs is proposed.

Keywords: Biogas; Anaerobic digestion; Energy self-sufficiency; Sewage sludge; Energy recovery; GHG mitigation

1 Introduction

Urban India generates more than 72,000 million litres per day (MLD) of sewage, of which only about 37% is treated (Central Pollution Control Board [CPCB], 2021). Sewage treatment is energy intensive, with aeration, pumping and sludge handling accounting for most of the electricity demand of a plant. At the same time, sewage sludge contains a significant amount of chemical energy in the form of biodegradable organic matter. Anaerobic digestion (AD) converts this organic matter into biogas, a methane-rich fuel that can be used to generate electricity and heat on site (Appels et al., 2008).

Well-operated plants in Europe and North America recover between 50% and 100% of their electricity demand from biogas, and some have become energy-positive (McCarty et al., 2011; Shen et al., 2015). In contrast, many Indian STPs with installed digesters report low or irregular energy recovery because of incomplete gas use, equipment downtime and limited monitoring. There are few

published studies that use long-term operational data from large Indian plants to quantify this gap and identify practical ways to close it.

This paper addresses that gap through a case study of a 564 MLD municipal STP in Delhi, India. The objectives are: (i) to characterise the quantity and seasonal variation of biogas generation; (ii) to assess the energy balance and Energy Self-Sufficiency Index (ESI) of the plant; (iii) to estimate the gap between theoretical and recorded energy recovery; (iv) to quantify the economic and GHG benefits of current and improved biogas use; and (v) to identify and prioritise optimisation measures.

2 Literature review

Mesophilic anaerobic digestion of mixed primary and waste activated sludge typically destroys 40 to 55% of volatile solids (VS) and yields 0.75 to 1.1 Nm^3 of biogas per kg VS destroyed, with methane content of 60 to 65%. Biogas yield is sensitive to digester temperature, hydraulic retention time, organic loading and the proportion of waste activated sludge (WAS), which is less biodegradable than primary sludge (Appels et al., 2008; Tchobanoglous et al., 2014).

Energy self-sufficiency is commonly expressed as the ratio of on-site renewable electricity to total electricity demand. Benchmarks reported in the literature range from 0.5 to 0.8 for conventional activated sludge plants with AD, and above 1.0 (Wett et al., 2007) for plants that use co-digestion and thermal hydrolysis, such as Strass in Austria (Nowak et al., 2015; Wett et al., 2007). Common reasons for underperformance include biogas flaring, low CHP availability, poor gas storage management and digester temperature drift in winter (Gandiglio et al., 2017; Shen et al., 2015).

In India, policy initiatives such as the National Action Plan on Climate Change (NAPCC), the CPCB guidelines on sewage sludge management and the SATAT scheme for compressed biogas (CBG) encourage energy recovery from wastewater (CPCB, 2022). However, published plant-level evaluations based on long-term data remain limited, which motivates the present study.

3 Materials and methods

3.1 Study site

The study plant, located in Delhi, has a design capacity of 564 MLD. It treats domestic sewage using the A2O biological nutrient removal process, followed by disinfection. Primary sludge and thickened WAS are stabilised in mesophilic anaerobic digesters. Biogas is collected, stored in gas holders and used in gas-engine CHP units, and excess gas is burnt in a safety flare. Digested sludge is dewatered and dried in solar drying beds.

3.2 Data collection

Monthly average operational data for October 2025 to October 2026 (13 months) were obtained from plant records. The data included influent flow, biogas production (Nm^3/day), electricity produced from biogas, electricity purchased from the grid and total electricity consumption (kWh/month). A site visit on 10 July 2026 was used to observe the digesters, gas handling system and CHP units.

3.3 Data analysis

Descriptive statistics (mean, range and coefficient of variation, CV) were calculated for each parameter. Months were grouped into post-monsoon, winter, summer and monsoon seasons to study seasonal effects.

Theoretical electrical potential was estimated as: annual biogas volume × methane fraction (0.62) × methane calorific value (35.8 MJ/Nm^3) ÷ 3.6 × electrical efficiency (0.35), following Tchobanoglous et al. (2014). The Energy Self-Sufficiency Index was calculated as ESI = biogas electricity ÷ total electricity consumption.

Economic savings were calculated using an average industrial tariff of Rs. 8/kWh. Avoided GHG emissions were calculated using the grid emission factor of 0.716 kg CO_2/kWh (Central Electricity Authority [CEA], 2024).

4 Results and discussion

4.1 Biogas generation

Biogas production averaged 16,524 Nm^3/day over the study period, corresponding to about 6.03 million Nm^3/year (Fig. 1). The maximum was recorded in November 2025 (18,269 Nm^3/day) and the minimum in July 2026 (14,442 Nm^3/day). The low CV of 7.39% indicates that the digestion process remained stable throughout the year.

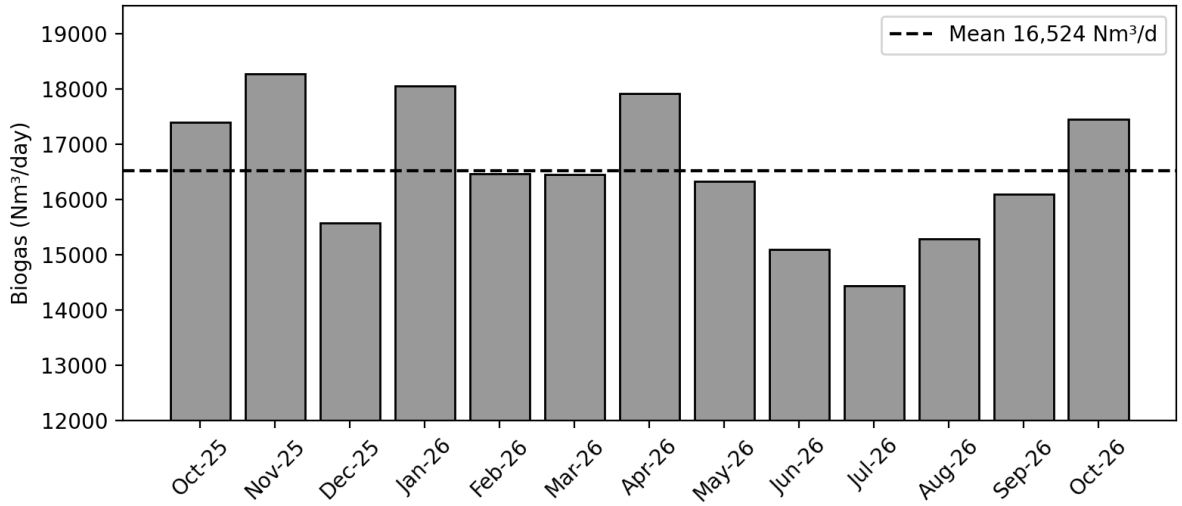


Figure 1. Monthly biogas generation compared with the annual mean.

4.2 Seasonal variation

Biogas output was highest in the post-monsoon and summer months and lowest during the monsoon (July to August 2026). During the monsoon, stormwater inflow and infiltration dilute the sewage and reduce the organic load reaching the digesters. Production recovered in October 2026 as the monsoon ended. A slight drop in December 2025 is likely related to lower digester temperature at the start of winter, which reduces microbial activity when digester heating is not fully maintained.

4.3 Energy balance and self-sufficiency

Total electricity consumption averaged 106,215 kWh/month with a CV of 3.7%, showing a steady demand regardless of season (Fig. 2). Biogas electricity averaged 35,062 kWh/month (CV 10.4%), and the remaining 72,891 kWh/month (67%) was taken from the grid. The mean ESI was 0.330, ranging from 0.269 (July 2026) to 0.403 (November 2025). This is well below the best-practice benchmark of 0.80, showing large scope for improvement.

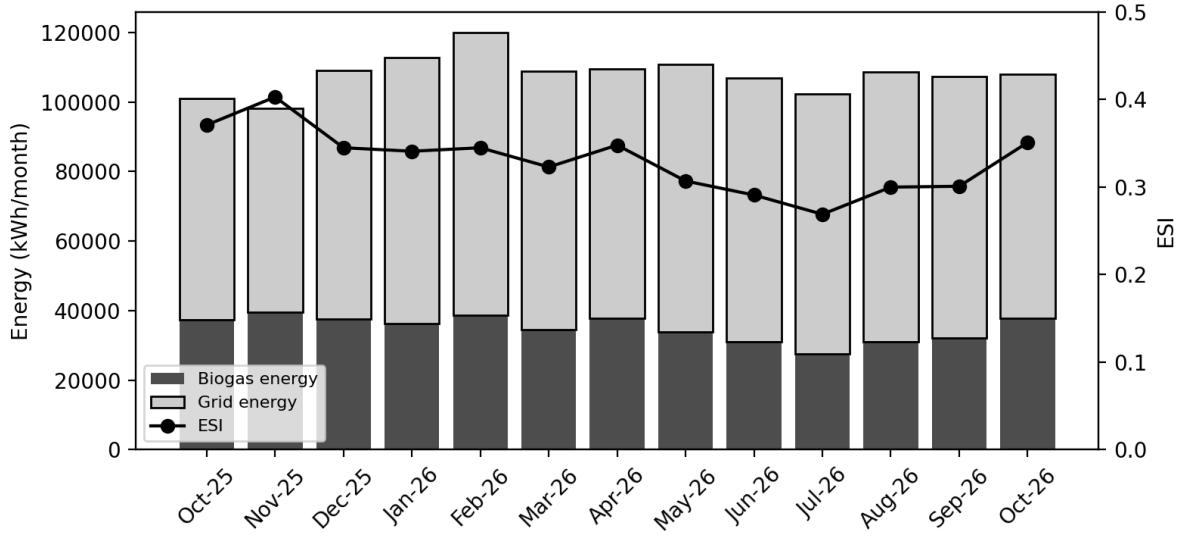


Figure 2. Monthly biogas energy, grid energy and ESI.

4.4 Theoretical versus recorded energy recovery

Annual biogas production of 6,031,260 Nm^3 contains about 3,739,381 Nm^3 of methane, equal to 37,230 MWh of energy. At 35% electrical efficiency, the theoretical electricity potential is about 13,030 MWh/year (1,085,875 kWh/month). The recorded biogas electricity is 35,062 kWh/month, which is only about 3.2% of this theoretical value.

Such a large difference suggests that: (a) a large share of the biogas may be flared or used for digester heating rather than for electricity generation; (b) CHP engines may have extended downtime; (c) the actual methane content or calorific value may be lower than assumed; or (d) the recorded energy values may cover only part of the plant load or a single metering point. Confirming the gas balance through dedicated flow meters on the engine and flare lines is therefore a priority for plant management and for future research.

4.5 Economic benefits

Biogas electricity of 420,744 kWh/year saves about Rs. 33.66 lakh per year in grid purchases at Rs. 8/kWh. Grid electricity still costs about Rs. 69.97 lakh per year. Raising ESI from 0.33 to 0.50 would save an additional Rs. 20 lakh per year.

4.6 Greenhouse gas benefits

Using the grid emission factor of 0.716 kg CO_2/kWh, current biogas electricity avoids about 301 tCO_2e/year. Under the optimised scenario (ESI = 0.50), avoided emissions increase to about 503 tCO_2e/year, and fugitive methane emissions fall from 1,870 to about 1,200 tCO_2e/year through better

gas capture. Capturing and using methane also prevents its release to the atmosphere, where its global warming potential is about 28 times that of CO_2 (Intergovernmental Panel on Climate Change [IPCC], 2019).

4.7 Optimisation measures

Five measures were identified from the gap analysis and the site visit (Table 1). Minimising flaring and maintaining digester temperature are low-cost, short-term actions. Co-digestion with food waste or fat, oil and grease (FOG) offers the largest gain but needs a reliable supply of feedstock. Thermal pre-treatment of WAS requires capital investment and is a longer-term option.

Table 1. Biogas optimisation measures and estimated impact.

Sr. No.	Measure	Estimated ESI Gain	Priority
1	Minimise flaring through better gas holder management and engine scheduling	+0.03 to +0.05	High (quick win)
2	Maintain digester temperature at 35–37 °C in winter	+0.02 to +0.03	High (seasonal)
3	Regular engine maintenance to keep efficiency at 38–40%	+0.03 to +0.05	Medium
4	Co-digestion with food waste and FOG	+0.08 to +0.15	Medium
5	Thermal or ultrasonic pre-treatment of WAS	+0.05 to +0.10	Low (capital cost)

Taken together, measures 1 to 3 can raise ESI to about 0.45–0.46, and adding co-digestion can push ESI above 0.50, close to international practice.

4.8 Comparison with benchmarks

The ESI of 0.33 at the study plant is lower than the typical range of 0.5 to 0.8 reported for plants with anaerobic digestion, and far below energy-positive plants that exceed 1.0. However, the stable biogas output (CV 7.39%) shows that the digestion process itself is reliable. The gap therefore lies mainly in gas use and energy conversion, which can be corrected through operational improvement rather than major new infrastructure.

5 Conclusions

1. The study plant produced a stable average of 16,524 Nm^3/day of biogas (CV 7.39%), with lowest output during the monsoon due to dilution of organic load.
2. Biogas electricity met 33% of plant demand (ESI = 0.330), well below the best-practice benchmark of 0.80.
3. Recorded electricity output is a small fraction of the theoretical potential, pointing to flaring, engine downtime, gas quality variation or metering limits.
4. Current biogas use saves about Rs. 33.66 lakh and 301 tCO_2e per year; raising ESI to 0.50 would add about Rs. 20 lakh per year and raise avoided emissions to about 503 tCO_2e/year.
5. Reducing flaring, maintaining digester temperature and regular engine maintenance are the most practical short-term actions, while co-digestion offers the largest long-term gain.

Limitations: the study uses monthly averages, assumed methane content and engine efficiency, and no direct measurement of flared gas. Future work should include gas composition analysis, separate metering of engine and flare gas, co-digestion trials and a techno-economic study of upgrading biogas to CBG under the SATAT scheme.

Acknowledgement

The authors thank the plant operator and the municipal water utility for providing operational data and site access.

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