A Hybrid Biogas System for Kolkata

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Abstract*-Municipal solid waste (MSW) is a global problem. Four processes for treatment include landfilling, incineration, recycling and composting the organic fraction. Landfilling can cause the release of the potent greenhouse gas methane into the atmosphere. In many parts of the world, including the European Union, legislation to limit the amount of generated Organic Fraction Municipal Solid Wastes (OFMSW) going to landfill has been introduced. An alternative to landfilling is to anaerobically digest the OFMSW. This paper investigates the concept of a Hybrid Biomass System (HBS) consisting of solar thermal Flat Plat Collector (FPC) providing heat energy to the thermophilic (55^{o}C) anaerobic digestion process, and the potential energy yield of hotel OFMSW in Kolkata. The methodology comprises development and assessment of a theoretical model representing the anaerobic digestion process for optimum biogas yield and TRNSYS simulation of a 5m^2 and 10m^2 FPC. Theoretical biogas production rates derived are 0.44m^3/kgVS or 0.21m^3 biogas/guest/day with a C/N ratio of 35:1. 5m^2 and 10m^2 FPC simulations maintained the thermophilic temperature of 55^{o}C within -1.9 and +2.1. 10m^2 FPC provides largest energy contribution at 11% of the annual energy requirement. In is concluded that FPCs can support thermophilic digester heating requirements with heat store or direct integration. In order to meet optimum biogas yield, legislation and policy is required to evolve the current waste management processes with emphasis on infrastructure development and source segregation.

***Index Terms*-Hybrid, OFMSW, Biogas, Solar Thermal, Anaerobic Digestion, Kolkata**

I. INTRODUCTION

Waste management is becoming increasingly prominent in the global struggle against climate change. The Indian Municipal Solid Waste (MSW) (Management and Handling) Rules 2000 [1] sets out governance of MSW separation, processing and use of biodegradable waste. Municipal authorities in India report instances of non-compliance through lack of financial resources, technical intervention and community involvement [1], [2]. Around the world, nations are reducing quantities of biodegradable waste sent to landfill. Legislation such as European Union Landfill Directive (1999/31/EC) [3] which obliges member states to reduce biodegradable MSW sent to landfill to 35% of 1995 levels by 2016, provide a framework for which international states, such as India, could be engaged and potentially assessed.

The city of Kolkata has a population of 4.5million and generates around 968,000 tonnes of Municipal Solid Waste (MSW) per year [4]. Between 50-90% of the annual waste generated in India's urban areas is directed to landfill and around 47% of this is biodegradable waste [4]. On this basis Kolkata contributes up to 412,950 tonnes per year (1131 tonnes per day) of Organic Fraction MSW (OFMSW) to landfill sites. Landfill gas collection reduces the amount of methane that is produced with benefit of energy generation potential. However, this does not prevent or reduce OFMSW being directed to landfill sites in the future [4]. This paper investigates the potential biogas yield from thermophilic anaerobic digestion (AD) of the OFMSW generated by Kolkata hotels. To optimise the biogas yield available for external use, the Hybrid Biomass System (HBS) concept integrates a Flat Plat Collector (FPC) to provide solar thermal energy for digester heating. Performance assessment is conducted in a combination of theoretical anaerobic digestion model, and solar thermal simulation in TRNSYS.

The quality of biogas and digestate from AD is dependent on the characteristics of the OFMSW food waste, garden waste and paper [5]. Source separation of OFMSW generally provides a higher quality OFMSW than mechanically separated OFMSW [5]. The environmental temperature ranges for anaerobic bacteria are mesophilic at 20-40^{o}C and thermophilic at 45-60^{o}C, with optimum digestion temperatures of OFMSW for energy generation at 35-37^{o}C and 55^{o}C respectively [6]. Although conventional AD is carried out within the mesophilic range [7], thermophilic conditions perform better under high organic loading with shorter Hydraulic Retention Times (HRT) [8] of 15-20 days [9], in comparison to 20-30 days for mesophilic [10]. Thermophilic conditions also provide higher bacteria activity and higher volatile solids reduction [11] contributing to biogas output of approximately 60% methane [12] and higher rates of destruction of pathogens and weeds seeds [7]. The thermophilic process has increased sensitivity to changes in the environment [13] and requires increased energy consumption to maintain the higher temperature.

The most common use for methane generated from AD of OFMSW is to provide a proportion of the heat necessary for the microbial process [14]. In an AD performance assessment it was found that between 12% and 50% of biogas produced is used to heat the digesters, depending on system design characteristics [15]. Using solar thermal energy for digester heating utilises proven technology, with low running costs and environmentally sustainable optimisation of biogas yield. System models have been developed to investigate the potential of solar thermal AD in the thermophilic range for cow manure in Egypt [16] and OFMSW in Mexico City respectively [17]. However, there is currently no single solution or universal approach to defining solar thermal AD system parameters. The aim of this paper is to model a hybrid solar thermal anaerobic digester. An auxiliary heat source for the system is assumed to available for system balance. The feedstock for the digester will be hotel OFMSW under solar irradiance conditions of Kolkata.

II. METHODOLOGY

The HBS concept was developed through detailed analysis of the three interconnected functional groups: Anaerobic Digestion, Solar Thermal and System Application. The development of each functional group utilised processes and tools best suited to the analysis and performance assessment of the specific technology, whilst maintaining consideration for functional relationship influences. AD was analysed and assessed through development of a mathematical model. Solar thermal was modelled in TRNSYS, providing detailed simulation outputs for analysis and assessment. System application considers HBS introduction and in service support within the current waste management and renewable energy framework in India.

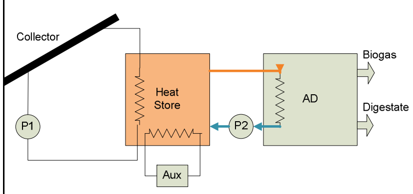
A. Anaerobic Digestion

The AD model was developed to incorporate processes to derive the performance characteristics of thermophilic digestion for optimum biogas yield. Volumes and rate of OFMSW generation per hotel, numbers of guests, waste composition and the volume and subcomponents of the OFMSW was defined per person. Biochemical characterisation of each component provided the contribution to potential biogas generation in m^3/guest/day.

B. Solar Thermal

To optimise solar thermal performance the system is to maximise solar thermal gain, minimise heat losses and have provision of back up heating [18]. The HBS system configuration and control philosophy are optimised for consistent thermophilic environment in the anaerobic digester at 55°C. The system configuration incorporates primary and secondary heating circuits. The primary circuit is a pumped solar collector system with heat store supported by auxiliary heater; secondary heating circuit is pumped from the heat store to maintain AD temperature at 55°C. The system characteristics are presented in Table 1.

TABLE 1 - SYSTEM CONFIGURATION

System Configuration	Technical Considerations
	Pumped solar collector with heat store supported by auxiliary heater connected to AD. Considerations: - Heat storage facility providing stored solar thermal energy; - Heat store manages temperature fluctuations; - Minimal AD temperature management complexity due to single heat source at AD; - Reduced demand on auxiliary heater response; - Additional heat transfer stages with corresponding hardware, losses and physical interfaces; - Additional hardware and physical interfaces; - Secondary heating control circuit;
Key: Collector = Solar Thermal collector; P1 = Solar thermal system pump; Aux = Auxiliary heater; AD = Anaerobic Digester; P2 = secondary system thermal pump	

The solar characteristics for Kolkata give an annual average solar resource between 4.0-4.5 KWh/m^2/day [19], 1600 kWh/m^2 per year [20]. Direct Normal Irradiance (DNI) at 22.55°N 88.35°E, ranged from 2.23kWhr/m^2/day to 5.39kWhr/m^2/day with an annual average DNI of 4.12kWhr/m^2/day and Global Horizontal Irradiance (GHI) from 4.17kWhr/m^2/day to 6.58kWhr/m^2/day with an average GHI of 5.06kWh/m^2/day [19]. The usable collector energy is energy available after the energy absorbed has convection and radiative losses removed, shown by Equation (1) [20].

$$Q_u(t) = q_u(t)A_c = (\tau\alpha)_{eff}\, q_s(t)A_c - \bar{U}\, A_e(\bar{T}_e - T_a) - \varepsilon_{eff}\,\sigma\, A_e(\bar{T}^4_e - T^4_a) \quad (1)$$

Where:

Q	Energy per unit time
u	usable
t	time
q	energy per unit area
A	Area
c	collector
τ	transmissivity
α	absorptivity
eff	effective value
s	solar
Ū	heat transfer coefficient
e	element of collector
T	absolute temperature
a	ambient
ε	infrared emissivity
σ	Stefan-Boltzmann Constant

5m^2 FPC and 10m^2 FPC were simulated in TRNSYS for comparative analysis. The accuracy of TRNSYS is within 5-6% measured data [21]. To enable assessment of the configuration and performance characteristics, the heat store volume and auxiliary heating element power are fixed at 1m^2 and 4kW (14400kJ/hr) respectively and constant effectiveness heat exchanger used to represent thermal transfer to anaerobic digester.

The control philosophy was to maintain anaerobic digester at thermophilic temperature of 55^{o}C (represented by constant effectiveness heat exchanger) by ensuring heat source at 66^{o}C (allowing for 80% efficiency of heat exchanger). Further operating rules are defined below:

- When collector temp is 2^{o}C above tank temp, pump is on;
- Collector output temp above 130^{o}C pump to be deactivated (safety feature);
- Maintain heat exchange output at 55^{o}C;
- Maintain heat store at 66^{o}C (desired heat exchange output 55^{o}C x 20%);
- Heating element set point at 66^{o}C with 5^{o}C dead band.

Constant volume heat store assisted in achieving research objectives, and was also a limitation. Further knowledge can be gained through simulating the system configuration at increment heat store volumes

III. Results and discussion

A. Anaerobic Digestion

MSW generated per capita in Kolkata 2006 was 0.59kg/day [2] and [4], whereas the average waste generated by a hotel guest is about three times this at 1.56kg/day [22], [23], [24], [25]. The OFMSW ranged from 55% [4] up to 83% [26] with an average of 74.2%. The OFMSW was assumed to be 1.16kg/guest/day (74.2% of 1.56kg/g/d MSW). The biogas yield available during digestion of 1.16kg/g/d OFMSW is determined through analysis of individual feedstock characteristics and application of derived equation 2.

$$BY_F = ((OFMSW_F * DM_F) * VS_F) * B_{PF} \qquad (2)$$

Where:

BY_F = Biogas Yield of feedstock (m^3/guest/d)
$OFMSW_F$ = OFMSW of feedstock (kg/guest/d)
DM_F = Dry Matter content (%)
VS_F = Volatile Solids content of feedstock
B_{PF} = Biogas potential of feedstock

The biogas yield based on the characteristics and volumes of each OFMSW feedstock would provide 0.21m^3/guest/d biogas (0.13m^3/guest/d of methane).Guest/day values derived were applied to a range of guest numbers to calculate potential biogas yield and digester volume across range of OFMSW weight contributions for a thermophilic AD with 20 day HRT, using Equation (3) and (4) respectively.

$$BY (m^3/d) = \text{Number of Guests} * BY(m^3)/g/d \qquad (3)$$

$$\text{Digester Volume } (m^3) = OFMSW (m^3/d) * HRT (days) \qquad (4)$$

Corrected for 1 ton of OFMSW (approx 800 guests) the AD would produce 172m^3 Biogas (107m^3 Methane) with a digester tank volume of 46m^3. Biogas production rate of 0.44m^3/kg VS derived using Equation (5) corresponds to maximum methane yields of 0.43m^3/kg VS for AD of source segregated OFMSW in thermophilic conditions [27].

$$m^3Biogas/kgVS = BY (m^3) / kgVS \qquad (5)$$

The percentage of each feedstock in the OFMSW were multiplied by the C/N Ratios to give the operational C/N ratio will be approximately 35:1 for the digester. The optimum C/N ratio is in between 20-30 [15] and under current conditions the high carbon content could result in lower than expected gas yield. Correction can be obtained through reducing the amount of high C/N material, such as the paper, or mixing lower carbon content organic waste such as sewage sludge.

B. Solar Thermal

Annual solar resource in Kolkata [19] is plotted alongside sunlight hours [20] and DNI received by a surface in Fig. 1. Hourly irradiance data has been analysed to produce a representative daily irradiance of hourly sunlight hours in January, April, May and Oct [19] as shown in Fig. 2. April receives peak radiation for just over an hour from 1200 and during 7 hours between 1000 and 1500 irradiance level is over 700Wh/m^2.

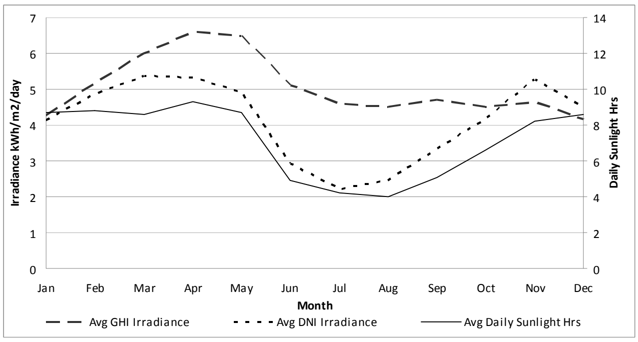


Fig. 1 - Kolkata Average Irradiance and Sunlight Hrs

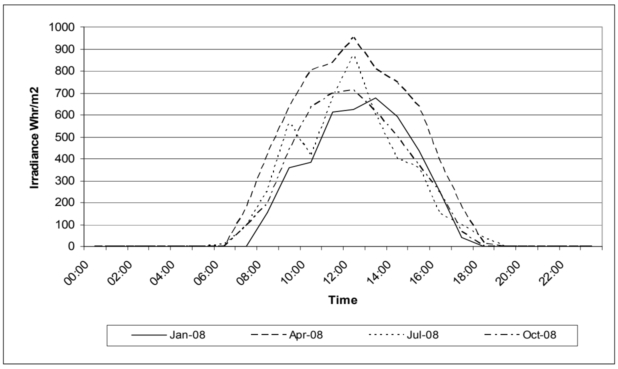


Fig. 2 - Kolkata Hourly Irradiance

During solar thermal simulation, the heat store and heat exchange output temperatures were successfully maintained at 66°C and 55°C respectively, for the 8760 hours (one year) duration. FPC annual energy gain and output temperature profiles correspond to the annual irradiance plot of Kolkata, with collector energy gain and output temperatures highest during winter, summer and the post monsoon season. The TRNSYS outputs in Fig. 3 and Fig. 4 illustrate the annual performance for 5m^2 and 10m^2 FPCs respectively.

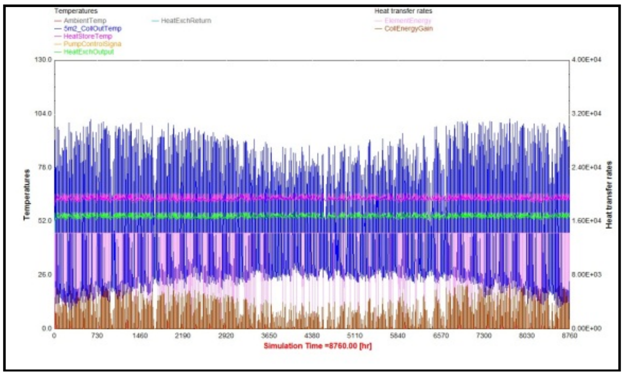


Fig. 3 - 5m^2 FPC Annual Performance

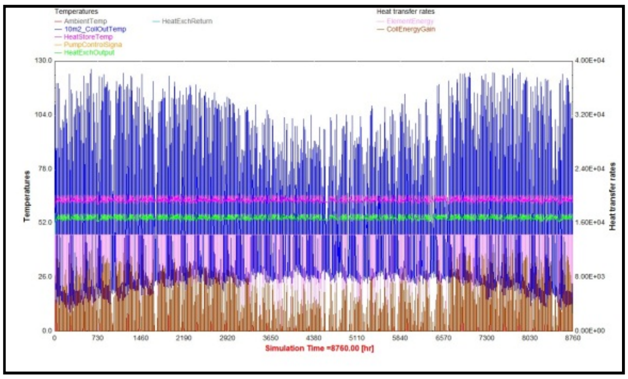


Fig. 4 - 10m^2 FPC Annual Performance

The heating element requires 126GJ/yr to maintaining heat store at 66°C and heat exchange output at 55°C. Integration of solar thermal system of 5m^2 or 10 m^2 FPC provides a sustainable contribution to the thermal requirement, reducing the annual heating element load to 119.5GJ/yr or 113GJ/yr respectively. At 11%, the contribution of the 10m^2 FPC is greater than 5m^2 FPC and corresponds to the reported solar fraction of community solar thermal projects of 12% [28]. The increase in FPC surface area from 5m^2 to 10m^2 increases total energy gain by 76% and FPC output temperature by 10% on average. FPC output temperature has gains of up to 30% during peak hours of high irradiance. The 10m^2 FPC meets annual thermal capacity for 810 hours reducing the dual operation hours to 1977. There is minimal change to ‘element only’ hours due to constraints in the energy gain period, however improvement in energy utilisation is illustrated in the average hourly energy gain and thermal energy contribution plots in Fig. 5 and Fig. 6 respectively.

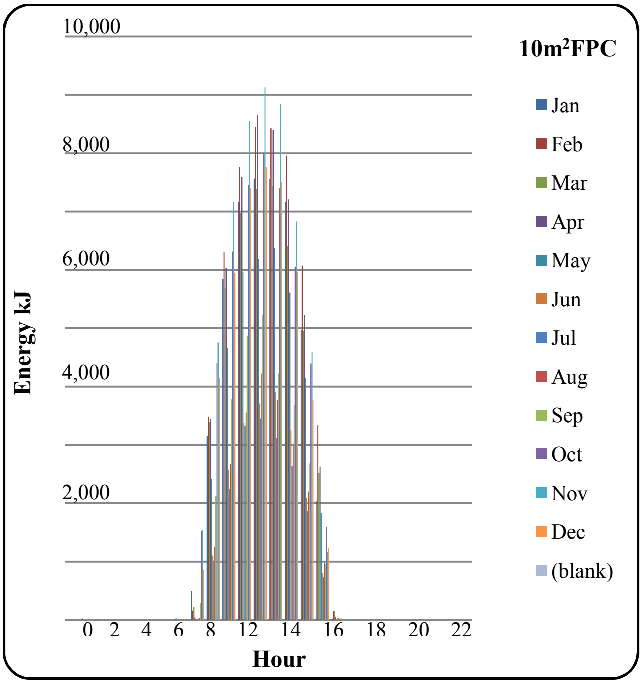


Fig. 5 - 10m^2 Average Hourly Energy Gain

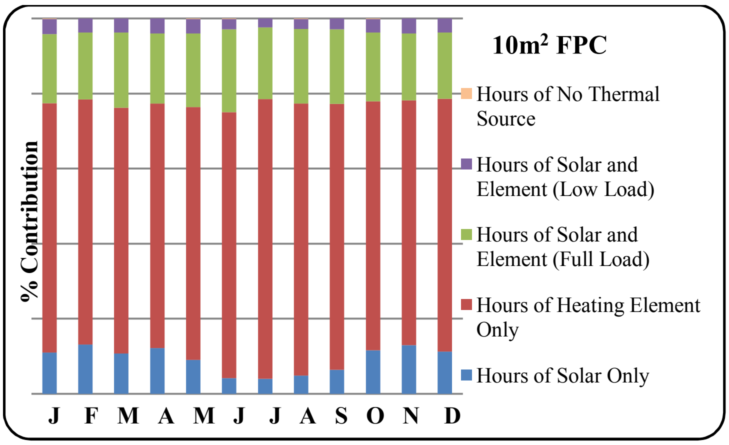


Fig. 6 - 10m^2 Thermal Energy Source Contribution

In high irrariation months of February, April and November the FPC output temperature is above the heat source requirement for 5 to 7 hours of which FPC is independantly providing thermal energy for a maximum of 2 hours. During this 2 hour period FPC output temperature goes through peak of over 90°C whilst the heat store temperature drops 5°C, requiring the heating element to be energised. The peak solar thermal energy is not maintaining heat store temperature independantly and during months with low solar radiation the 5m^2 FPC is providing thermal support to the fully loaded heating element only. 10m^2 FPC has similar operational characteristics, however the increase in solar thermal utilisation is due to heat store reaching 66°C earlier in the solar heat gain period, allowing earlier shut down of the heating element. The heat store temperature falls at a reduced rate and element returns on line at a comparable time. The heat store temperature does not go above the threshold whereby heating element will not operate (66°C) identifying the 5m^2 and 10m^2 FPCs simulated here are not able to provide excess thermal energy for thermal storage. The characteristics for 5m^2 and 10m^2 from the simulation export of sample 3 days in April (days 98 to 101) are shown in Fig. 7and Fig. 8.

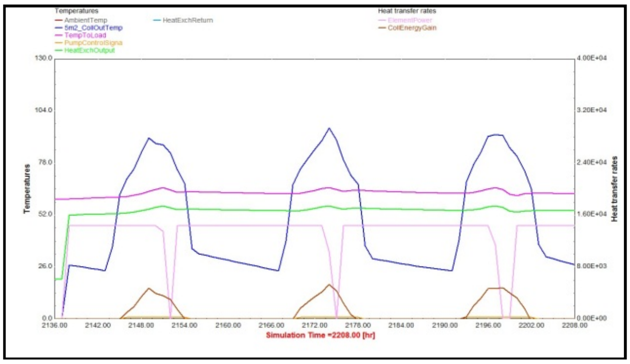


Fig. 7 - 5m^2, 3 Day Simulation Sample (April)

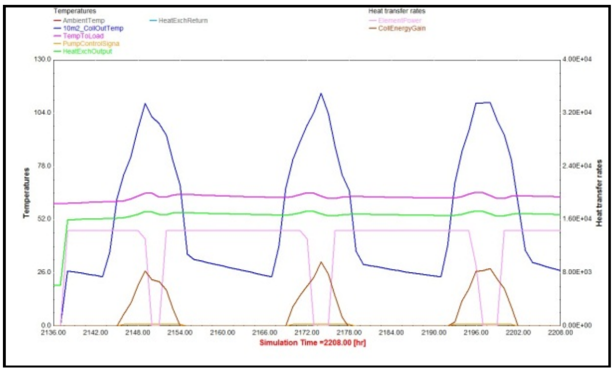


Fig. 8 – 10m^2, 3 Day Simulation Sample (April)

As there is no solar thermal storage for exploitation outside of solar energy gain periods, HBS energy performance would benefit from direct integration of solar thermal to digester, with temperature control threshold at 55°C. The simulation has proved sufficient temperature control management for direct connection to thermophilic digester and system performance would be enhanced through removing losses from the heat storage stage of thermal energy transfer. As FPC load requirement is lowered from 66°C to 55°C supporting heating element size will be reduced. Direct integration corresponds to solar thermal collectors used with hot water and space heating services that raise temperature to a minimum of 52°C [18].

IV. CONCLUSIONS

The aim of this paper was to model a hybrid solar thermal anaerobic digester system. This has been achieved to provide optimum biogas yields from hotel OFMSW in the thermophilic range. A potential biogas contribution per guest (0.21m^3/d) could be utilised in waste-to-energy assessments. C/N ratio needs active management for optimum biogas yield.

Solar thermal technology can assist in meeting thermal requirement of thermophilic AD in Kolkata. FPC is suited to providing digester heat and would contribute to India's solar mission. Achieving consistent temperature suggests the direct integration of FPC to digester could maintain thermophilic conditions and could improve performance through omitting temperature demand of heat store. However, under the scenario this contribution is limited and an auxiliary heat source was needed. System application requires further work in optimisation and validation such as increasing the FPC area, using different solar thermal collectors or operating the AD process under mesophilic conditions.

Without policy, legislation and/or incentives the current levels of landfill use will not be reduced. A clear vision valued by local communities is required to instil a culture of source segregation and community ownership for waste management. The high solar resource is consistent across the much of India. Therefore, solar thermal-AD has the potential to be utilised across many regions of India and assist the country towards meeting environmental goals and political targets for waste management.

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