AIP | Journal of Renewable and Sustainable Energy

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Citation: Journal of Renewable and Sustainable Energy **8**, 023101 (2016); doi: 10.1063/1.4942783
View online: http://dx.doi.org/10.1063/1.4942783
View Table of Contents: http://scitation.aip.org/content/aip/journal/jrse/8/2?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **8**, 023101 (2016)

A practical biogas based energy neutral home system for rural communities of Bangladesh

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(Received 27 June 2015; accepted 12 February 2016; published online 2 March 2016; publisher error corrected 15 March 2016)

Growing demand of energy consumption, subsequent increase in energy generation costs, and increased greenhouse gas (GHG) emissions, as well as global warming from the conventional energy sources, encourages interest worldwide to bring a higher percentage of renewable energy sources such as biogas into the energy mix to build a climate friendly environment for the future. Moreover, due to high investment and maintenance costs, governments are not providing enough support for grid extension and delivering electricity to remote locations or rural areas, in particular, in under-developing countries like Bangladesh. Therefore, this paper presents an Energy Neutral Home System (ENHS) that can meet all its energy requirements from low-cost, locally available, nonpolluting biogas generated from animal waste, in particular, chicken and cow manure. The proposed ENHS has been developed for rural community, typically an area of 200 families, and will not only provide cooking gas and sustainable and affordable power supply to the community with low emissions, but will also facilitate high quality fertilizer for agricultural purposes. In-depth analysis clearly demonstrates that the proposed ENHS not only offers electricity and cooking gas to the community with the lowest costs, but also reduces the energy crisis and GHG emissions and can play an active role in developing socio-economic infrastructure of rural communities in Bangladesh in many ways. *© 2016 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4942783]

I. INTRODUCTION

Energy demands are increasing at unprecedented rates worldwide in both developed and developing countries, already reaching formidable levels. The lack of the ready energy availability to meet these demands causes inevitable disparity between people and nations globally. Around the world, 1.3×10^9 people or roughly a quarter of the global population have no access to reliable electricity.[1] Most of the rural areas that are far from the mainland or city and Islands lack access to modern facilities as well as energy services, which have to be considered as a significant global development challenge today. Reliable and continuous electricity supply is required for economic development of the communities as well as delivery of key public services, including health, education, and infrastructure. Moreover, energy is currently being generated mainly from fossil fuelled power generation that contributes greenhouse gas (GHG)

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emissions into the atmosphere causing changes in global climate condition. These impacts include land, water, and air pollution, widespread habitat annihilation, along with swelling evidence of links between fossil fuel use and climate change due to global warming.[2–4]

Augmented concern about global warming, acid rain, and air pollution has rejuvenated attention in the application of renewable energy (RE) resources,[5] which has started to be used as a panacea for solving climate change and also reducing the energy crisis worldwide. Among all renewable sources, bioenergy is estimated to be the fourth largest resource in the world.[6] Biogas is one of the major categories of an exploitable form with huge biopotential, and it can be produced from almost all kinds of waste sources.[7] There have been colossal researches on biogas production and plant efficiency, so the present key research factor is optimization of biogas systems.[8]

In one research paper, operational aspects of two large industrial anaerobic digestion (AD) amenities and their performances for two years of operation are discussed, which indicates that proper monitoring and management can increase biogas production by 40%,[9] but the system is implemented only for urban areas.

The technical and economic performance of an anaerobic digestion family size biogas plant (15 m^3 volume) installed in Turkey is investigated in a study which corroborates that the lowest Pay Back Time (PBT) is 3.92 years considering the retailing price of natural gas and solid fertilizer follow the Turkish market rates of €0.256/m^3 and €180/t, respectively. It is concluded from the research that the PBT will decreases even more if Energy Maize (EM) utilization rates increase and a lower PBT can also be obtained with a greater income from biogas and fertilizer.[10]

In an inclusive research, the AD of cattle, swine, and poultry wastes with carefully chosen ratios is carried out to evaluate their biogas yields. The research affirms that a farm owner can get optimum biogas by blending cattle dung, swine, and poultry wastes in the precise ratio of 1:0:1 or 4:1:3 and that temperature variations within the mesophilic range do not affect biogas formation.[11]

A study illustrates that the popularity of biogas surges to a peak by upgrading to numerous available efficient forms of fuel. Taking into account energy efficiency and global warming potential, the study of conversion of biogas to compressed biogas (CBG), liquefied biogas (LBG), Fischer-Tropsch Diesel (FTD), methanol, and dimethyl ether (DME) revealed that DME gave the best performance of the fuel conversion scenarios considered.[12]

In another research paper, the effects of storage time and storage temperature on subsequent biogas production from cow manure are investigated and its outcomes are that storage of digestate at 9 °C has no significant effect on consequent biogas production, but at 20 °C, it decreases from 16.4 m^3/t to 5 m^3/t of fresh digestate and a decline of volatile solid concentration in the stored digestate to 0.4 g/kg/week is also observed.[13] Another remarkable method named *flexible biogas production* is employed, which offers the opportunity to minimize the necessary gas storage capacity and thus saves storage investments predominantly. The authors conclude that biogas can be produced with high flexibility using diurnal flexible feeding and precise combinations of substrates with different degradation kinetics.[14]

Evaluation of distinctive economic and ecological metrics for multiple objective considerations is undertaken in a life cycle-based accounting model of a domestic biogas system. A typical household biogas system in Gongcheng, China, is ideal for a case study. The outcomes are $US 6520 net benefit for each family unit compared to no biogas-linked peasants, savings of 1266.67 m^2 firewood for each household biogas unit, and reductions of 4120 kg of CO_2 and 34.7 kg of SO_2 emissions, which equate to 1.86×10^9 J and 1.70×10^7 J of environmental emission energy saved. The resulting CO_2 reduction would be worth $US 2.34×10^7 of potential carbon trading value for the whole of Gongcheng. Indirect social benefits include diminution of germs dispersal, enhancement of labor intensity, etc.[15]

In a noteworthy article,[16] the authors show that biogas production can affect the emissions of GHGs in a number of ways, but considering other factors relating to farm-scale AD like fertilizer replacement, firewood substitutes, lighting kerosene, increased agricultural production, green area augmentation, etc., these GHGs are well-balanced.

Household air pollution is ascribed as the cause of global deaths of 4.3×10^6 people and 60% of those are owing to cardiovascular complications while 40% are due to adverse effects on respiratory health.[17] Most conspicuous sufferers are women and children because of the deficiency of ventilation, fuel type, kitchen volume, stove type, eave spaces in kitchen walls, etc.[18] High levels of cardiovascular disease, stroke risk, high blood pressure, etc., are found among adult females of rural areas where solid wood is used for cooking.[19] An allied research team conducted an epidemiological study to assess the real-life impact of biogas interventions on the risk of hypertension in rural Nepal considering two groups of cooks—(i) aged greater than 50 years and (ii) aged between 30–50 years. The study indicated that systolic blood pressure (SBP) increases with increasing age, diastolic blood pressure (DBP) decreases after 50 years, and lower SBP and DBP are more marked in biogas users than wood users.[18] Statistics show that, in India, 90% of total household energy consumption is for cooking, and most of this uses biomass resources like cow dung, fuel wood, crop residues, etc.[20] Cooking takes up about 6 Hr/day in rural areas for a typical family due to the low calorific value of solid fuels, which causes slow burning and low efficiency of mud stoves. The study correspondingly relates that one of the major reasons of school dropouts among rural children is being busy with wood collection.

In another study, it was observed that AD-induced increases in phytotoxic substances such as ammonia, volatile organic compounds, or nutrient discrepancies counteracted by agronomic measures, which in turn recuperates plant growth and overwhelms disease likelihoods.[21]

An excellent planning concept has been pioneered for implementation of renewable energy in local communities in developing countries, exemplified by a Vietnamese case.[22] Comprehensive researches and pilot projects have been performed in many countries like Germany, Denmark, Sweden, China, Serbia, Kenya, Croatia, and so on, and demonstrate benefits that cut across issues of dimension, scale, and resilience.[23–28] Germany has made auspicious progress through amendments in legislation requiring 80% renewable power consumption by 2050 and the direct retailing of biogas power in the German electricity market.[27]

Bangladesh is a land of opportunities, but the energy crisis is one of the largest threats to its development. 70% of the total 161×10^6 population of Bangladesh inhabit rural areas; however, only 59.6% of total inhabitants have access to electricity, and almost 48% of rural areas are still without electrification.[29] The present peak power demand of Bangladesh is 10 283 MW, and the highest generation is 6674 MW;[30,31] demand is predicted to increase to 33 708 MW by 2030.[32] 66.4% of the existing power plants are natural gas based[33] while prevailing natural gas resources are decreasing continuously and are assumed to dry up by 2030.[32] Hence, the country is urgently exploring short, medium, and long term alternatives,[32] including planning to set up nuclear power plants to meet this increasing demand, but there are many technical complications and debates in this issue.[34] Limited diesel generator facilities exist but are too expensive and burning fossil fuels is not a sustainable long term option. Owing to climate change and global warming, Bangladesh is in a potentially catastrophic hotspot of various natural calamities, including floods, cyclones, storm surges, salinity intrusion, extreme temperature, drought, etc.[35,36] However, burning of fossil fuels worldwide for power generation will, in time, intensify these types of threats alarmingly. Renewable energy sources are regarded as a promising solution of these pivotal issues.[37] Although the Solar Home System (SHS) has spread out to some extent in rural areas of Bangladesh, contrariwise, the high price of solar systems and the low efficiencies of solar panels mean that the SHS certainly cannot be deemed as an outright solution for the underprivileged populaces of rural communities.[38,39] Besides, only 6% of the total population of urban areas gets access to a natural gas cooking facility[40] and most of the rural areas are without any natural gas supply.[41] Those rural people mainly utilize wood and kerosene for cooking and lighting requirements which, at the end of the day, triggers obliteration of green territory and precarious environmental impacts.[42]

In a biogas based research in Bangladesh, the authors report that Bangladesh has an enormous biogas resource potential with its about 200×10^6 poultry fowls in over 200 000 poultry farms. Hardly any biogas plants have been installed in these farms till date, so the possibility of electricity generation has been estimated to have the potential of producing 1.33 TWh of electricity per year from the poultry industry. The investigation also summarizes the impact of different factors on production of biogas in different biogas plants of Bangladesh ranging from 6.4 m^3 to 4000 m^3 capacity and concludes that 75% more biogas can be achieved from well-equipped biogas plants with modern controlling stratagems.[43] But the cost factors associated with providing such control systems deter the rural people from adopting these types of plants. Because the power systems in poultry farms are anticipated to operate in generally isolated locations with no alternative supply, they must be safe and reliable under all operating conditions. Hence, the authors in a parallel study[44] examined the power system stability of a stand-alone poultry based biogas plant of Bangladesh under different operating conditions using software simulation. A research on off-grid electrification carried out for rural Bangladeshi areas,[45] but the capacity of those ranged from 10 to 50 kW, which is a major constraint for these systems as electricity demand cannot be so severely limited for proper rural development.

The proposed Energy Neutral Home (ENH) is a system where the homes are clearly energy neutral by meeting their energy demand via renewable energy resources devoid of taking electricity from grid. The ENH may well provide abridged costs for infrastructure, such as line capacity and peak load generation facilities, plus abbreviated network losses and also promote long-term energy supply security.[46,47] The energy neutral home system (ENHS) is developed from Bangladesh perspective and is aimed at two cases: (i) ENHS with only biogas for a single home, which results in a per kWh electricity generation cost of 2.92 BDT (Bangladeshi Taka) which would be less for a larger collective of houses in an area,[46] (ii) hybrid ENHS using biogas and solar panels collectively as input renewable energy sources, which is found to be more cost effective in urban areas, yielding a per kWh electricity generation cost of 6.74 BDT. The study also indicated that this per unit cost is lower than the ENHS design based on a solar system alone, but is still not cost effective for rural areas.[47] In another research, it is revealed that an ENHS is significantly beneficial for load shedding backup in urban areas using human waste and found to be more advantageous than the widely used Instant Power Supply.[48] But this system is not pertinent in rural areas as those are completely without electricity, which does not validate the question of load-shedding. Additionally, there are no high-rise buildings in rural areas; hence, human waste collection is not feasible as indicated in the research.[48]

In this paper, an effectual biogas based ENHS system is developed to light rural areas, provide ample cooking gas and bio fertilizer, thereby supporting sustainable rural development by using readily available cow and poultry manure as the primary sources of energy. This system also contributes to GHG balancing and promotes a healthy and clean living environment. This research is designed for a community of 200 houses such that they obtain the basic needs of modern life; it is an extension of earlier work on the ENHS accomplished for a standard home.

From the experimental and mathematical analysis, it is clearly evident that the proposed ENHS not only reduces the cost of energy generation, but also assists in the reduction of the energy crisis and global warming. Per unit electricity production price of this proposed system is 1.90 BDT ($US 0.0247 [1 BDT = $US 0.013 is considered]) and the distribution price is considered at 5.00 BDT ($US 0.065), which is lower than the present tariff rate. As rural people are dependent on agriculture and fishing for living, slurry of this system can be used as high quality biofertilizer in fields and as fish food in fishing farms. Though this system is designed for Bangladeshi rural areas, it can be implemented anywhere around the world where needed. The research will thus generate new knowledge on how an ENHS can be a viable and efficient solution to facilitate the provision of electricity to rural communities around the world, not only ameliorating the energy and environmental crises, but also adding value in areas of the economy and sustainable development.

II. MATERIALS AND METHOD

The proposed ENHS is designed for a rural community of Bangladesh, which includes a farming business where 200 nearby houses are considered as the consumers. This system basically comprises a biogas plant having an inlet chamber, a digester, and an outlet or hydraulic chamber as presented in the block diagram of the ENHS shown in Figure 1. The gas production

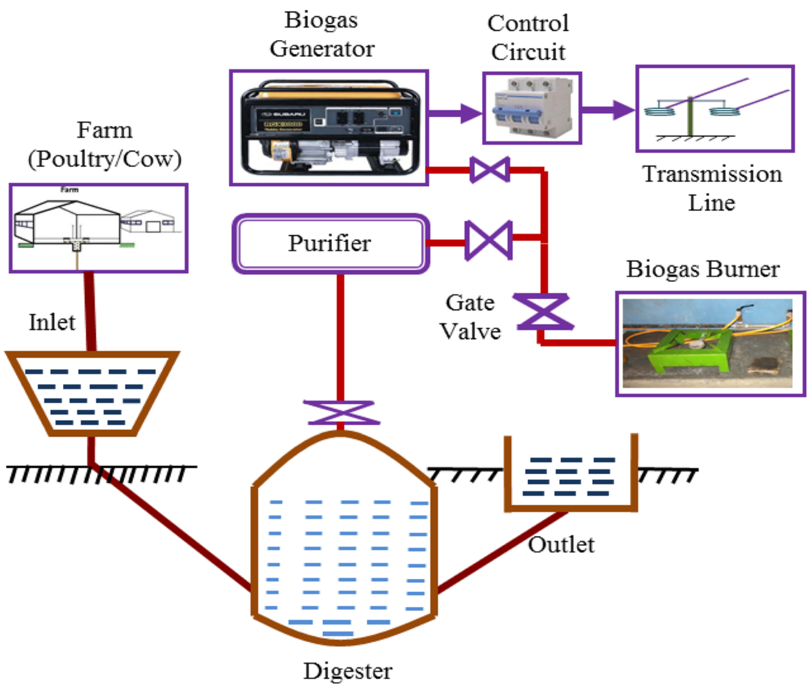

FIG. 1. Block diagram of the proposed ENHS.

rates of chicken and cow manures are 0.07 m^3/kg and 0.037 m^3/kg, respectively, which are comparatively higher than other waste sources.[49,50] Hence, this system considers chicken and cow manures as the primary waste sources from a farm having 96 thousand layers (these are the chickens which lay eggs and their waste contain high total solid (TS) value) for biogas generation and 350 cows for optimum performance. Manures are fed to the inlet of the plant, mixed with water at an appropriate ratio and sent to the digester. The biogas produced by means of the AD process is collected through a specially designed purifier and processed into both a biogas generator and a cooking gas line. Electricity is distributed to the 200 houses through transmission lines associated with control and protective circuitry. For cooking purposes, specially designed burners are used whose gas nozzles are bigger than usual as biogas pressure is lower than with natural gas. After digestion, the waste eructates from the digester to an outlet or hydraulic chamber in wet slurry form owing to high gas pressure in the top of the digester. This can be used for fish feeding directly and the dry slurry can be used as bio-fertilizer in agriculture after necessary processing.

A. System demand and management plan

To determine energy demand and other managerial specifics, a standard home of a rural Bangladeshi region is considered as the analytical base of the proposed research. The gas containing capacity of that standard energy neutral home is 6 m^3, which is used for both cooking and electricity generation purposes in the proportion of 33% and 67%, respectively.[46] The total energy demand of that system is 669 W,[46] which is also considered as the benchmark for the proposed ENHS with the inclusion of computer provision and slight tweaking in load configuration as demonstrated in Table I. The expected load curve for electricity supply of a standard home is displayed in Figure 2.

The total estimated daily electricity demand for the proposed ENHS of a rural community of 200 houses is 577.3 kWh and the corresponding load curve is depicted in Figure 3. This assumption is made according to the load condition of a standard home combined with considering some other factors, viz., financial condition, family size (number of family members), size of houses, etc. Although the system includes a standard home rating, given the factors

TABLE I. Energy demand of a standard home for the proposed system.

Load	Rating (W)	Number	Total Power (W)
Energy saving bulb	15	2	30
Energy saving bulb	25	2	50
Energy saving bulb	12	2	24
Ceiling fan	75	3	225
Color TV	100	1	100
Refrigerator	150	1	150
Computer	80–90	1	90
		Total	669

stated above, not all homes use a refrigerator, computer, etc., which may establish a variation in the load assumptions of Figure 3. The load curve discloses that maximum electricity demand is 59.4 kW in the peak hours from 6 pm to 10 pm. By and large, 1.4 kWh electricity generation entails 1 m^3 biogas and a biogas burner requires 0.4 m^3 of biogas for a 1 Hr cooking period.[50] The ENHS scope considers two biogas burners for 2.5 Hr of cooking for a family per day, which amounts to 2 m^3 biogas. Hence, for the total community, the required biogas for electricity generation is 426.64 m^3 and cooking gas is 400 m^3 per day. Therefore, the percentages of biogas usage for electricity generation and cooking of the designed ENHS are 52% and 48%, respectively, as shown in Figure 4.

B. System design

The main part of the entire system is the biogas plant and its two core components are the digester chamber and hydraulic chamber. Schematic design details of the biogas plant are exhibited in Figures 5 and 6. The various design parameters are listed in Table II. Manure from cow/poultry farms is fed to the inlet via a waste storage chamber and mixed with water at ratios of 1:1 and 1:2 for cow and poultry wastes, respectively.[50] A water supply system is assimilated with the inlet to supply essential water during the mixing process. A specially designed mixer, coupled with a motor, is set in the interior of the inlet chamber and is used to blend the digestate to yield the anticipated total influent by dint of an appropriate control system. The total load of this mixing system is assessed as 10 kW in light of four 1-Φ induction motors each of 3 hp, 1600 rpm, plus a water pump of 1.5 hp and 2 Hr mixing time per day. The coupling of motor to impeller shaft is via a gear box of ratio near to 4:1 for operating the mixer at around 400 rpm to ease the mixing process; else the apt mixing is not achievable, i.e., the mixing time increases with lower rpm and, for higher rpm, the mixing mechanism may collapse. The total

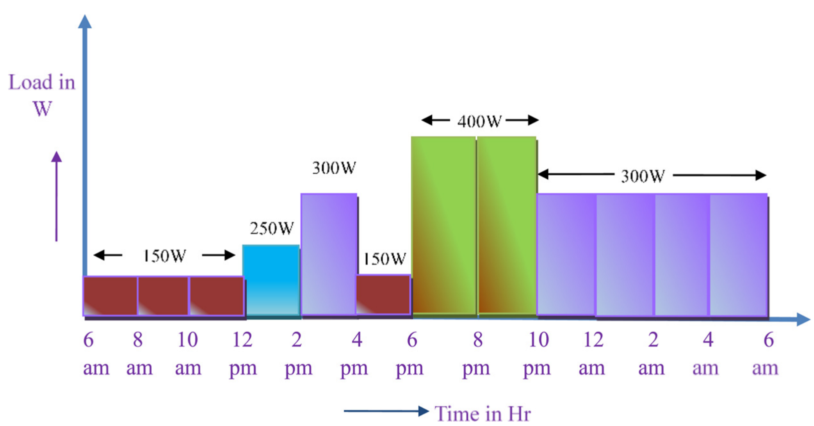

FIG. 2. Load curve for electricity supply of a standard home.

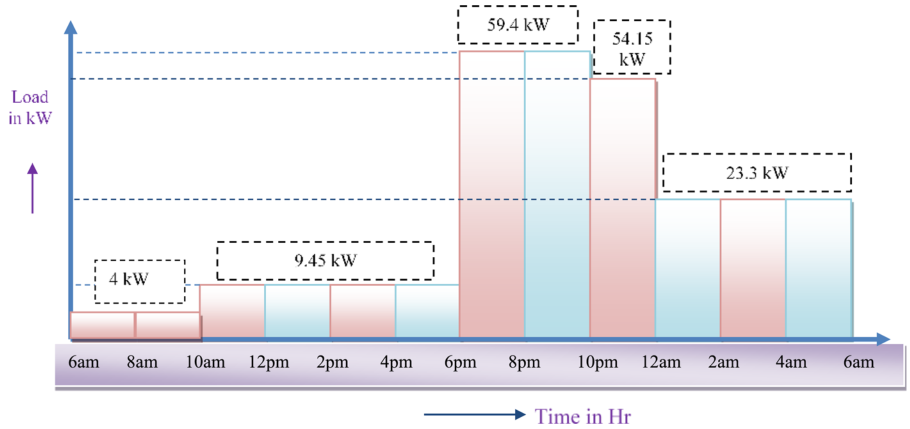

FIG. 3. Load curve of the ENHS for a community.

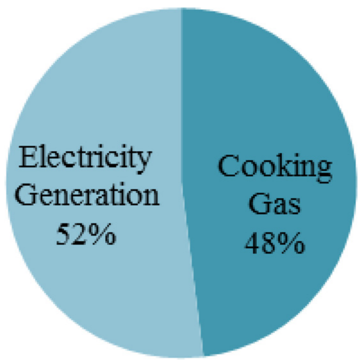

FIG. 4. Proportion of biogas for electricity generation and cooking.

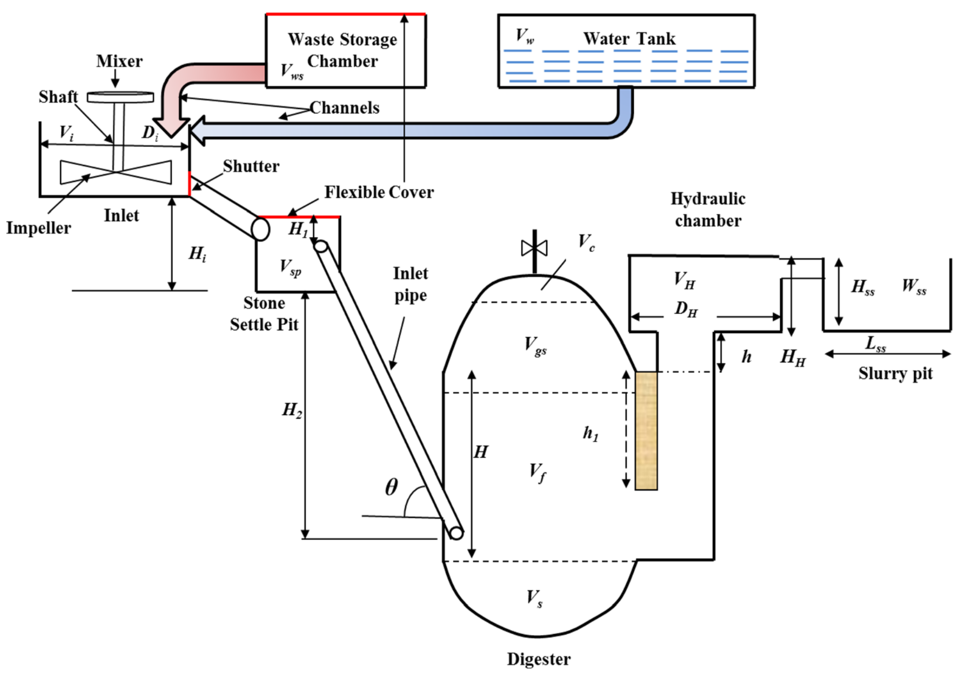

FIG. 5. Schematic diagram of biogas plant.

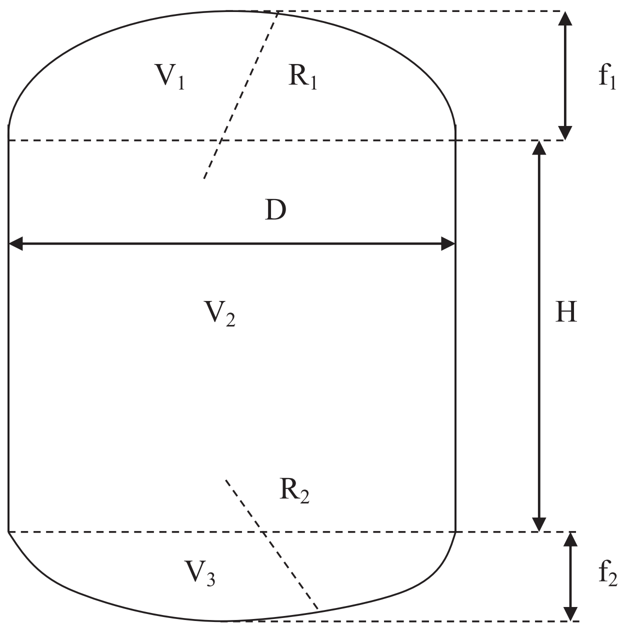

FIG. 6. Measurement parameters of digester.

mixed influent is channeled throughout a manual shutter to the stone settle pit, from where the detrimental contents of poultry or cow manure such as small stones, snails, etc., can be readily removed before the entry of digestate to the digester dome, thus extending the life time of the digester. The generated biogas is drawn from the gas collecting chamber of volume $\boldsymbol{V_c}$, as indicated in Figure 5. The wet slurry from the hydraulic chamber exits automatically to the slurry pit whose construction should be such that facile collection of dry slurry is possible (usually the length should be double the height). For an optimum design of the plant, some factors are

TABLE II. Design parameters of the biogas plant.

List of design parameters	
V_i = Volume of inlet	f_1 = Extent of upper parabolic chamber of digester
V_c = Volume of gas collecting chamber	f_2 = Extent of lower parabolic chamber of digester
V_{gs} = Volume of gas storage chamber	H_i = Clearance between lower level of both inlet and stone settle pit
V_f = Volume of fermentation chamber	H_1 = Clearance of inlet pipe from flexible cover of stone settle pit
V_s = Volume of sludge layer	H_2 = Level of stone settle pit from insertion point of inlet pipe to digester
V_H = Volume of hydraulic chamber	H = Height between lower level of gas storage chamber and sludge layer
V_{sp} = Volume of stone settle pit	h_1 = Height of the hydraulic chamber from digester manure level;
V_{ws} = Volume of waste storage chamber	h = Height of the hydraulic chamber to lower level of gas storage chamber
V_w = Volume of water tank	H_H = Height of the hydraulic chamber
V_1 = Volume of upper parabolic chamber of digester	H_{ss} = Height of the slurry pit
V_2 = Volume of middle cylindrical portion of digester	W_{ss} = Width of the slurry pit
V_3 = Volume of lower parabolic chamber of digester	L_{ss} = Length of slurry pit
V = Total volume of the digester $= V_c + V_{gs} + V_f + V_s$	θ = Inclined angle of inlet pipe
D_i = Diameter of inlet	
D = Diameter of digester	
D_H = Diameter of hydraulic chamber	
R_1 = Radius of upper parabolic chamber of digester	
R_2 = Radius of lower parabolic chamber of digester	

presupposed, viz., $\boldsymbol{V_{ws} > V_i}$, $\boldsymbol{V_w \approx V_{ws}}$ for cow waste and $\boldsymbol{V_w \approx 2V_{ws}}$ for poultry waste according to the mixing ratio, $\boldsymbol{V_{sp} \approx V_i /4}$, $\boldsymbol{L_{ss} \approx 2H_{ss}}$, etc. Design parameters of the biogas plant are computed considering these prerequisites along with Infrastructure Development Company Limited (IDCOL) standards,[50] but the parameters may diverge depending on the plant location. Geometrical assumptions for digester design calculations are displayed in Table XII in Appendix A. For continuous system operation, three different digesters, each containing 32 000 layers and another fourth digester with 350 cows are deemed necessary. Hydraulic Retention Time (HRT) at 30 °C temperature is considered as 40 days.[50] 10 kg and 100 g manure are obtained per day from each cow and layer, respectively.[51,52] TS percentages of fresh discharge are 16% and 20%, respectively, and total influent is calculated considering 8% favorable condition of TS value.[53] According to these standard data and using Table XII in Appendix A and Eq. (B1), design calculations of digester and hydraulic chamber for both 350 cows and 32 000 layers are presented in Table III. The assumed value of inclined angle of inlet pipe, θ, is the same for all digesters of the system and its value is 60°.[50] The rest of the design parameters revealed in Figures 5 and 6 are appraised based on assumptions which may vary on account of the geographical location of the plant. Thus, the system is optimized based on available literatures, practical implementation,[46] associated technologies and necessary assumptions.

According to the above calculations, an overview of the plant, including inlet, outlet, and digesters, with generators in combination, are detailed in Figure 7 where all evaluated design parameters, generator capacities and running times, and generators' connections with the specific number of digesters are portrayed. Figure 8 exhibits the overall supply connection of digesters-generators-users and digesters-common biogas line-users. The generated electricity and biogas of the ENHS are delivered to the users from the generator block through a common grid line and common biogas line, respectively.

Biogas comprises some undesirable impurities, viz., H_2S, moisture, vapor, etc., which must be removed before consuming the gas. Amongst these, H_2S is the most problematic, since it is toxic as well as corrosive. Although the proportion of H_2S in biogas composition is very low (0–1%),[54] even its slight presence can cause some damage to the generator and hence lowers the system life time while environmental aspect is beyond the discussion.[55,56] Hence, a specialized purification unit is employed in the system, as shown in Figure 9, which contains 3 chambers.[50,52] Chamber 1 is known as the water trap and it sucks the water content from the biogas. Chamber 1 acts as a simple filter, which has a pipe inside with a certain height and span where the biogas strikes to the inside wall. Hence, the water content of biogas is detached and stored

TABLE III. Volume calculation data of digester and hydraulic chamber.

Parameters	Value: 350 cows	Value: 32 000 layers	(Hydraulic chamber) Parameters	Value: 350 cows	Value: 32 000 layers
Total influent (Q)	7000 kg	8000 kg			
Water to be added	3500 kg	7360 kg			
Working volume (Digester)	280 m^3	320 m^3	V_s	52.5 m^3	60 m^3
			V_{gs}	196 m^3	224 m^3
			V_{dis}	7 m^3	8 m^3
V	350 m^3	400 m^3	Gas chamber volume	89.32 m^3	101.85 m^3
D	9.22 m	9.63 m	P_i	4 kPa	4 kPa
H	3.69 m	3.85 m	P_f	9.8 kPa	12.79 kPa
f_1	1.844 m	1.926 m	h_1	0.7 m	1 m
f_2	1.1525 m	1.2 m	h	0.3 m	0.3 m
R_1	6.6845 m	6.98 m	H_H	1 m	1 m
R_2	9.8 m	10.23 m	D_H	2.98 m	3.19 m
V_1	64.82 m^3	73.85 m^3			
V_c	17.5 m^3	20 m^3			

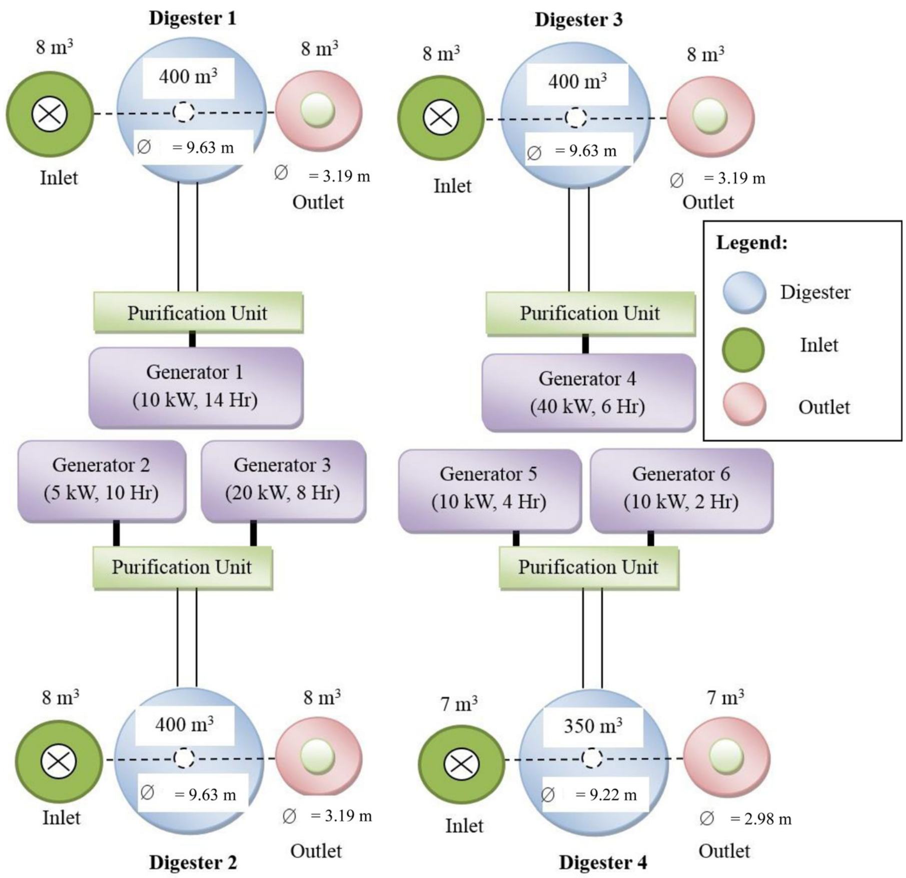

FIG. 7. Overview of the ENHS for a community of 200 homes.

at the bottom of the chamber. The stored water is removed using a tap under chamber 1 after six months.[52] Chamber 2 holds iron (Fe) chips and it is the most significant portion, as this chamber eliminates the noxious H_2S according to following reaction:

$$Fe + H_2S = FeS + H_2$$

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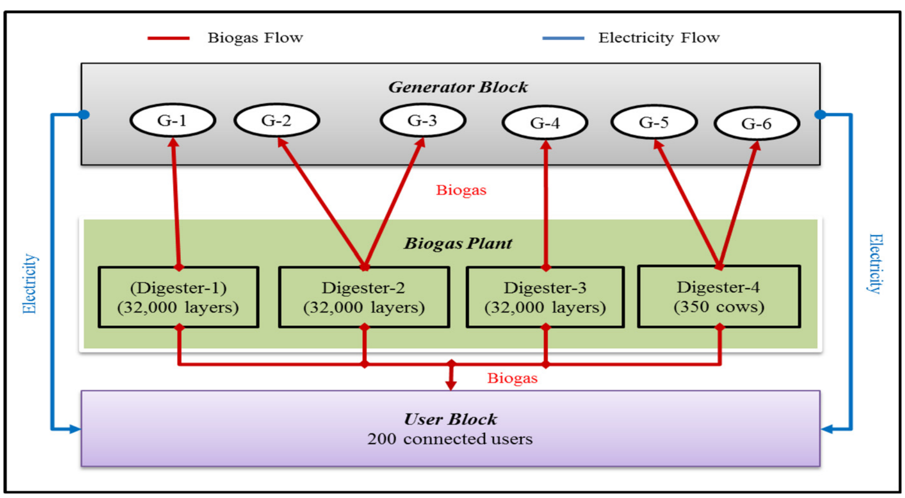


FIG. 8. ENHS for rural community.

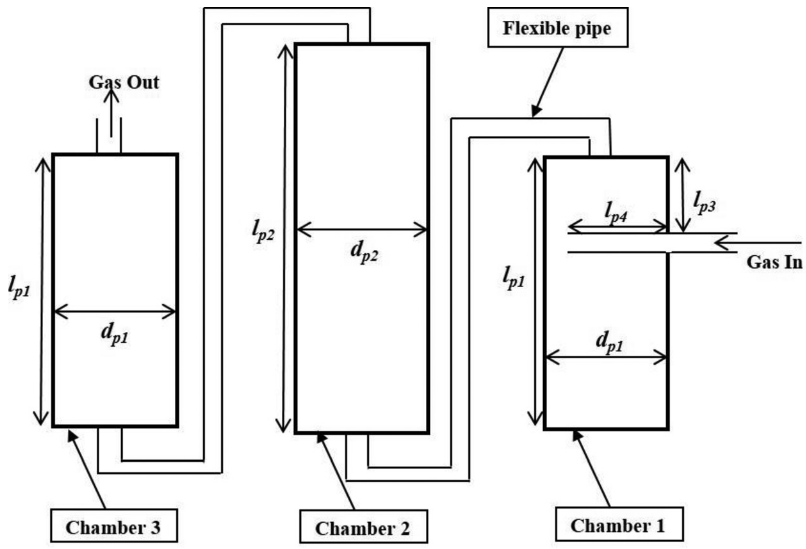


FIG. 9. Schematic diagram of biogas purifier used in the ENH system.

Chamber 3 has silica gel within it and removes vapor or moisture from the biogas.[57] Iron chips are inspected at least twice a year and regenerated or replaced if required, depending on its condition, whether it is fully oxidized or not. On the other hand, the silica gel is inspected quarterly every year and replaced when its original color changes, which depends on biogas flow rate through the purifier.[52]

The design parameters of the biogas purifier are denoted in Figure 9, where l_{p1} and l_{p2} are spans of the respective chambers, l_{p3} is height of inlet pipe placement, l_{p4} is span of inlet pipe into chamber 1, d_{p1} and d_{p2} are the diameters of the cylindrical chambers. These are assumed such that $l_{p3} \approx l_{p1}/3$, l_{p4} is slightly less than overall diameter d_{p1}, $d_{p2} > d_{p1}$, and $l_{p2} > 1.5 l_{p1}$, which vary with digester size and generator capacity.[52]

Table IV indicates gas production capacity (V_{gs}) of each of the three chicken manure digesters is 224 m^3 and the fourth one for cow manure is 196 m^3, which sums the total gas production capacity of the system as 868 m^3 and indicates generator capacities for the best performance. Gas generators for generating electricity from biogas are reliant on load demands around different times as displayed in Figure 10. Figure 11 explores generator operating schedule at different times to meet the pivotal load demand of this system in an assured way. The graph in Figure 12 presents electricity generation by the system for 24 Hr according to the schedule periods of Figure 11. As generator 6 is dedicated for running inlet systems and other auxiliaries, it is not included in further load analysis.

The test case prototype of this developed ENHS is implemented (as shown in Figure 13) for a standard home at Mr. Anil Kanti Das's residence, located in Rangunia, Chittagong, Bangladesh. Figure 13 provides some photographs of the implemented prototype.[46] An area within a 1 km radius is assumed, including 200 families, as a test case area for this system. The

TABLE IV. Digester vs. generator capacity.

Digester No.	Designed for	Gas production capacity(m^3/day)	Generator No.	Generator capacity (kW)
1	32 000 layers	224	Gen-1	10
2	32 000 layers	224	Gen-2	5
			Gen-3	20
3	32 000 layers	224	Gen-4	40
4	350 cows	196	Gen-5	10
		(Sum = 868 m^3)	Gen-6	10

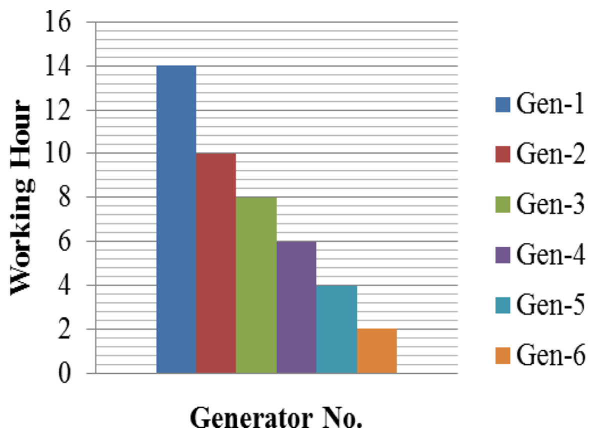


FIG. 10. Effective working time of generators.

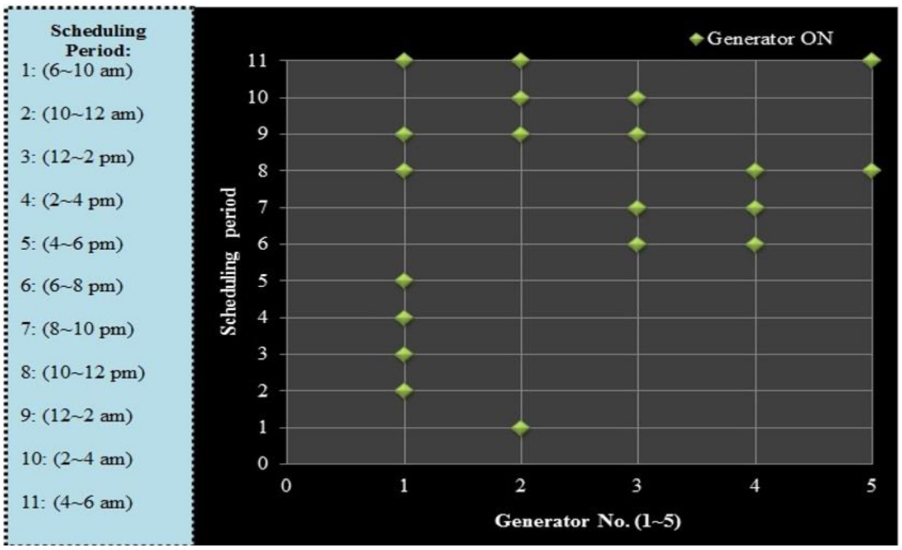


FIG. 11. Generator scheduling.

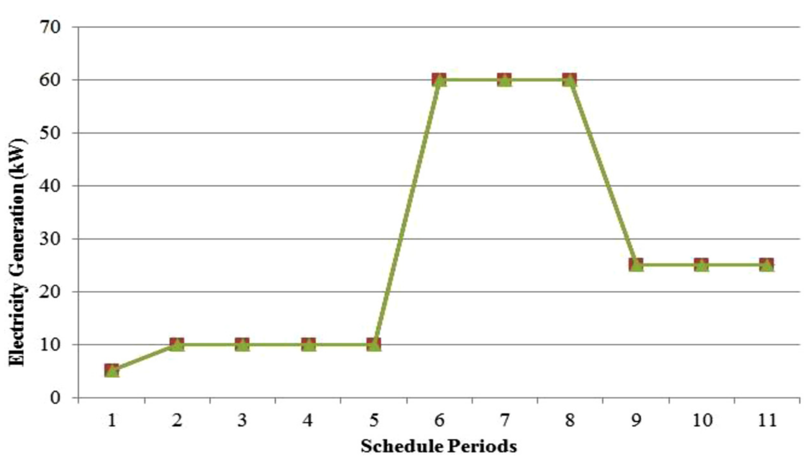
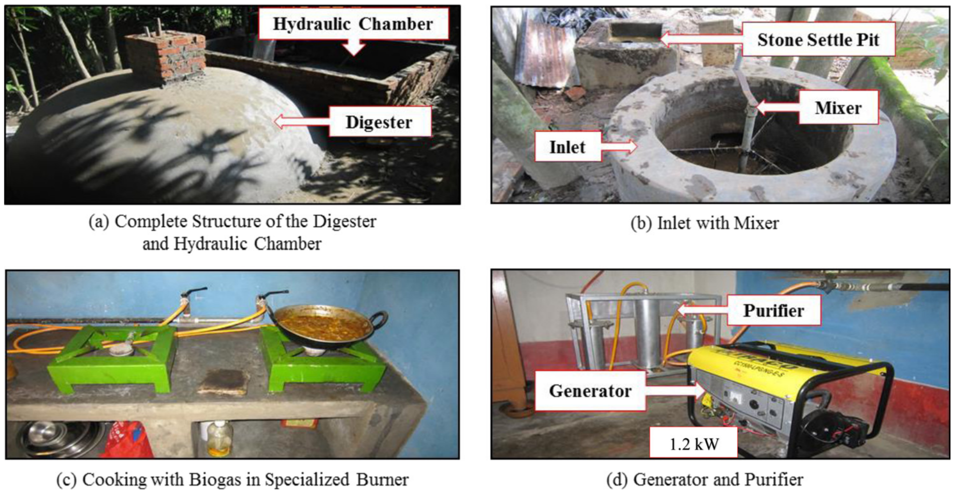


FIG. 12. Electricity generation over a day.



(a) Complete Structure of the Digester and Hydraulic Chamber
(b) Inlet with Mixer
(c) Cooking with Biogas in Specialized Burner
(d) Generator and Purifier

FIG. 13. Implemented energy neutral home system.

analysis and related design calculations are made based on the practical data from this prototype, GTZ (Deutsche Gesellschaft fur TechnischeZusammenarbeit) and IDCOL Bangladesh.[51,52]

III. RESULT AND ANALYSIS

Net present value (NPV) and payback period analysis are used to determine economic viability of the model. The equation for NPV is presented in the following equation:[58,59]

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+k)^t}. \quad (1)$$

Here, CF_t = cash flow of the investment in time period t; k is the discount rate; and t is the time period from 0 to n years.

Again, payback period (PBP) is calculated as[60]

$$\text{PBP} = \text{Cinit} / \text{Cin}, \quad (2)$$

where Cinit = initial investment and Cin = annual cash inflow.

All costs are estimated based on vendor's retail price.[50,52] Taking the total life time of this ENHS for a rural community to be 20 years[61] and given the cost of a 500 CFT (Cubic Foot) [1 m^3 = 3.283 CFT] digester is about 70 000 BDT ($US 910),[62] brief digester costs in addition to hydraulic chamber and inlet recharge chamber costs are set out according to Figure 7, which results in a total cost of 7 963 710 BDT ($US 103 528) to construct the stated four digesters. The purification system cost is dependent on digester size plus generator capacity and is determined according to market prices of 80 000 BDT ($US 1040) for each digester for 32 000 layers and 60 000 BDT ($US 780) for the digester for 350 cows. The model requires 4 stone settle pits of 10 000 BDT ($US 130) each and 4 waste storage chambers of 40 000 BDT ($US 520) each.[52]

$$\begin{aligned}\text{Cost for mixing system} &= 4 \times (3\,\text{hp Induction motor} + \text{Gear box (for motor controlling)} + \text{Impeller}) \\ &= 4 \times (14\,500 + 4\,200 + 10\,000)\text{BDT} = 114\,800\,\text{BDT (\$US 1492)}.\end{aligned}$$

$$\begin{aligned}\text{Cost for water supply system} &= 1.5\,\text{hp water pump} + 3 \times 8000\,\text{L water tanks [for digesters 1, 2 and 3]} \\ &\quad + 4000\,\text{L water tank [for digester 4]} \\ &= 16\,000 + 3 \times (8000 \times 9) + 4000 \times 9\,\text{BDT} \\ &= 268\,000\,\text{BDT (\$US 3\,484)}.\end{aligned}$$

Complete purification cost for this model is estimated as 300 000 BDT ($US 3900) and pipeline and other costs as 600 000 ($US 7800). Total plant cost (TPC) is thus determined as 13 499 884 BDT ($US 175 498), and the detailed cost calculations are tabulated in Table V.

For long term operation, additional costs comprising top overhaul cost and major overhaul cost along with the ongoing repair cost should be reckoned. Top overhauling is entailed after 10 000 Hr of generator operation that costs 15% of G_{cost} and the major overhauling has to be done after a further 10 000 Hr of operation at a pricing of 50% of $G_{cost.}$[62] Total operating cost for the system taking into account overhaul and repair costs of the generators is 2 315 500 BDT ($US 30 101) as analyzed in Table VI.

From Figure 4, electricity used in a day is calculated as 577.3 kWh to meet load demand. Additional 20 kWh electricity is also required to keep the inlet, mixer, and water supply system running. The total required electricity generation per day is 597.3 kWh, which requires 426.64 m^3 biogas.[50] 400 m^3 biogas is necessary for cooking purpose of 200 families considering 2 m^3/day gas demand to each family.

In accordance with the percentage split of biogas consumption, as shown in Figure 4, cooking gas generation cost encompasses 52% of total biogas generation and supply related costs while the cost of electricity generation is estimated considering 48% of total biogas generation costs together with generator, transmission line, and other circuitry costs.

$$\begin{aligned}\text{Cooking gas generation cost} &= 52\%\text{ of digester cost} + 52\%\text{ of inlet system cost}\\ &\quad + 52\%\text{ of purification cost} + \text{pipelining cost}\\ &= 5\,200\,186\text{ BDT} \approx \$\text{US }67\,602\end{aligned}$$

$$\begin{aligned}\text{Per unit cooking gas generation cost} &= \text{cooking gas generation cost} / \text{total gas generation in 20 years}\\ &= 1.78\text{ BDT} \approx \$\text{US }0.023\ (\text{per m}^3)\end{aligned}$$

Electricity generation cost = 48% of digester costs + 48% of inlet system cost + 48% of purifier cost + generator cost + total operating cost of generators + transmission line and other circuitry costs = 8 299 698 BDT ≈ $US 107 896.

Per unit electricity generation cost = electricity generation cost / total electricity generation in 20 years = 1.90 BDT ≈ $US 0.0247 (per kWh).

Monthly cooking gas bill is assumed 800 BDT (≈$US 10.4) for each family. The daily electricity consumption varies from home-to-home due to the socio-economic conditions of rustic people. The monthly income of the ENHS for electricity consumption with a rate of 5.00

TABLE V. Total plant cost of the designed model.

SL	Capital cost item	BDT
1	Digester construction	7 657 390
2	Hydraulic chamber and inlet construction	306 320
3	Stone settle pit	40 000
4	Waste storage chamber	160 000
5	Mixing system	114 800
6	Water supply system	268 000
7	Purification unit	300 000
8	Pipeline and others	600 000
9	Generator cost	1 530 000
	Subtotal plant cost (SPC) [1 + 2 + 7 + 8 + 9]	10 393 710 ($US 135 118)
10	Transmission line and protective circuitry (2% of SPC)	207 874
11	Total operating cost of generators	2 315 500
	Total plant cost (TPC)	13 499 884 ($US 175 498)

TABLE VI. Generator Overhaul and Repair Costs.

		Top overhaul		Major overhaul					
Gen. No.	Operating time (Hr)	Required times	Total cost (15% of G_{cost} each time) (BDT)	Required times	Total cost (50% of G_{cost} each time) (BDT)	Total overhaul cost (BDT)	Total generator overhaul cost (BDT)	Repair cost (BDT)	Total Operating Cost of generators (BDT)
Gen-1	102 200	5	127 500	5	425 000	552 500	2 115 500	200 000	2 315 500 ($US 30 101)
Gen-2	73 000	4	42 000	3	105 000	147 000			
Gen-3	58 400	3	135 000	2	300 000	435 000			
Gen-4	43 800	2	195 000	2	650 000	845 000			
Gen-5	29 200	1	25 500	1	85 000	110 500			
Gen-6	14 600	1	25 500	…	…	25 500			

BDT (≈$US 0.065) per kWh is detailed in Table VII, and the yearly revenue of the system is enumerated in Table VIII.

As the system incorporates the employees of the farming business into the ENHS also, it does not require more workers for system management. However, the system employs two laborers at 10 000 BDT (≈$US 130) each per month and an accountant at 15 000 BDT (≈$US 195) per month on a fulltime basis. The total operating cost (TOC) of the model is summarized in Table IX, and all investments, expenses, and earnings are briefed in Table X. Finally, the financial evaluation of the proposed model is calculated and presented in Table XI, which results in the system being economically viable.

IV. DISCUSSION

This study developed an ENHS for rural communities which will not only play an active role in reducing the energy crisis and costs of energy generation worldwide, but also reduces greenhouse gas emissions into the atmosphere. From the study, it can be clearly demonstrated that the proposed system will be beneficial to society in a number of ways, which are presented in Subsections IV A–IV H.

A. Case-1: Retail price of electricity

According to the retail tariff plan of the Rural Electrification Board (REB) for the fiscal year 2013–2014, the per kWh electricity price for domestic users is 3.36–3.87 BDT,[63] and including line charge and all other service charges, it becomes 5.92 BDT, which is proposed to increase from 7% to 18.86% depending on the load level.[64] But load shedding is a very common hazard in rural areas and no new electricity connections are allowed. In this ENHS, electricity price is estimated as 5.00 BDT per kWh, which is lower than the REB tariff with the ENHS providing assurance of supply continuity and reliability. The costs of electricity from

TABLE VII. Monthly electric bill calculation.

House No.	Electricity consumption/day (kWh)	Per unit rate (BDT)	Monthly bill (BDT)	Total monthly electric bill (BDT)
1–10	114.6	5	17 190	86 610 ($US 1126)
11–40	147	5	22 050	
41–60	63.6	5	9540	
61–80	50	5	7500	
81–100	16.2	5	2430	
101–150	141	5	21 150	
151–200	45	5	6750	

TABLE VIII. Yearly revenues from the model.

Revenues	BDT/month	BDT/year
Cooking gas charge	160 000	1 920 000
Electric bill	86 610	1 039 320
Total revenues		2 959 320 ($US 38 471)

TABLE IX. Summary of total operating cost (TOC) of the System.

Item	Cost item	BDT/year
	Fixed operational cost (FOC)	
1	Personnel cost	420 000
2	Overheads	35 000
	Variable operational cost (VOC)	
3	Repair and maintenance	50 000
	Total operating cost (TOC)	505 000 ($US 6565)

TABLE X. Summary of investment, expenses, and earning.

Investment (TPC)	13 499 884
Yearly income	2 959 320
Yearly expenses (TOC)	505 000
Yearly earning	2 454 320 ($US 31 906)

TABLE XI. Financial evaluation of the proposed System.

Discount rate	%	12
Payback period (PBP)	Years	5.5
NPV, 20 years	BDT	18 332 405
Net Profit	BDT	50 313 560 ($US 654 076)

other renewable sources are much higher, viz., electricity from solar system costs 13.7 BDT (≈$US 0.178) per kWh.[65]

B. Case-2: Per unit electricity generation cost

It has been seen from the results that the electricity generation cost for this system is 1.90 BDT covering transmission and distribution costs. However, the per unit cost of electricity generation for recently available quick rental power plants (QRPPs) and Independent Power Producers (IPPs) is 4.75 to 5.39 BDT and 1.40 to 3.80 BDT, respectively, from natural gas while it is 15.21 to 15.30 BDT and 16.27 to 16.70 BDT, respectively, from furnace oil.[66] Government is subsidizing this sector to provide electricity at reasonable prices, which costs a huge amount of the budget every economic year. The country subsidizes in two categories, power generation and distribution. The first step reduces the generation cost to an average of 5.36 BDT per kWh, and the second step minimizes the distribution tariff to consumers, which was a cost to the national budget of 65.6×10^9 $US in 2013.[67]

C. Case-3: Lighting (ENHS vs. kerosene)

People usually use kerosene for lighting purposes in rural areas, which costs almost 500–600 BDT per month for a standard family[68] and also causes environmental as well as health hazards due to kerosene burning at home.[69] In this system, electricity supply from the renewable source abolishes this kerosene cost and safeguards the healthy environment at home. Lighting of houses, schools, etc., of remote areas with the ENHS gives rural kids and students better conditions for study and hence they can utilize their time effectively, which finally leads to social development of rural areas.

D. Case-4: Cooking benefits

The present tariff rates of single and two burner stoves are 400 BDT and 450 BDT, respectively.[70] But recently a price increment proposal of 1000 BDT for two burners and 850 BDT for one burner was submitted to the Bangladesh energy regulatory commission, being 122.22% and 112.50% increments, respectively.[71] A survey in a village Pomra, Rangunia, Chittagong, Bangladesh, reveals that the cooking wood cost for a typical family is around 2000 BDT/Month while Liquified Petroleum Gas (LPG) costs around 3000 BDT/Month. Again, some people use kerosene stoves for cooking, which costs almost 2500 BDT per month. In this system, the cooking gas price is fixed at 800 BDT, which is cheaper than the current cooking cost in a rural area considering the factors as stated above. Therefore, this ENHS provides a significant saving from cooking gas usage. As can be predicted from the statistics,[40,41] there is no chance of a natural gas supply facility being available in rural areas in the foreseeable future; hence, this ENHS brings this facility to rural people along with good financial savings, which finally leads to the socio-economic development of rural communities of Bangladesh. This cooking gas facility additionally ensures a healthy cooking environment and saves cooking wood collection time,[20] which leads to rural life development. In such instances, the mothers will get more hygienic cooking conditions which will reduce the probability of food poisoning and sickness, particularly among poor children. Therefore, ENHS will be a wonderful solution in rural areas of Bangladesh where the potential of biomass and biogas energy sources is enormous.

E. Case-5: Environmental impact

Natural gas required for 1 kWh electricity generation is 1000 CFT.[72] Consequently, this system generates a total of 577.3 kWh electricity for consumer supply with biogas which saves 577 300 CFT of natural gas resources per day. Furthermore, per kWh electricity production from natural gas emits a maximum 891 g CO_2[73] to the environment which would cause about 514.4 kg CO_2 emission per day to serve this rural community system demand using natural gas, while a maximum 333.6 kg CO_2 is emitted by electricity generation from biogas in this proposed ENHS.[54,74] In rural areas, usage of non-purified biogas containing H_2S is evident from the fact that tin shaded rooftops of kitchens are damaged very quickly with burning and hence introduces extra cost, hazards, etc.[75] Again, it stimulates oxides of sulfur while burning which ultimately prompts severe acid rain and serious greenhouse effects.[76] It also reduces generator lifetime significantly, and GI pipeline is damaged very early if the supplied biogas contains even a small portion of H_2S. However, in this system, biogas is purified with the removal of H_2S as it is a very perilous component of biogas for generator and cooking. Consequently, this system will reduce the emission of GHGs from the generation sector as well as the residential sector, which will diminish global warming and climate changing impacts.

F. Case-6: Ease of waste management

As the business of poultry and cow farming is spread through rural areas along with the system, it makes the waste management of the farm easy and profitable. In large scale poultry and cow farms, massive amount of wastes are created every day, which are incredibly difficult to dispose of in an environment-friendly way. In rural areas of Bangladesh, these fresh wastes are openly used as biofertilizer on crops, which is not useful focusing various factors as discussed in this research.[21] However, such fresh wastes require a lengthy period to turn into a fertilizer and, in the course of this open digestion process, the high methane content of those fresh wastes causes 21 times greater greenhouse effects than of a CO_2 molecule.[77] From that point of view, this system introduces an environment-friendly way of appropriate waste management. An attractive benefit of this system for rural people is that the raw slurry discharged from the digester outlet can be used as fish nutrition in pond or fish farm adjacent to the plant, and also as quality biofertilizer[21,78–84] in agriculture.

G. Case-7: Social impact

In this research, provision for using computers in a rural community where electricity has not yet reached may not seem appropriate, but bearing in mind the country's goal of exploiting modern technological advancements and telecommunications, it is readily foreseeable that, if proper amenity is bestowed to these diligent and talented rural people, this will create a significant difference and there will be a technological revolution countrywide. As electricity is a key factor to improve medical services in remote areas, implementation of a system like this permits vaccination, sterilization, and surgery, and hence, an improvement over time in the quality of the medical services will be possible. These better working conditions may attract more qualified doctors and nurses to work in rural environments. Moreover, this system creates job opportunities for rural people as plant operators, accountants, etc., generates opportunities for both small and large businesses outside the heavily populated cities of the country by dint of improved accessible amenities and, as a consequence, the ENHS helps to diminish poverty.

H. Case-8: Reduction of deforestation

The cooking wood requirement for a standard family per year is 4.24 tons.[85] Thus, this system saves the community 884 tons per year of wood from household cooking, which in turn saves a large amount of trees from being cut down. Again, these saved green trees will reduce GHG effects on the environment in a substantial way and assist with greenhouse gas balance.[16]

V. FUTURE RESEARCH SCOPES

The comprehensive model will yield a sensible and simplified platform that provides the detailed information for possible deployment of an ENHS for rural communities not only in Bangladesh but also in other countries around the world. This study is still in its preliminary phase and so there is an ample scope for ancillary research on this system in the following areas:

- Development of simulation model to validate the experimental and mathematical analysis.
- Development of ENHS based chain business model for a rural community.
- Development of ENHS in larger scale.
- ENHS with more enhanced purification capacity.
- Updating of the system considering other socio-environmental factors.
- ENHS design for urban areas where a vast quantity of municipal and human waste is available.

VI. CONCLUSION

Energy crisis in the rural areas, costs of energy generation, and environmental awareness have encouraged interest to generate more energy from renewable energy sources either through off-grid or grid connected systems. Therefore, in line with the current initiatives, this study developed the methodology for a reliable and efficient ENHS that can provide reliable and uninterrupted power supply to a rural community. This research presents a new and applicable solution to assist rural communities by providing affordable renewable energy, cooking gas, high quality fertilizer, job opportunities, and environmental safety, and hence enhance the overall scope for the sustainable development of rural life. This designed system can produce

577.3 kWh electricity per day, sufficient for 200 houses, which is greatly profitable for plant owners. This system not only provides energy at least cost but also ensures environmental safety as well as high quality fertilizer for agriculture and fishing. This system provides gas to rural people for cooking which in fact saves green territory. Therefore, to overcome energy crisis and improvise large rural communities of Bangladesh as well as other countries alike, this community based energy neutral home system can be a reliable and effective solution.

APPENDIX A: GEOMETRIC ASSUMPTIONS OF DIGESTER CALCULATIONS

See Table XII.

TABLE XII. Geometrical assumptions for digester design.[51]

For volume	For geometrical dimensions
$V_c \leq 5\%$V	$D = 1.3078 \times V^{1/3}$
$V_s \leq 15\%$V	$V_1 = 0.0827D^3$
$V_{gs} + V_f = 80\%$V	$V_2 = 0.05011D^3$
$V_{gs} = V_H$	$V_3 = 0.3142D^3$
$V_{gs} = 0.5(V_{gs} + V_f + V_s)K$, where K = gas production rate per cubic meter volume per day. For Bangladesh $K = 0.4\ \text{m}^3/\text{day}$	$R_1 = 0.725D$
	$R_2 = 1.0625D$
	$f_1 = D/5$
	$f_2 = D/8$

APPENDIX B: BOYLE'S LAW

- The normal pressure of the digester = P_i.
- The final pressure of the digester = P_f.
- According to Boyle's law, for pressure calculation of hydraulic chamber,

$$P_i \times (\text{total gas produced} + 4.09) = P_f \times 4.09. \qquad \text{(B1)}$$

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