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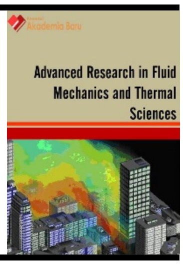

Economics of biogas plants and solar home systems: For household energy applications

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ABSTRACT

Electricity and clean cooking fuels are the two basic ingredients that are indispensable to alleviate energy poverty and bring about human development, but still today, globally, more than one billion people do not have access to these two forms of energy. The major reasons for the lack of these two energy services are economic constraints. Biogas plants and solar home systems (SHS) are two technically feasible renewable energy technologies to deliver cooking and electricity loads in rural areas. The negative economic perception (i.e. high cost) of these two renewable energy technologies is primarily responsible for making their diffusion slow in developing countries. This work presents a model to examine the economic performance (i.e. benefit to cost ratios) of these new energy technologies against three household load categories. Applying this model, this study shows that biogas plants used together with SHS show attractive economic performance e.g. a benefit cost ratio (BCR) of 6.6 for load Category 1(basic load). It is evidenced from this work that biogas plants together with SHS are economically promising in rural areas in developing country situations particularly in Bangladesh.

Keywords:
Biogas plant, SHS, Clean cooking, Economic benefit, Household

1. Introduction

Globally, about 1.2 billion people still remain without access to electricity and 1.7 billion people use conventional solid-biomass as their cooking fuels [1]. In Bangladesh, a developing country, a huge proportion of the population lacks access to electricity and uses solid biomass for their cooking fuels in rural areas. Electricity and clean-cooking fuels are the two basic requirements to enhance human development and to alleviate energy poverty [2–4]. Electricity and clean-cooking fuels bring huge benefits to users through the provision of brighter lighting, hazard-free cooking, space-cooling, entertainment, and communication [5]. Rural households in Bangladesh usually use conventional cooking-stoves fuelled by solid-biomass, which are very inefficient and suffer from heavy smoke and particulate emission [6]. Households usually use kerosene lanterns or paraffin candles for lighting. The inefficient use of solid biomass and kerosene has implications for the environment, health and

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energy security [7]. Although rural households experience lower affordability, studies show that they still have willingness to spend money on their energy needs [8,9]. Households spend money on buying solid biomass, kerosene and other fuels for use in conventional technologies such as mud-stoves and lanterns [10]. Biogas plants and solar home systems (SHS) are the two renewable energy technologies that, can serve both electricity and cooking needs [11,12]. These alternative technologies offer technically feasible energy alternative in rural areas. The primary inputs for these technologies, i.e. biomass and solar irradiation, are available and almost evenly distributed in rural areas. However, success of these technologies does not merely depend on economic performance; rather, it depends on the three sustainability dimensions, namely social, economic and environment. Several studies examined the techno-economic performances of biogas and solar resources for small-scale electricity generation [13-16]. Studies also showed that biogas plants and solar electricity are environmentally sound and bring net benefits to society [17-22]. Katuwal and Bohara [23] found that biogas plants have been proved to be a clean and environmentally friendly source of energy in rural areas and provide huge benefits to society. Asif and Barua [24] found that SHS present numerous benefits to society and has been recognised as an environmentally friendly technology. Although biogas plants and SHS have emerged as technically feasible and promising technologies, their dissemination rate is slow, primarily due to the negative economic perception among the prospective users that renewable technologies are more expensive than conventional ones [25,26]. To overcome this conceptual barrier, this study presents a model to examine the economic performance of biogas plants and SHS over conventional energy services. This study focuses on economic performance of biogas plants and SHS in terms of benefits and costs. Since biogas plants and SHS individually are not practically viable to serve both cooking and electricity needs, these two technologies are considered to serve the household requirements together.

The remainder of this paper is organized as follows: Section 2 briefly describes the two proposed technologies i.e. biogas plants and SHS. Section 3 presents detailed technique for determining the economic performance of these technologies. Section 4 presents the applied datasets, which will be applied to demonstrate the proposed technique. Section 5 presents main results of this analysis according to the proposed technique and applied datasets. Finally section 6 highlights the main conclusions of this work.

2. Overview of Biogas Plants and Solar Home Systems (SHS)

2.1 Biogas Plants

Biogas plant is an anaerobic digester that produces biogas from agricultural or other kind of bio-wastes [11,23]. Biogas is a type of bio-fuel that is produced via anaerobic digestion of organic bio-wastes through decomposition by bacteria. Biogas plant consists of an airtight underground digester tank, a gas holder, mixing devices, and gas regulator valves (Figure 1). Digesters under this study are continuous type as they receive dumped wastes in a regular interval (i.e. every day). The gas holder harnesses the gases from the digested slurry and delivers to the pipes [25–28]. The effluents are removed from the outlet tank in a regular interval and are used as fertilizer. The resulted biogas is methane-rich gas consists of 50–75% methane, 25–50% carbon monoxide, and 0–10% nitrogen and hydrogen. The installed capacity of biogas plant is determined by the amount of biogas a plant produces (in m3) within 24 hours. In average, 25 kg of fresh cattle dung produce 1 m3 of biogas through digestion in biogas plants [29]. Biogas burns with blue flames without or with very little smokes which results in almost CO2 neutral combustion [30].

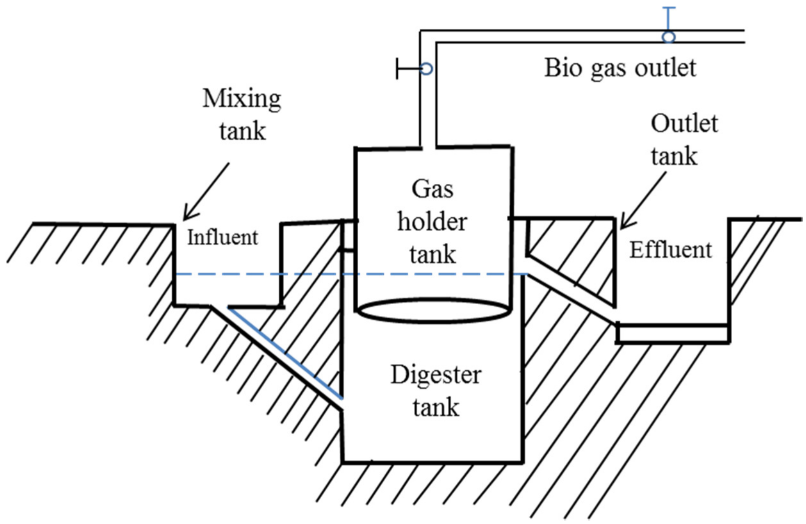

Fig. 1. Simple schematic of a biogas plant

2.2 Solar Home System (SHS)

A typical SHS is an assembly of standalone photovoltaic system that supply power for lighting and electric appliances in households. SHS consists of an array of photovoltaic (PV) modules, rechargeable batteries, charge controller, inverter, and few wires and sockets (Figure 2). It is a fixed installation in the household, where the PV array is placed in an open place on the rooftop or with a mast to be exposed to the best possible sunlight [11]. The charge controller, battery bank, and other devices are placed inside the room of a household [31–33]. The capacity of a SHS is defined by the maximum watt (W) it can generate in standard irradiation and weather conditions [34]. The daily energy generation (kWh/d) of a SHS is estimated with panel generation factor (PGF). The PGF is the amount of energy generation of a solar panel per watt peak per day in any particular region (i.e. *total energy generation per day = PGF · Wp*). The PGF values vary with the geographic locations. Bangladesh is having average PGF of 3.43 Wh/W-d, which means this country endowed with good solar irradiation [35].

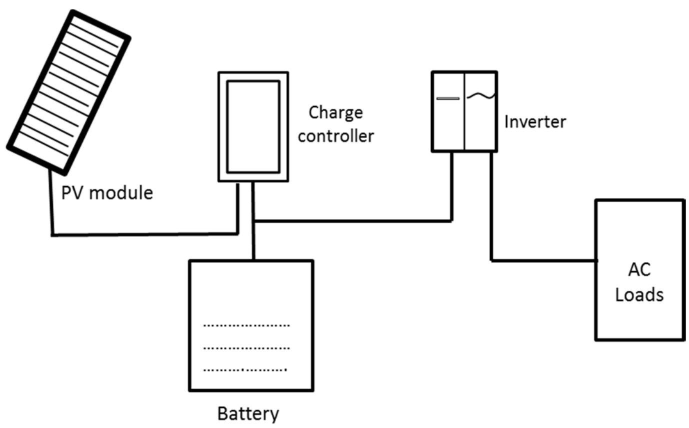

Fig. 2. Simple schematic of a typical SHS

3. Methodology
3.1 Energy Sources in Use in Rural Households

The main purposes of energy use in rural households are cooking and lighting. The other basic energy applications beyond them include heating and cooling, home-appliances and telecom devices. Rural households can be categorized into three groups, i.e. Category 1, Category 2 and Category 3, based on energy applications [9,10,36,37]. Because of geographic and climatic conditions, space and water heating needs in rural households in Bangladesh are very small [38]. Households use a variety of energy sources for cooking such as forest-wood, agricultural residues, and kerosene (Figure 3). The uses of other fuels such as plant oils, biomass briquettes, charcoals, liquefied petroleum gas (LPG), liquefied natural gas (LNG), and electricity are negligible. The lighting services are provided mostly by purchased sources such as kerosene and paraffin candle. The other energy applications such as home-appliances for leisure and cell-phone battery charging are served with either car-battery or dry-cell battery. Three-stone mud burners are usually used for cooking by biomass fuels; gas and kerosene stoves are used for cooking by kerosene and CNG. Lighting services in the rural households are provided by paraffin candles, hurricane lantern or wick lamps. The common home-appliances for leisure/entertainment and communication are radio, cassette player, TV, and mobile phone.

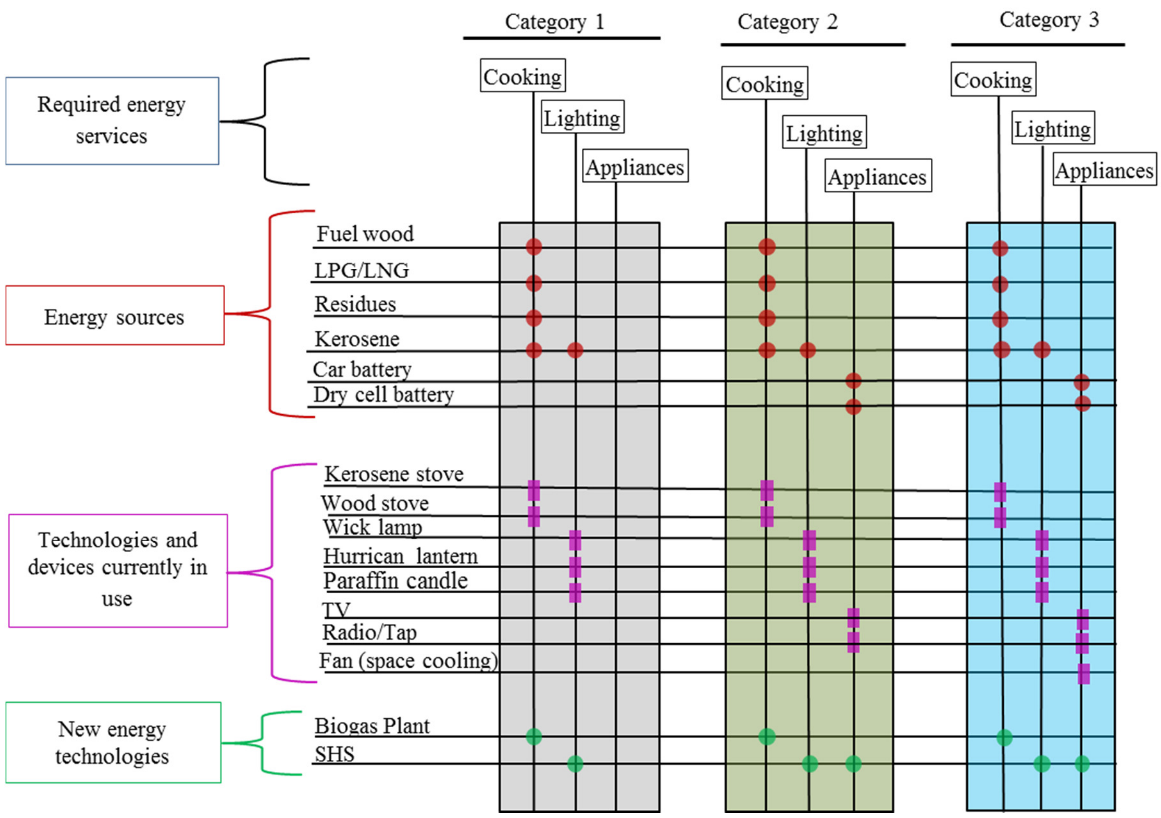

Fig. 3. Energy application pattern in rural households

3.2 Household-level Loads

To formulate the monetary benefits from the two technologies, we require to model household-level loads. The cooking (heat), lighting and appliances energy demands for the three household-load categories are presented in Table 1 and 2. The households use biogas-stove for serving their cooking loads and CFL (compact florescent lighting) bulb for serving lighting loads. This study considers that biogas-stove produces thermal output for cooking with 60% conversation efficiency. The gas burner operates 4–8 hours a day and produces 1.6 MJ/h of final thermal energy per burner [39,40]. The daily cooking demands for load category 1 (Category 1), load category 2 (Category 2) and load category 3 (Category 3) are 4, 8, and 8 burner-hour, respectively [36].

Table 1
Cooking (heat) energy demand per household per day

Device	Thermal output per burner (MJ/h)	Household load categories					
		Category 1		Category 2		Category 3	
		Burner-hour[b]	Daily final heat consumption (MJ/d)	Burner-hour	Daily final heat consumption (MJ/d)	Burner-hour	Daily final heat consumption (MJ/d)
Gas-stove	1.6	4	6.40	8	12.8	8	12.8

[b]Household uses 4 burner-hour means it operates 1 burner for 4 hours or 2 burners for 2 hours and so on.

Table 2
Electricity energy demand per household

Appliances	Power (W)	Operation time (h/d)	Household load categories		
			Category 1	Category 2	Category 3
			Number of appliances	Number of appliances	Number of appliances
CFL bulb	10	6	3	4	6
TV	40	4	0	1	1
Radio/Cassette player	10	4	0	1	1
Mobile charger	5	2	0	1	1
Others	10	2	0	1	1
Ceiling fan	75	6	0	0	2

3.3 Determination of Costs and Benefits for Alternative Technologies

This model first determines the costs for alternative technologies (i.e. biogas plant and SHS) against the size of the energy technologies to meet the loads. The model proposes a set of cost-functions to quantify the costs of the alternative technologies.

3.3.1 Costs of biogas plant
3.3.1.1 Capital cost of biogas plant

The capital cost of biogas plant includes all the costs for supplying, installation, fittings, and fixing of digester-well, gas-holder, and piping systems. For obtaining the capital cost for the biogas plant of various sizes, a generalized cost-function is required. Based on the work done by Rahman *et al.* [11] and Kandpal *et al*. [41], we have developed generalized linear Equation (1).

$$C_{cap,bg} = C_{0,bg}[\alpha + \beta(V_{bg} / V_{0,bg})] \tag{1}$$

where, $C_{cap,bg}$ (US$) is the capital cost of biogas plant of size V_{bg} (m^3), $C_{0,bg}$ (US$) is the capital cost of biogas plant of reference size, $V_{0,bg}$ (m^3) is the volume of biogas plant of reference size, α and β are the two curve-fitting coefficients.

The capital cost of biogas plant varies slightly over the service providers and plant locations. We have utilised the cost data which featured the average value for biogas plants in Bangladesh. The coefficients α and β have been reached by solving Equation (1) with Least Squares (LSQ) technique (minimising the sum of squared errors). The final equation for obtaining capital cost of biogas plant ($C_{cap,bg}$) is given below. The equation is applicable for biogas plant sizes between 1.6 and 12 m^3.

$$C_{cap,bg} = 77.6 + 40.2V_{bg} \tag{2}$$

where, V_{bg} (m_3) is the size of biogas plant.

3.3.1.2 Operation and maintenance (O&M) cost of biogas plant

The operation and maintenance costs of biogas plant consist of two cost components: cost of fresh-dung and other bio-feedstock, and operation and repair costs for digester system. The cost of fresh-dung is the direct function of daily gas requirements. The operation and repair costs, in contrast, depend on many factors such as the operational skill of the operator, location of the plant, quality of the materials etc. The operational activities involve draining out of condensed water in the pipeline, oiling of gas valves and gas taps, cleaning of stoves and lamps, cleaning of overflow outlet, checking of gas leakage through all joints and valves etc. It is impractical to develop a generalised cost function equation for operation and repair cost of the biogas plant, due to heterogeneity of the cost elements. However, experience reveals that the annual operation and repair costs can be represented by a fraction of the total capital cost [41]. We proposes the following Equation (3) for calculating the annual operation and maintenance costs, $C_{O\&M,bg}$ (US$/y) of biogas plant.

$$C_{a,O\&M,bg} = 365V_{bg} f_{CUF} d_u P_d + mC_{cap,bg} \tag{3}$$

where V_{bg} (m^3) is the size of biogas plant, f_{CUF} is the capacity utilization factor of digester, d_u (kg/m^3) is the fresh dung required to produce 1 m^3 of biogas, P_d (US$/kg) is the price of raw dung, m is the fraction of capital cost to be required as annual operation and repair costs of the biogas plant.

3.3.1.3 Size of the biogas plant

The installed capacity of the biogas plant (V_{bg}) (see section 2.1) for serving the household's cooking loads can be calculated by Equation (4) as below

$$V_{bg} = \left(\frac{L_{bg}}{Q_b \eta_{bg}}\right) / f_{CUF} \tag{4}$$

where L_{bg} (MJ) is the cooking load served by biogas, Q_b (MJ/m3) is the calorific value of biogas, η_{bg} (%) is the thermal efficiency of biogas for cooking, and f_{CUF} is as defined in Equation (3).

3.3.2 Costs of SHS
3.3.2.1 Capital cost for SHS

We also propose a linear cost-equation for capital cost of SHS as the following form

$$C_{cap,SHS} = C_{0,SHS}[\gamma + \delta(S_{SHS} / S_{0,SHS}) \tag{5}$$

where, $C_{cap,SHS}$ (US$) is the capital cost of *SHS* of size S_{SHS} (W), $C_{0,SHS}$ (US$) is the capital cost of *SHS* of reference size, $S_{0,SHS}$ (W) is the reference size of *SHS*, γ and δ are curve fitting coefficients.

The final equation [Equation (6)] are reached by applying costs data obtained from Bangladesh and solving with the Least Squares (LSQ) method [42].

$$C_{cap,SHS} = 60.6 + 6.14S_{SHS} : [20W \leq S_{SHS} \leq 500W] \tag{6}$$

where the parameters are as defined in Equation (5) above.

The size of SHS (W) for serving lighting and other electrical appliance loads can be calculated by Equation (7).

$$S_{SHS} = \frac{(L_{SHS,L} + L_{SHS,ap}) \times 1000}{(\phi_{df} f_{PGF} f_{DV}) \times 3.6} \tag{7}$$

where, $L_{SHS,L}$ (MJ/d) is lighting load served by the *SHS*, and $L_{SHS,ap}$ (MJ/d) is the appliance loads served by the *SHS*, f_{PGF} (Wh/W-d) is panel generation factor, ϕdf is derating factor (sometimes refer to as efficiency factor) for solar module, f_{DV} is diversity factor of the electrical loads.

3.3.2.2 Operation and maintenance (O&M) cost of SHS

The maintenance of SHS includes battery replacement and occasional cleaning of PV surfaces from dust and dirt during their lifetime of over 20 years [43,44]. The cleaning of PV surfaces incurs very little or no costs. SHS batteries are required to replace several times within the lifetime of SHS. The SHS package includes PV module, battery and other accessories and, therefore, for obtaining the capital cost of the system, the costs for battery and other accessories are not required separately. For obtaining the battery replacement costs, it is necessary to know the capital cost of the battery unit. Batteries with various lifetimes and types are available in the markets. Hence it will be appropriate to obtain the battery cost in terms of energy to be served by the battery in its whole lifetime instead of capacity. Capital cost of battery $C_{cap,bat}$ (US$) can be obtained in terms of energy to be served within its lifetime as Equation (8) and (9):

$$C_{cap,bat} = S_{bat} f_{bat} P_{bat} \tag{8}$$

$$S_{bat} = \frac{D(L_{SHS,L} + L_{SHS,ap})}{3.6 \times \eta_{bat} \eta_{dod}} \tag{9}$$

where, S_{bat} (kWh) is the size (or capacity) of the battery, f_{bat} is the number of charge cycles of the battery to an acceptable depth of discharge η_{dod}, P_{bat} (US$/kWh) is the unit price of energy generated by the battery in its lifetime, D (d) is the day of autonomy for the battery, η_{bat} is the efficiency of the battery, and $L_{SHS,L}$ and $L_{SHS,ap}$ are as defined in Equation (7). The present value of annual maintenance cost due to replacement of battery can be obtained as Equations (10-15) below [45]:

$$C_{a,rep,bat} = C_{cap,bat} f_{rep} SFF_{bat} \tag{10}$$

$$f_{rep} = CRF_{proj} / CRF_{rep} \tag{11}$$

$$SFF_{bat} = \frac{r}{(1+r)^{t_{bat}} - 1} \tag{12}$$

$$t_{rep} = t_{bat} \cdot INT\left[\frac{t_{proj}}{t_{bat}}\right] \tag{13}$$

$$CRF_{proj} = \frac{r(1+r)^{t_{ptoj}}}{(1+r)^{t_{proj}} - 1} \tag{14}$$

$$CRF_{rep} = \frac{r(1+r)^{t_{bat}}}{(1+r)^{t_{bat}} - 1} \tag{15}$$

Here, $C_{a,rep,bat}$ (US$/y) is the annualized battery replacement cost, f_{rep} is battery replacement factor, SFF_{bat} is sinking fund factor for lifetime of battery t_{bat} (y), CRF_{proj} and CRF_{rep} are the capital recovery factor for lifetime of the project t_{proj} (y) and duration of replacement t_{rep} (y) respectively, and r (%) is real interest rate.

3.3.3 Total annualised cost

The total annualised cost (US$/y) of biogas plants and *SHS* can be calculated as the sum of annualised capital costs, and annual operation and maintenance costs of biogas plant and *SHS* as Equation (16) below

$$C_{a,tot} = (C_{cap,bg} + C_{cap,SHS})CRF_{proj} + C_{a,O\&M,bg} + C_{a,rep,bat} \tag{16}$$

3.3.4 Benefits for using biogas plants and SHS

The monetary benefits (savings) for using biogas plants and *SHS* can be determined using equations developed based on the methodology of [11,41,46][41] as Equation (17).

$$B_{a,tot} = \left[\sum_{n=1}^{N} \frac{x_n L_{bg,c}}{Q_n \eta_{n,c}} p_n + \frac{L_{SHS,L}}{Q_k \eta_{kL}} p_k + \frac{L_{SHS,ap}}{\eta_{bat} \eta_{dod} \times 3.6} p_{bat}\right] \times 365 \tag{17}$$

where $B_{a,tot}$ (US$/y) is the annual monetary benefits for using biogas plant and *SHS*, x_n is the fraction of cooking energy currently met by biomass type n (e.g. fuel-wood, crop-residues or briquette etc.), n denotes the biomass type used for cooking, Q_n (MJ/kg) is the calorific value of biomass type n, $\eta_{n,c}$ is the efficiency of combustion of biomass type n for cooking, P_n (US$/kg) is the price of biomass type

n, Q_k (MJ/kg) is the thermal value of kerosene, η_{kL} is the efficiency of kerosene for lighting, P_k (US$/kg) is the price of kerosene.

3.3.5. Benefit-cost ratio (BCR)

The benefit-cost ratio is the ratio of the annual total benefit to annualized total cost. The BCR can be calculated by using Equation (18) as below

$$BCR = \frac{B_{a,tot}}{C_{a,tot}} \tag{18}$$

4. Demonstration of the Model

The economics of biogas plant and SHS are exemplified by demonstrating the proposed method for rural households in Bangladesh. The applied data are presented in the following section.

4.1 Applied data

The values of various parameters used for calculation of costs and benefits from biogas plant and SHS are presented in Tables 3 and 4. The calorific value of fuel-wood varies with moisture content and fuel-wood types, we have taken average value of 16 MJ/kg for 15% moisture content. The other parameters for biogas plant are taken from a comprehensive World Bank report– namely Bangladesh's Rural energy reality [10]. The economic parameters for SHS are also taken from published literatures [43,47–50].

Table 3
Parameters for economic analysis of biogas plant

Parameters	Values
Calorific value of biogas	23 MJ/m^3
Calorific value of fuel-wood	16 MJ/kg
Calorific value of kerosene	43 MJ/kg
Efficiency of biogas cook-stove	60%
Efficiency of kerosene lighting	6%
Capacity utilization factor of digester	80%
Availability of nitrogen in fresh dung	2%
Retention factor of Nitrogen	60%
Price of kerosene	1.0 US$/kg
Efficiency of fuel-wood for cooking	15%
Price of fuel-wood	0.02 US$/kg
Price of urea	0.25 US$/kg
Price of dung	0.001 US$/kg
Lifetime of the project	20 years
Real Interest rate	5%

Table 4
Parameters for economic analysis of SHS

Parameters	Values
Derating factor (sometimes refer as to efficiency factor)	64%
Panel generation factor of PV	3.43
Diversity factor of the electrical loads	1.2
Efficiency of battery	85%
Depth of discharge of battery	60%
Price of battery in terms of per unit energy generation in lifetime of the battery	0.06 US$/kWh
Lifetime of the SHS	20 years
Replacement period of battery	5 years
Charge-cycles of battery	2000 number
Days of autonomy	1 day

5. Results

5.1 Benefit to Cost Ratios

We have calculated the benefit (saving) and costs in monetary terms for adopting biogas plant and SHS technologies for the three household load categories. The annual benefits (savings) for load Category 1, Category 2 and Category 3 are 180, 281, and 415 US$/y respectively when adopting the new energy technologies. The benefit to cost ratios (BCR) are 6.6, 2.95, and 1.32 respectively. This means that Category 1 and Category 2 can gain 6 and 3 times greater monetary benefits by adopting the new energy technologies, respectively, while Category 3 can reach the break-even point.

5.2 Influence of Conventional Fuel Prices on Benefit to Cost Ratio (BCR)

The monetary benefit (saving) depends on the price of feedstock materials, which varies significantly depending on household location and season. The benefit to cost ratio (BCR) decreases exponentially with increases of the cattle dung price. Nevertheless, even with higher dung costs, for example 0.006 US$/kg, the BCR still remains more than 1.0 for household load Categories 1 and 2 (Figure 4). The break-even dung price for household load Category 3 is 0.005 US$/kg. The annualised total cost increases linearly with the increases in the dung price (Figure 4). For example, the annual total cost would be 95 US$/y for a dung price of 0.001 US$/kg whereas it would be 231 US$/y for a dung price of 0.009 US$/kg for load Category 2.

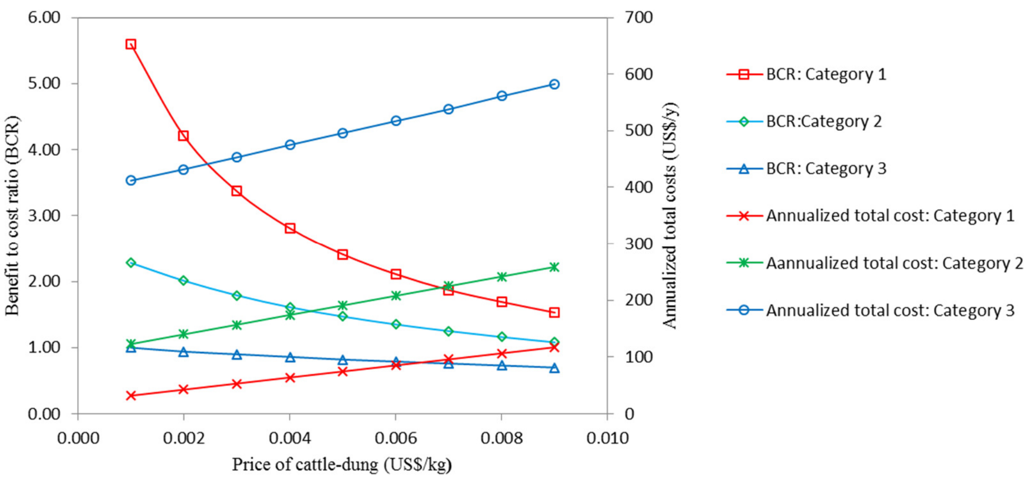

Fig. 4. Benefit to cost ratio (BCR) and annualized total costs for various cattle-dung prices

The variation in fuel-wood and battery costs also affect BCR. The BCR increases linearly with increases of fuel-wood prices and decreases with the increases of battery prices (Figure 5). For example, the BCR is 2.74 for a fuel-wood price of 0.01 US$/kg and 4.38 for a fuel-wood price of 0.09 US$/kg for load Category 2. The BCR does not change significantly with the changing of battery price, for example, BCR is 2.91 and 2.66 for battery prices of 0.01 US$/kWh and 0.09 US$/kWh respectively for load Category 2 (Figure 5). The battery prices also have a significant effect on annualized total cost. The total costs increase linearly with the increase of battery prices.

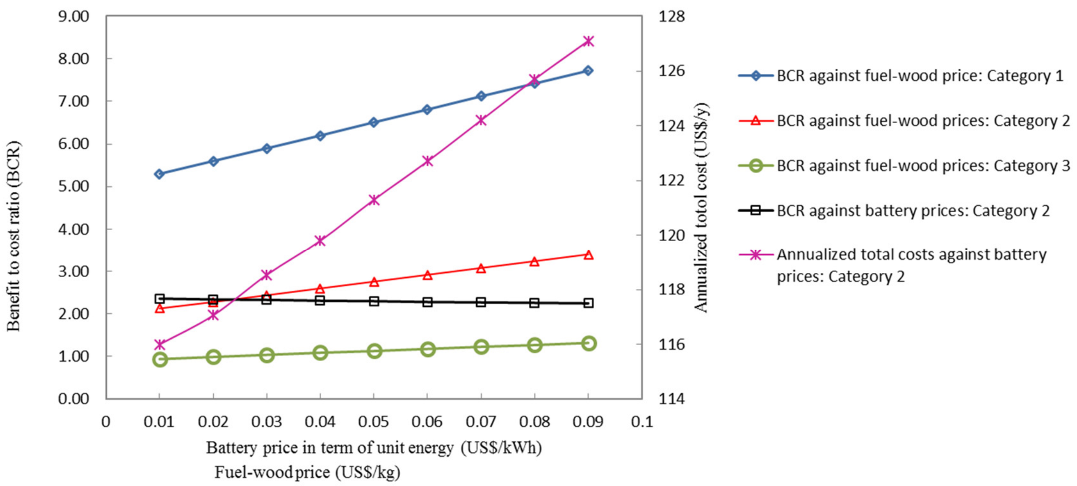

Fig. 5. Benefit to cost ratio (BCR) and annualized total costs against various fuel-wood and battery prices

6. Conclusions

Biogas plants and solar home systems (*SHS*) are two renewable energy technologies that can deliver both electricity and clean-cooking fuels in rural areas. Despite the resources being abundant in rural areas, their technology diffusion is slow due to lack of awareness about the relative economic benefits with compare to conventional technologies. This study describes a method for examining the economic performance of these two technologies comparing them with conventional energy services. By applying the presented method, we found that all the three household load categories gained attractive annual savings (e.g. 180, 281 and 408 US$) for household load Categories 1, 2 and 3 respectively for these technologies. The benefit to cost ratio (*BCR*) also shows that the benefits are much higher than the costs of adopting the new technologies. Although the *BCR* depends on the replaced fuel and feedstock prices, a wide selection of prices gives *BCR* more than unity. Despite these above findings, the high initial costs of these two technologies will still remain as a barrier for their rapid adaptation until a suitable and efficient financing skim is available to the rural users. The presented study will help us to understand the economic performance of these two technologies and provide evidence for a fair comparison with conventional energy services, and will encourage households to employ these two clean technologies for their household needs.

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