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# Economic viability of biogas energy production from family-sized digesters in Uganda



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## ARTICLE INFO

### Article history:

Received 11 March 2013

Received in revised form

3 March 2014

Accepted 6 March 2014

Available online 12 April 2014

### Keywords:

Biogas energy

Economic viability

Family-sized

Fixed-dome digesters

Uganda

## ABSTRACT

Biogas is among the renewable energies being evaluated to augment traditional energy in Uganda. Its development remains low, partly because of lack of information on its economic viability. Based on primary data from Central and Eastern Uganda, this study assesses economic viability of biogas energy production in Uganda. The empirical results show that biogas energy production is economically viable with a payback period of 1.17, 1.08 and 1.01 years for 8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup> biogas plants, respectively. The positive net present values of 4500\$, 7000\$ and 9500\$ for 8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup> plants, respectively, show that biogas systems are economically viable. The most profitable levels were determined through sensitivity and break-even analysis. The cost structure of the biogas systems offers useful guidelines to households about which levels they should operate in order to remain economically viable. The annual interest rates at which households should borrow to invest in biogas systems and remain economically viable should not exceed 36%, 37% and 39% for 8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup> plants. The study reveals that the viability of biogas is greatly affected by variation in discount rates, capital and operating and maintenance costs.

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## 1. Introduction

Efforts to evaluate alternative energy sources to complement traditional sources and mitigate the current energy crisis in Uganda have been stepped up. There is a growing interest in evaluating renewable energy sources for this purpose. Among the renewable energies, biomass has shown high potential for energy production in developing countries [1]. Biogas is attracting more attention from both public and private

initiatives in Uganda because of its advantages over other energy sources [2]. Despite these advantages and the existence of favourable conditions for its production, the development of biogas technology in Uganda has been poor [3]. This could partly be because of the lack of information regarding the economic viability of biogas energy production which has resulted in the potential of this environmentally friendly technology not being fully exploited.

Literature on factors influencing the adoption and development of biogas energy has burgeoned with, among others,

Abbreviations: FGD, Focus group discussion; NGO, Non-governmental organisation; PBP, Payback period; PRA, Participatory Rural Appraisal; UPBP, Undiscounted payback period.

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<http://dx.doi.org/10.1016/j.biombioe.2014.03.008>

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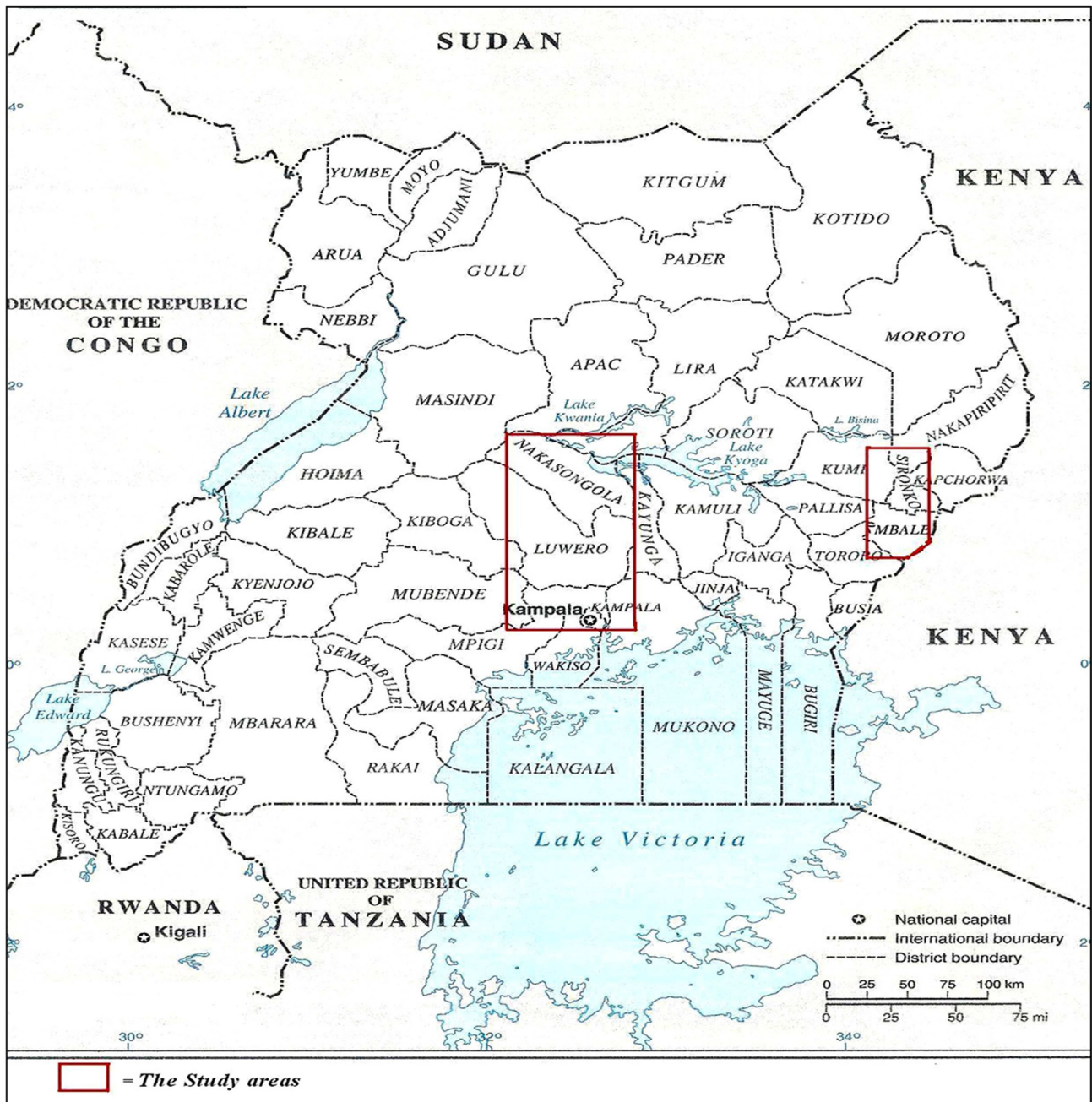


Fig. 1 – Map of Uganda showing the study areas.

economic, social, technical and organisational factors highlighted as critical [2,4,5]. While the technical potential of certain fuels may be high, there is a need to further establish the economic feasibility of the fuels because this will show whether the consumers can actually afford them. While a number of studies have shown that economic factors significantly influence the adoption and development of biogas energy, few have extended their analyses to investigate economic viability of biogas energy. Abort and Vancil [6] attribute this to lack of knowledge about three key issues: (1) the exact percentage of the waste refuse used in the recovery systems that is of potential use; (2) the percentage that can be recovered; and (3) the market value after the recovery process.

The need to quantify the benefits and costs of biogas energy systems is thus crucial. Srinivasan [7] observes that domestic biogas programs are often justified on the basis of the private benefits and costs accruing to individual households. However, he adds that the economic surpluses from domestic biogas programs are realized beyond such narrowly defined project boundaries. This implies that the total benefits accruing from the installation of biogas plants exceed the benefits to the individual who invests in it, receives it or runs the service. Society is perhaps, likely to benefit more than the individual recipient does. The importance of establishing the economic feasibility of biogas systems therefore cannot be underscored.

These studies generally affirm that economic appraisal of the technology is required to quantify the significant benefits and costs accruing to biogas energy production and utilization in order to promote the uptake of biogas technology. Inadequate information about the economic viability of biogas energy production systems could be a hindrance to potential investment in this sector, perhaps accounting for its low performance in Uganda. This paper thus envisages that to stimulate public and private interest and attract large-scale capital investment in biogas technology, there is a need to provide information on the economic viability of biogas technology in Uganda to guide potential investors in the industry.

A fundamental question that has remained unanswered which this study attempts to address is: How economically feasible is biogas energy production from family-sized digesters in Uganda? Put differently: “Does biogas energy production from family-sized digesters have lower costs relative to the associated benefits?” More specifically the paper aims to assess the economic viability of biogas energy production from fixed-dome biogas family-sized digesters, hereafter also referred to as family-sized biogas plants, attempting to take into account the costs and benefits accruing to the overall biogas energy production chain.

## 2. Materials and methods

### 2.1. Description of the study area

The study sites were the districts of Luwero, Nakaseke and Nakasongola in Central Uganda, and Mbale, Sironko and Manafwa in Eastern Uganda.<sup>1</sup> These districts are relatively densely populated with approximately 133 persons per square kilometre [8]. Subsistence agriculture remains the dominant economic activity on heavily fragmented land holdings. Fuel wood is the most important energy source for cooking and kerosene for lighting purposes. Charcoal burning is also an important economic activity, particularly in Nakasongola District. Given the high population density in the study sites coupled with high dependence on fuel wood as the major energy source, deforestation and other forms of environmental degradation are an eminent threat. With the limited landholdings, intensive agricultural production systems (especially confined animal feeding operations) and ecology friendly energy sources like biogas are being proposed and promoted as most suitable.

These districts were purposively selected for the study because they have been specifically targeted by NGOs promoting biogas technology in Uganda. They have also been identified and documented as districts with high concentrations of households with operational digesters and confined animal feeding operations in Uganda [2]. In Uganda, cow dung was the major feedstock for biodigesters at the time of the study and is likely to remain so in the foreseeable future. It

was therefore considered that the potential of adopting biogas technology in these areas with adequate supplies of raw materials would be greater than in other parts of the country; that is, the districts were representative of the regions with the highest potential of adopting biogas technology in Uganda (Fig. 1).

### 2.2. Data collection and analysis

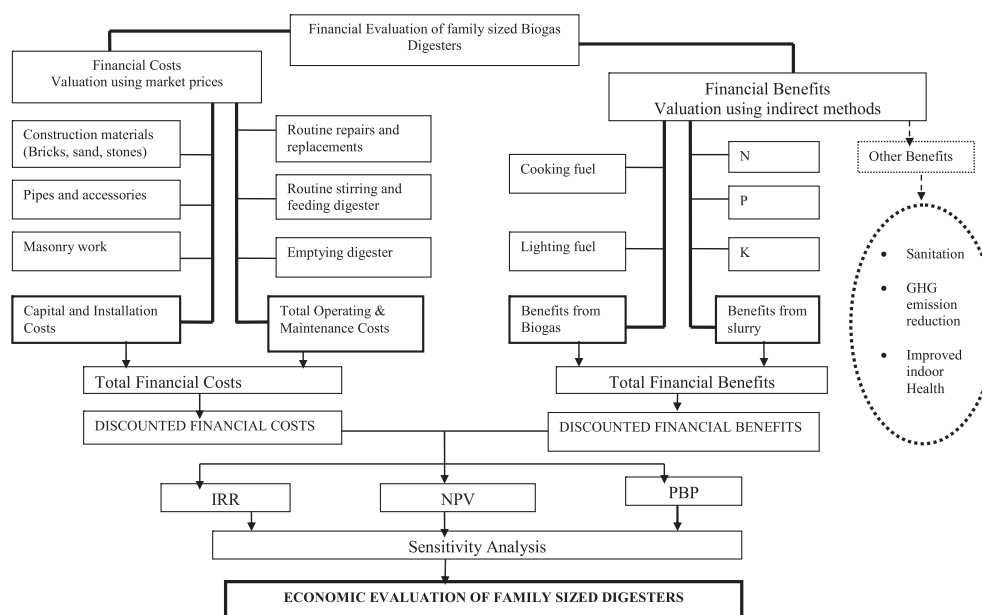
Fieldwork was conducted from November 2007 to April 2008 mainly through open-ended interviews with households categorised as biogas producers and users, hereafter referred to as households. Supplementary data on biogas plants installation and operational costs were collected between January and February 2009. The interviews were combined with simple Participatory Rural Appraisal (PRA) tools because these have been well known to facilitate quick acquisition of information [9].

Prior to the survey, a reconnaissance visit to the study sites was conducted and focus group discussions (FGDs) held with households and key informants to develop the interview guide for the survey and to ascertain the sampling frames obtained from NGOs. The visit was also useful for identification of the common biogas plant designs and other important socio-economic data required for the study. The three most common types of family-sized biogas plants identified in Uganda are well explained in Ref. [2]. A sampling frame of 150 households with operational plants was obtained from NGOs involved in promoting biogas technology in Uganda from which 120 households were randomly selected and interviewed. After thorough data cleaning, a final sample of 100 households formed the basis of our analysis.

The data collected included socio-economic and demographic characteristics of households (age and educational status of household head, experience of household in biogas production and use and household size) and detailed financial biogas plants installation and operational costs and benefits. Standard analyses of economic viability of biogas energy production systems tend to emphasize primarily the direct financial costs and benefits associated with biogas production [10]. However, when considering the feasibility of biogas plants, non-economic factors must also be considered [11].

In this analysis, a comprehensive estimation of costs of the three most common biogas plant capacity designs (8, 12 and 16 m<sup>3</sup>) was undertaken. This was followed by the economic valuation of benefits of biogas energy from the digesters. An overall economic evaluation of the viability of biogas energy production model was then undertaken by use of economic decision criteria commonly used to evaluate the viability of alternative investment opportunities. These include net present value, internal rate of return and payback period [10]. This is important because the use of biogas-based systems often leads to both tangible and intangible benefits [4]. While all the likely tangible benefits are normally taken into account in the financial evaluation exercises, the intangible benefits (such as additional benefits in terms of incremental fertilizer saving) are invariably not considered in the analysis [12], rendering such evaluations questionable. All the three decision criteria were used because they consider different (but complementary) attributes of economic viability. Consistent

<sup>1</sup> Luwero (0°57'36.11"N 32°15'55.40"E), Nakaseke (1°31'30.32"N 32°04'33.88"E), Nakasongola (1°19'31.48"N 32°27'17.65"E), Mbale (1°4'50.56"N 34°10'02.75"E), Sironko (1°13'48.96"N 34°14'46.78"E) and Manafwa (0°54'40.30"N 34°22'22.65"E).



**Fig. 2 – Framework for evaluation of economic viability of biogas from family-sized plants in Uganda.**

results from the three decision criteria can help improve robustness of the analysis, as well as increase confidence in the viability of the investment opportunity. Other studies that used these criteria to assess the financial feasibility of on-farm biogas energy include [2,10,13–16]. Sensitivity analysis through varying parameter values for costs and revenues of the three biogas plant capacity designs ( $8 \text{ m}^3$ ,  $12 \text{ m}^3$  and  $16 \text{ m}^3$ ) was undertaken. Finally break-even analysis points for the three capacity designs were determined to establish the economic feasibility levels within which the biogas systems were to operate to remain profitable.

### 2.3. Framework for analysis of economic viability of biogas energy from family-sized biogas plants

In evaluating the economic viability of biogas plants in Uganda, the framework developed by Kandpal et al. [17] was adopted with some modifications. This framework is presented in Fig. 2, while the socio-economic parameters, technical parameters and key descriptive statistics used are shown in Tables 1–3, respectively.

#### 2.3.1. Costs of the family-sized biogas plants in Uganda

Detailed data on inputs of the most adopted fixed-dome biogas plant design in Uganda were obtained and used to arrive at the various costs involved. The costs of establishing and running a biogas digester are dependent on the specific type and size of the digester [11]. These include capital and installation costs and operating and maintenance costs.

**2.3.1.1. Capital and installation costs of family-sized biogas plants.** Capital costs included the cost of civil construction of the digester plant (bricks, sand, cement, steel and iron bars, pipes, stone chips, labour for masonry work) and installation.

**Table 1 – Socio-economic parameters used in the economic viability analysis of family-sized biogas plants in Uganda.**

Parameter	Symbol	Unit	Value
Discount rate	$i$	Percent	12.0
Market price of bricks	–	\$/brick	0.06
Market price of sand (lake)	–	\$/ton	10
Market price of sand (plaster)	–	\$/ton	8
Market price of stone chips	–	\$/ton	32
Market price of stones (hard core)	–	\$/ton	32
Market price of ordinary cement	–	\$/kg	0.18
Market price of water-proof cement	–	\$/kg	1.2
Market price of lime	–	\$/kg	0.12
Market price of PVC pipes (4")	–	\$/m	1.6
Market price of chicken mesh	–	\$/m <sup>2</sup>	2.0
Market price of weld mesh	–	\$/m	1.2
Market price of timber (2" × 4")	–	\$/m	0.6
Market price of nails	–	\$/kg	2.0
Market price of galvanised pipes (3/4" and 1/2")	–	\$/m	1.8
Market price of gas valves	–	\$/piece	4.0
Market price of filter	–	\$/piece	1.2
Market price of biogas stove	–	\$/piece	3.6
Market price of biogas lamp	–	\$/piece	4.4
Market price of urea	$p_u$	\$/kg	0.48
Market price of single super phosphate	$p_p$	\$/kg	0.4
Market price of muriate of potash	$p_m$	\$/kg	0.4
Market price of fresh cowdung	$P_{w_{du}}$	\$/kg	0.02
Market price of kerosene	$P_k$	\$/litre	0.79
Market price of fuelwood	$P_f$	\$/kg	0.02
Market price of unskilled labour in rural areas	$WR_{ul}$	\$/man-day	0.08
Market price of skilled masonry labour	$WR_{sl}$	\$/man-day	4.0

**Table 2 – Technical parameters used in the analysis of economic viability of family-sized biogas plants in Uganda.**

Parameter	Symbol	Unit	Value
Total annual benefits from biogas plant	TAB <sub>g</sub>		
Total annual benefits for use of biogas for cooking	TB <sub>c</sub>		
Total annual benefits for use of biogas for lighting	TB <sub>l</sub>		
Total capital and installation costs	TC <sub>c</sub>		
Total annual cost of biogas plant	TAC <sub>b</sub>		
Total annual operating and maintenance costs	AOT <sub>c</sub>		
Amount of wet cowdung required to produce 1m <sup>3</sup> biogas	wd <sub>u</sub>	kg	25
Calorific value of fuelwood	Q <sub>f</sub>	MJ kg <sup>-1</sup>	19.7
Calorific value of kerosene	Q <sub>k</sub>	MJ dm <sup>-3</sup>	38.2
Calorific value of biogas	Q <sub>c</sub>	MJ m <sup>-3</sup>	19.7
Cooking efficiency of utilization of fuelwood stove	n <sub>ef</sub>	fraction	0.12
Cooking efficiency of utilization of biogas stove	n <sub>eb</sub>	fraction	0.6
Lighting efficiency of biogas lamp	n <sub>bl</sub>	fraction	0.04
Lighting efficiency of kerosene lamp	n <sub>kl</sub>	fraction	0.06
Useful lifetime of biogas plants	n	year	20
Rated biogas plant capacity	V	m <sup>3</sup> d <sup>-1</sup>	
Annual average gas production	a <sub>p</sub>	fraction	0.8
Fraction of gas used for cooking	g <sub>c</sub>	fraction	0.8
Fraction of gas used for lighting	1 – g <sub>c</sub>	fraction	0.2
N in fresh dung	N	fraction	0.02
P in fresh dung	P	fraction	0.063
K in fresh dung	K	fraction	0.025
Retention factor	Z <sub>f</sub>	fraction	0.6

Source: [15,17].

The capital costs also include interest on financing of the plant [11]. To reduce capital costs, digesters in Uganda were built with local construction materials to local specifications. The economic prices of locally available materials (such as sand,

**Table 3 – Selected household socio-economic and demographic household data from survey results.**

Parameter	Unit of measurement	Value
Average household size including visitors	Number of persons	7.6
Average cattle herd size owned	Number of animals	3.5
Average cooking energy demand (biogas equivalent)	Cubic metres	2.5
Average number of cooking times/household/day	Frequency	2.8
Average land size owned by the household	Acres	9.0
Average household daily fuelwood cost for cooking purposes	\$	0.28
Average household monthly kerosene cost for lighting purposes	\$	3.66
Average maximum price of fuelwood household willing to pay	\$	0.02
Average price maximum of fresh cowdung household willing to pay	\$	0.02

stone chips and bricks) were valued at their market prices, while those of tradable components (such as cement, steel bars, etc.) were valued at retail market prices (Table 1) to arrive at the final capital and installation costs (Table 4).

Kandpal et al. [17] assert that the capital cost of any given plant design could be obtained using the following cost function:

$$C = C_0[a + b(V/V_0)] \quad (1)$$

where  $C$  is capital and installation cost for a biogas plant of capacity  $V$  m<sup>3</sup> (in \$),  $a$  and  $b$  are constants, the values which depend on the capacity,  $V_0$ , of the reference plant (m<sup>3</sup>) with the capital cost of  $C_0$  (in \$). Coefficients  $a$  and  $b$  are calculated by minimizing the least-square function for the cost of the biogas plants for different capacities. For this study, total capital costs,  $TC_c$  (in \$), were computed as costs of civil construction and installations (Tables 1, 2 and 4). As a first approximation of capital costs, the annual economic value of the land occupied by the biogas system should be determined and included in the analysis. The land occupied by a biogas system has several alternative uses. A rough estimate of the cost of establishing an unheated biogas digester, not including the purchase or opportunity costs of land, was approximately 50–75 \$dollars per m<sup>3</sup> capacity [11]. However, a number of

**Table 4 – Estimation of capital and installation costs of family-sized biogas plants in Uganda.**

Name of component	8 m <sup>3</sup>	12 m <sup>3</sup>	16 m <sup>3</sup>
	Cost (\$)	Cost (\$)	Cost (\$)
<b>A. Civil construction</b>			
Bricks	108	120	144
Sand-lake	40	4	40
Sand-plaster	32	48	80
Stone chips	48	64	80
Stones -hard core	32	32	32
Ordinary cement	144	180	225
Water-proof cement	6	7.2	84
Lime	12	18	21
PVC pipes (4")	10	13	16
Chicken mesh	4	6	8
Weld mesh	5	7	11
Timber (2" × 4")	3	5	6
Nails	10	12	14
Subtotal	454	552	685
<b>B. Labour</b>			
Digging the pit	200	320	400
For construction	120	200	280
Mason	200	320	400
Subtotal	520	840	1080
<b>C. Supply line</b>			
Market price of galvanised pipes (3/4" and 1/2")	9	9	9
Market price of gas valves	12	20	28
Market price of filter	1	1	1
Market price of biogas stove	36	36	36
Market price of biogas lamp	4.4	44	44
Subtotal	102	110	118
Total cost (A + B + C)	1076	1502	1883
Miscellaneous (5% of total cost)	54	75	94
Grand total	1130	1577	1078

studies on economic evaluation of biogas systems in developing countries [4,10,13–15] have excluded the cost of land in their capital cost analysis because the biogas systems are often sited on the households' land. Increasing the cost of land would exaggerate the total cost of biogas plants and could discourage households from investing in this sector. This study has also excluded the cost of land in the analysis.

**2.3.1.2. Operation and maintenance costs of family-sized biogas plants.** The operation and maintenance costs of the biogas system include the cost of various inputs to the system as well as the cost of manpower required to operate it [12]. Acquisition of raw materials for the substrate, water for mixing materials, feeding and operation of the plant, regular maintenance, supervision, storage and disposal of the slurry, gas distribution and utilisation, and administration are some of the operation and maintenance costs associated with running a biogas plant [11]. Total operation and maintenance costs often include the sum of operating labour costs, feedstock costs, feedstock transportation costs and maintenance costs [14].

The cost of fresh dung input for the family-sized biogas plants, especially where cow dung is purchased, is considered the main operational cost. Where it is not purchased, its economic cost could be estimated on the basis of monetary worth of (a) equivalent amount of fertilizer saved, (b) equivalent amount of fuels purchased (such as fuel wood, kerosene, etc.), and (c) gathered fuel wood [12,15,18]. However, since the dung was assumed to be readily available to the households in the study areas, an average price derived from the survey results as the maximum price the household was willing to pay

for the cow dung has been used to estimate the cost of fresh dung (Table 5).

The other annual operation and maintenance costs of the biogas plants were repair, maintenance and replacement costs. The main repair and maintenance requirement of a digester usually consists of the cost of maintenance and replacement of gas valves, lamps and cook-stove parts and fixing gas leakage points. Emptying the digesters of accumulated solid particles after every five years was also required for the plant to achieve the maximum lifespan. For the analysis presented here, following Kandpal et al. [17], a figure of 4% of the capital cost is assumed to be adequate for the maintenance cost because the approximate cost of these and other routine maintenance costs have been shown to be roughly proportional to the capital costs of the plant capacity. Similar studies [15,19] note that the annual maintenance cost is always about 4% of the capital cost of the plant. Thus, once the capital is known, the total annual maintenance cost,  $M_c$ , for a biogas plant of capacity  $V$  m<sup>3</sup> can be estimated as:

$$M_c = 0.04C \tag{2}$$

where  $M_c$  is the annual maintenance cost (in\$) for a biogas plant of capacity  $V$  (m<sup>3</sup>) and  $C$  is its total capital and installation costs (in \$). The total annual operating and maintenance costs,  $AOT_c$  (in \$) for a plant with the capacity volume of gas  $V$  (m<sup>3</sup>) with capital cost  $C$ , could thus be:

$$AOT_c = 365VWP_{wdu} + 0.04C \tag{3}$$

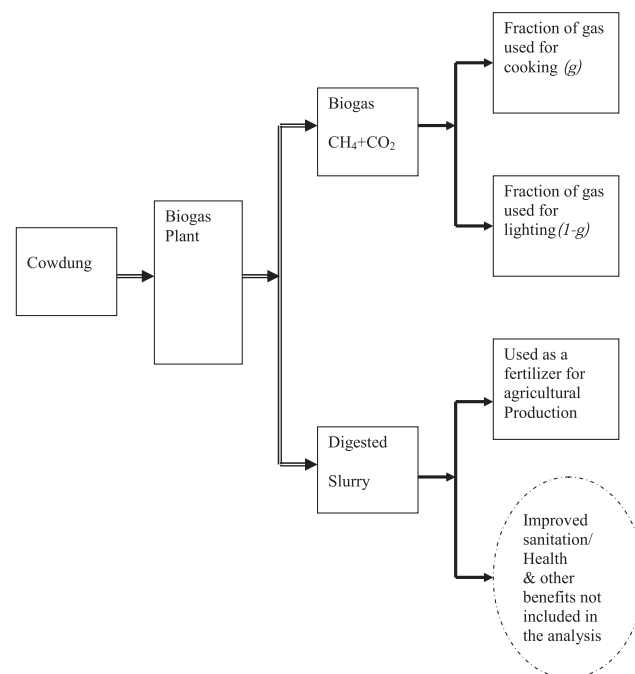
where  $W$  is quantity (kg) of wet dung required to produce 1 m<sup>3</sup> of gas,  $P_{wdu}$  is the price of the dung in \$ kg<sup>-1</sup> and 365 refers to 365 days in a year. For end-use equipment, materials and fuels (such as biogas stove, chemical fertilizers, diesel, kerosene,

**Table 5 – Estimation of total annual costs for family-sized biogas plants in Uganda.**

SN	Name of component	Capacity of biogas plant		
		8 m <sup>3</sup>	12 m <sup>3</sup>	16 m <sup>3</sup>
1	Total dung requirement (kg)	73,000	109,500	146,000
2	Total annual cost of dung (\$)	1460	2190	2920
3	Total capital and installation costs (\$) (From Table 4)	1130	1577	1078
4	Annual Maintenance costs (\$) (4% of capital and installation costs)	45	63	79
5	Annual depreciation (\$) (4% of capital and installation costs)	45	63	79
6	Total operational and maintenance (O&M) costs (\$) (2 + 4+5)	1551	2316	3078
7	Total annual costs for biogas plant (\$) (3 + 6)	2680	3894	5056

Note.

- (i) Average price of 1 kg of fresh dung is taken at 0.02\$.
- (ii) Total annual dung cost has been estimated as: Total dung requirement × average price of fresh dung.
- (iii) Annual dung requirement (kg) has been estimated as follows: Plant capacity × 25 × 365 because 1 m<sup>3</sup> of biogas requires 25 kg of fresh dung per day.
- (iv) Annual depreciation cost has been estimated as 4% of Capital & Installation costs [18].



**Fig. 3 – Benefits from family- sized biogas plants in Uganda.**

etc.) the 2008 retail market prices were used in the calculations (Table 1). The total operation and maintenance costs and costs of depreciation were calculated as the fixed percentages (4%) of the capital costs (Table 5). The total annual cost,  $TAC_b$ , of the family-sized biogas plant included the total capital and installation costs,  $TC_c$  (Table 4) and the total annual operating costs,  $AOT_c$ , (Table 5).

### 2.3.2. Benefits of family-sized biogas plants

Quantification of the benefits of a biogas system is a crucial step in the economic viability evaluation of biogas generation. The benefits accruing from establishing and running a biogas digester fall into two basic categories: monetary and environmental [11] as shown in Fig. 3. The monetary benefits are the saved costs on fuels substituted by biogas, and on fertilizer costs substituted by digester slurry [12,13]. Environmental benefits include several other indirect benefits. The most notable is the mitigation of greenhouse gas emissions resulting from deforestation associated with burning firewood [7]. By encouraging increased zero grazing by farmers to capture manure conveniently, family-sized digesters could reduce overgrazing and greatly improve sanitary conditions of the household.

However, attributing market prices to the major benefits of biogas plants; the biogas and the digested manure (slurry) and other indirect benefits is rather difficult [15,17,20]. Some households do not appreciate the monetary value of biogas production because they have adequate supplies of biomass at almost no cost and they attach little or no value on time spent gathering the biomass [13,15]. Under-employment and unemployment also lead to a zero or negligible opportunity cost for collecting various biomass for domestic energy requirements [12]. Hence it is necessary to find an indirect method to evaluate the benefits, and the most logical method is to place market values in terms of alternative fuels for a given end use [17,18,21].

**2.3.2.1. Valuation of biogas from family-sized biogas plants for energy use.** Biogas in Uganda is mainly used for cooking and lighting purposes [2]. The benefits for the users of biogas systems in this study were therefore quantified in terms of the quantity of fuel wood the biogas replaces for cooking and the quantity of kerosene substituted for lighting. In Uganda, fuel wood meets about 80% of the energy needs for cooking, while kerosene is the major source of lighting for more than 90% of the households in rural areas where biogas has been largely promoted [22]. This makes it the most logical benchmark for comparison and evaluating the monetary benefits of family-sized biogas digesters in Uganda. The value of benefits from cow dung for generating biogas for cooking and lighting often depends upon the previous end-uses of the cow dung before being substituted for biogas production [21]. In this study, it has been assumed that the dung was previously used directly as farm yard manure only, but with the advent of biogas generation, most of the dung was reserved for the generation of biogas energy.

Following Kandpal et al. [17], for a biogas plant with capacity of gas volume  $V$  ( $m^3$ ), the total annual monetary worth of benefits from cooking,  $TB_c$  (in \$) was computed as:

$$TB_c = 365Va_p g_c \frac{Q_c n_{eb}}{Q_f n_{ef}} p_f \quad (4)$$

where  $a_p$  represents the annual average daily biogas production as a fraction of its rated capacity,  $g_c$  is the fraction of gas used for cooking,  $Q_c$  is the caloric value of biogas (in  $kJ/m^3$ ),  $n_{eb}$  is the efficiency of a biogas cooking stove,  $Q_f$  is the caloric value of fuel wood (in  $kJ/kg$ ),  $n_{ef}$  is the efficiency of fuel wood cooking stove, and  $p_f$  is the price of the fuel wood (in  $\$ kg^{-1}$ ).

The annual worth in terms of monetary benefits from the use of biogas for lighting,  $TB_l$  (\$) was similarly computed as:

$$TB_l = 365Va_p (1 - g_c) \frac{Q_c n_{bl}}{Q_k n_{kl}} p_k \quad (5)$$

where  $Q_k$  is the caloric value of kerosene (in  $kJ/l$ ),  $n_{bl}$  and  $n_{kl}$  are the efficiencies of biogas and kerosene lamp for lighting, respectively,  $(1 - g_c)$  is the fraction of gas used for lighting and  $p_k$  is the price of kerosene (in  $\$/litre$ ). Thus, the total annual benefits,  $TB_g$  (\$), from the use of biogas for lighting and cooking (in \$) are the sum of Eqs. (4) and (5) as follows:

$$TB_g = 365Va_p \left[ g_c \frac{Q_c n_{eb}}{Q_f n_{ef}} p_f + (1 - g_c) \frac{Q_c n_{bl}}{Q_k n_{kl}} p_k \right] \quad (6)$$

**2.3.2.2. Valuation of slurry as fertilizer from family-sized biogas plants.** The cow dung used to run a biogas plant is a double-pronged source of income to the household. Firstly, the biogas is a fuel of appreciable calorific value. Secondly, the residual slurry is a good manure of appreciable nutritional value [18]. Biogas plants thus provide fertilizer in the form of spent slurry and can be compared with aerobic composting processes or the provision of chemical fertilizers [15,17].

It has been documented that if post-digestion handling of slurry is appropriate, it may be assumed that there is no significant change in the fertilizer value of cow dung manure after undergoing anaerobic digestion [13,15]. Hence slurry contains reasonable quantities of the nutrients (sodium, potassium and phosphate) found in chemical fertilizers like urea, potash and superphosphates [13]. Therefore slurry removed after optimal retention time in the anaerobic digester has value as fertilizer and soil amendment, not only because it retains most of the macronutrients (N, P and K) in the original feedstock, but also because such nutrients are readily available as crop nutrients [10]. Similarly, if composting is appropriate, farmyard manure (FYM) will have almost the same NPK value as the fresh manure [21] and the quantity of residual slurry is the same as that of the cow dung fed in a biogas plant [14].

Some studies have reported that the digester effluent has more available nutrients than raw manure and it is more environmentally friendly and less costly than chemical fertilizers [11]. It has also been reported that nitrogen present in cattle dung is conserved when processed through a biogas plant, yet in open-pit composting, some of the nitrogen may be lost due to evaporation [17]. However, the nitrogen in ammoniacal form, which is present in the digested slurry, may also be lost when the slurry is spread or sun-dried [15]. In view of the differing claims by researchers, it is difficult to conclusively state how much of the quantifiable incremental benefit of using spent slurry from anaerobic processes over

FYM can be obtained through aerobic composting. But the general agreement in the various views is that slurry has significant value as fertilizer for boosting agricultural production.

This study used market prices of urea, superphosphate and muriate of potash, respectively (Table 1), to attempt to quantify the benefits for the N, P and K values in the digested slurry from a biogas plant as was done by some studies [12,15,18,21]. Hence cognizant of the varying views about the quality of the digested slurry as a fertilizer, it was assumed that a certain percentage of nitrogen remains after the animal dung is digested anaerobically in a biogas plant, and that this percentage is defined by the nitrogen retention factor,  $z_f$ . It is also worth mentioning that the quantity of residual slurry is said to be the same as that of the cow dung fed into a biogas plant [18]. If the quantity of wet dung required to produce  $1 \text{ m}^3$  of biogas is  $w d_u$  (kg), the nitrogen present in fresh dung (by weight fraction) is  $N$  and the price of urea is  $p_u$  ( $\text{\$ kg}^{-1}$ ). The annual worth of the monetary benefits (in terms of urea equivalent) from the digested slurry,  $S_b$  ( $\text{\$}$ ), was thus expressed as:

$$S_b = 365Vw d_u N z_f (100/46) p_u \quad (7)$$

where nitrogen content in urea was taken to be 46%. The NPK values of urea, superphosphate and muriate of potash were taken as 46, 16 and 40, respectively. The annual incremental benefits of the P and K values of the spent slurry were expressed, respectively, as follows:

$$S_b = 365Vw d_u P z_f (100/16) p_p \quad (8)$$

$$S_b = 365Vw d_u K z_f (100/40) p_m \quad (9)$$

The total annual incremental benefit from the spent slurry then became:

$$S_b = 365Vw d_u \left[ N z_f (100/46) p_u + P z_f (100/16) p_p + K z_f (100/40) p_m \right] \quad (10)$$

2.3.2.3. *Total annual benefits due to installation of biogas plant.* Thus the total annual benefits,  $TAB_g$ , due to the installation of a biogas plant with the capacity of gas volume of  $V$  ( $\text{m}^3$ ) were computed as the sum of the benefits arising from the use of biogas as well as those from the digested slurry used as fertilizer; the sum of Eqs. (6) and (10):

$$TAB_g = 365V a_p \left[ (1 - g_c) \frac{Q_c n_{bl}}{Q_k n_{kl}} p_k + g_c \frac{Q_c n_{eb}}{Q_f n_{ef}} p_f + 2.17w d_u N z_f p_u + 6.25w d_u P z_f p_p + 2.5w d_u K z_f p_m \right] \quad (11)$$

Biogas energy generation has indirect benefits. For the present analysis, the monetary values of these indirect benefits have not been included due to lack of sufficient data. These benefits include (i) partial sterilization of waste during fermentation, with the consequent reduction of public health hazard, (ii) improvement in sanitation, (iii) reduced transfer of fungus and other plant pathogens from year's crop residue to the next year's crop, (iv) provision of better fuel than natural

gas and liquefied petroleum gas because it does not contain sulphur, thereby reducing sulphur dioxide emission, (v) reduced deforestation as a result of reduced use of fuel wood and (vi) reduced overgrazing through increased use of zero grazing by farmers to capture manure conveniently.

### 2.3.3. Economic viability of biogas energy production from family-sized biogas plants

After quantification and valuation of the costs and benefits of the biogas systems, three economic decision criteria were used in the analysis of the economic viability, namely, payback period (PBP), net present value (NPV) and internal rate of return (IRR).

2.3.3.1. *Payback period.* Payback period refers to the number of years it would take for an investment to return its original cost of investment through the annual net cash revenues it generates. If the net cash revenues are constant each year, the PBP can be calculated as:

$$PBP = TI/NR \quad (12)$$

where, TI is the total amount of investment; and NR is the annual net revenue (net profit) which is annual gross income less annual operational cost. Where the net cash revenues are not equal, they should be summed year by year to find the year where the total is closest to the amount of investment. Investments with a shorter PBP are preferred. In this study, annual net revenues were assumed to be equal and the undiscounted payback period, UPBP ( $\text{\$}$ ), was used in the analysis because of its suitability for computations where annual benefits and annual operating costs are assumed uniform over lifetime of the project. It is calculated as:

$$UPBP = \frac{CI}{AP} \quad (13)$$

where CI is the total capital and installation costs ( $\text{\$}$ ), AP is the annual profit which is annual income less annual operational cost ( $\text{\$}$ ) [18].

2.3.3.2. *Net present value.* Net present value (NPV) is a way of comparing the value of money now with the value of money in the future. It refers to the sum of the present values for each year's net cash flow less the initial cost of investment. It is used to determine whether the total current <http://www.investopedia.com/terms/p/presentvalue.asp> value of a project's expected future cash flows is enough to satisfy the initial cost. The future sum of money is discounted back to the present to find the present value of that expected future sum.

A useful economic life of a fixed-dome digester of 20 years was assumed in this study as has been in other similar studies [4,13,15,21]. Investments with a positive NPV are preferable. This implies that the rate of return by the investment is higher than the discount rate used and is greater than the opportunity cost of capital used as the discount rate. A negative NPV should be rejected while a zero NPV makes the investor indifferent, in which case other factors and benefits relating to the investments should be considered. Assuming that the annual benefits,  $TAB_b$ , and annual operating costs,  $AOT_c$ , are uniform over lifetime,  $t$ , of the biogas plant, the expressions for  $TAB_b$  and  $AOT_c$ , given by Eqs. (11) and (3), respectively,

were used to calculate the NPV (\$) of the benefits from the expression:

$$NPV = TAB_b - AOT_c$$

This means the future benefits and costs arising from the biogas system for the period of the next 20 years have been discounted to get their equivalent current value at the moment. When the discounted costs are subtracted from the discounted benefits, this gives us the net present value arising from the biogas system.

**2.3.3.3. Internal rate of return.** Internal rate of return (IRR) is a financial analysis tool that estimates the interest rate that would make the present value of a stream of net cash revenues equal to zero. An alternative explanation might be the highest rate of interest (expressed as a percentage) at which an investment can be funded if cash flow generated is to be sufficient to repay the original outlay at the end of the project life. It was calculated as:

$$\sum_{t=0}^n (TAB_b - C)_t (1 + IRR)^{-t} = 0 \quad (14)$$

where IRR is the discount rate. A value of IRR higher than the discount rate means that the investment is profitable.

#### 2.3.4. Sensitivity analysis of selected economic parameters

Sensitivity analysis using estimated economic values (costs and benefits) from the family-sized biogas digesters was undertaken. There are many assumptions and uncertainties involved in the cost benefit analysis. The parameters may vary due to location (such as the price of fuel wood, interest rates), technology development (such as the change of lifetime biogas plants, improvement of cooking stove efficiency) and other factors [17]. Sensitivity analysis is used to incorporate uncertainty into economic evaluation in order to generalize the results for different situations where input parameters and costs differ [23]. It explores the net effect on the net present cost of the systematic changes in individual parameters [24]. Sensitivity analysis was thus performed by varying the discount rate, capital costs, and operation and maintenance costs to determine the economic stability of family-sized biogas energy production.

In this study, sensitivity analysis was performed at three different discount rate scenarios; 6% (50% reduction in the base case scenario discount rate), 12% (base case scenario) and 24% (doubling the base case scenario discount rate). Generally, the discount rate of 12% is conventionally used to annualise capital investments [25]. The 12% discount rate is thus regarded as the standard rate for valuation of most economic projects. It was thus chosen as the base case scenario for this study.

Although the 12% discount rate is conventionally used for evaluation of economic projects, the actual interest rates paid by the borrower may be much higher. In Uganda, some financial institutions, such as commercial banks, lend at interest rates as high as 24%, and even higher for some informal financial institutions like private moneylenders. For instance, the average commercial bank interest rate in Uganda was about 24% for short-term consumer loans at the time of this

study. This gives the most logical basis for deciding the discount rates to be used in the sensitivity analysis; the base case discount rate is doubled to 24% to cater for the effect of high discount rates (the prevailing rates at the time of the study) on the economic stability of the biogas energy production. Sometimes market situation changes in demand and supply for money can lead to a reduction in the interest rates charged. In Uganda, for instance, because of increased competition among commercial banks as a result of entry of many banks into the industry, a number of them have started decreasing their lending interest rates. This study hypothesizes that this trend could continue. However, the 50% reduction in the discount rate should be the feasible lower limit. Therefore, this formed the basis for the selection of 6% (a 50% reduction) as the minimum discount rate.

Market situation changes in demand and supply of inputs required for biogas energy production can lead to either a reduction or increase in capital and O&M costs. For instance, because of inflation, capital costs can double or even treble depending on the inflationary rate. Alternatively, in case of cost sharing or a government subsidy, capital costs incurred by a household can significantly drop. Also where households collect or buy the dung, operation and maintenance costs can be reduced if the household starts rearing cattle where the plant is sited. Alternatively, operation and maintenance costs can hike if the household starts hiring labour for biogas energy production. In this study, it is envisaged that such increases or reductions in capital and operation and maintenance costs may not exceed 50% based on the recent past, current and/or foreseeable future trends in biogas input and commodity markets in Uganda. Hence the basis for a 50% increase and decrease in capital and operation and maintenance costs for the sensitivity analysis. Other more specific reasons for the justification of 50% increase or decrease in the costs are indicated in Table 9. The results of the sensitivity analysis for the effect of selected economic parameters on the economic viability of family-sized biogas plants are shown in Table 9b.

A sensitivity analysis was also performed to determine the break-even points for the respective capacity plants. To ensure sustainable economic viability of biogas energy production, it is imperative that households avoid making losses. This can be achieved through monitoring the profitability of their biogas production systems. Break-even analysis is a crucial tool in empowering households to achieve this objective. The break-even point is where the NPV for the biogas plants equal to zero. This implies that the discounted stream of costs equal to discounted benefits, i.e., the profitability of the biogas system is equal to zero. This point is also known as the internal rate of return (IRR). Any increase in the cost streams beyond the benefits leads to negative NPV; the biogas production system starts incurring losses.

## 3. Results and discussion

### 3.1. Profile of households with family-sized biogas plants in Uganda

Results show that the average household size was 8 persons with an average cattle herd size of 4 (Table 3). Family-sized

**Table 6 – Estimation of annual monetary benefits from family-sized biogas plants in Uganda.**

Name of component	Capacity of the biogas plant		
	8 m <sup>3</sup>	12 m <sup>3</sup>	16 m <sup>3</sup>
Anticipated annual biogas production (m <sup>3</sup> ) (100% of installed capacity)	2920	4380	5840
Net quantity available for use (m <sup>3</sup> ) (80% of installed capacity)	2336	3504	4672
Net quantity available for cooking (m <sup>3</sup> ) (20% of Net quantity available for use)	467	701	934
Net quantity available for lighting (m <sup>3</sup> ) (80% of Net quantity available for use)	1869	2803	3738
Monetary benefits from fuelwood equivalent of net available for cooking (\$)	46.77	70.15	93.54
Income from kerosene equivalent of net available for lighting (\$)	507	761	1015
Income from gas (\$)	554	831	1108
Quantity of slurry available (kg)	73,000	109,500	146,000
Monetary benefits from N value of the slurry (\$)	421	631	841
Monetary benefits from P value of the slurry (\$)	1104	1656	2208
Monetary benefits from K value of the slurry (\$)	438	657	876
Income from slurry (\$)	1962	2943	3925
Total income	2516	3774	5032

biogas plants being labour intensive and operated by mainly family members, implies that most households had sufficient manpower for the generation of biogas. The average cattle herd size of four suggests that most households had sufficient quantities of cow dung to generate adequate gas for both cooking and lighting. Households were considered to have biogas plant potential if they had at least two cows per capita [4, 27,28]. Results therefore show that there was adequate feedstock and manpower potential for sustainable biogas energy generation in the studied areas. Insufficient dung (cattle number) and/or competitive uses for dung have often resulted in households abandoning the technology because of their inability of the biogas plants to generate adequate cooking energy [26]. Thirty percent of the households reported that all their normal daily cooking energy needs were met through biogas. The average number of cooking occasions per household per day was three. Other important household characteristics are highlighted in Table 3.

### 3.2. Costs of family-sized biogas plants in Uganda

Total annual costs of the most common fixed-dome family-sized biogas plants in Uganda (8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup>) were computed as total capital and installation costs plus total

operational and maintenance costs (Table 4 and 5). Results show that the bulk of the capital costs comprise civil construction and labour costs with supply line costs constituting only about 10%. As expected, the bigger the capacity of the biogas plant, the higher the costs of installation and operating the plants. The difference stems from the additional capital and installation inputs required for larger capacity plants. The cost of dung forms the highest proportion of the total annual O&M costs (Table 5). For biogas production to be sustainable, it is advisable that a household rears cattle to ensure a steady supply of feedstock. The high cost of cattle dung can be an inhibitive factor for biogas production and use if the household is to purchase the dung.

### 3.3. Benefits from family-sized biogas plants in Uganda

The results of the estimated total annual incremental benefits from the use of biogas show that a household derives more incremental benefits from lighting than from cooking (Table 6). This is because of the higher cost of kerosene for lighting compared to the cost of fuel wood for cooking which biogas replaces. The monetary benefits from biogas for cooking are low compared to the benefits from biogas for lighting (about 10% of the total benefits from lighting). As the price of fuel wood continues to increase in Uganda, for various reasons, the incremental benefits from using biogas are likely to be more pronounced. The benefits from biogas for lighting could have been much higher if another more expensive fuel for lighting had been used in valuation of the benefits because kerosene is amongst the cheapest fuels for lighting in Uganda. This therefore suggests that the benefits presented in this analysis are a bare conservative estimate of the potential benefits of biogas for cooking and lighting.

Estimated value of the total annual incremental benefits from the spent slurry show that benefits from slurry comprised over 50% out of the total annual benefits from the biogas plant (Table 6). This was followed by benefits from biogas for lighting purposes (40%), while benefits from biogas for cooking contributed only about 10% of the total annual benefits. This was mainly attributed to the high prices of the inorganic fertilizers on the local market which were used in the valuation of the slurry. This also highlights the

**Table 7 – Undiscounted payback period (UPBP) results for family-sized biogas plants in Uganda.**

SN	Name of component	Biogas plant capacity		
		8 m <sup>3</sup>	12 m <sup>3</sup>	16 m <sup>3</sup>
1	Total annual income (\$) (Table 5)	2516	3774	5032.48
2	Total capital and installation costs (\$) (Table 4)	1130	1577	1077.6
3	Total operational and maintenance (O&M) costs (\$) (Table 4)	1551	2316	3078.18
4	Total annual profit (\$) (1–3)	966	1458	1954.29
5	Undiscounted payback period (years) (2 ÷ 4)	1.17	1.08	1.01

UPBP = CI/AP where UPBP=undiscounted pay back period; CI = total capital and installation costs; AP = annual profit; annual profit = annual income – annual operational cost [18].

**Table 8 – Net present values for the base case scenario at discount rate of 12%.**

Biogas plant capacity	Net present value	IRR
8 m <sup>3</sup>	4535	35.96
12 m <sup>3</sup>	6998	37.39
16 m <sup>3</sup>	9542	38.60

importance of slurry as a potential source of comparatively low-cost fertilizers affordable by many households if they took up biogas energy generation.

### 3.4. Economic viability of family-sized biogas plants in Uganda

Results show that the 8 m<sup>3</sup> biogas plant capacity has the highest undiscounted payback period (UPBP) of 1.17 years, while the 16 m<sup>3</sup> has the lowest UPBP of 1.01 years (Table 7). This is attributed to the lower per unit cost of installation and annual operation and maintenance which decrease with the increase in the capacity of the biogas plant. Although there is no significant difference in the UPBP for the three plant sizes, results show that as the capacity of the biogas plant increases, the UPBP decreases. This conforms to the standard practices and trends in the economics of installation and operation of any technical project [18]. On the basis of the UPBP results, the 16 m<sup>3</sup> plant with a shorter period was the most economically viable. This implies that a household with a 16 m<sup>3</sup> biogas plant would take few years to recover the original cost of

**Table 9a – Sensitivity analysis parameters and scenarios for analysis of economic viability family-sized biogas plants in Uganda.**

Parameter	Scenario	Variation	Reason
Discount rate	One	Base case	No variations in cost or parameter values from the base case inputs
	Two	Doubled to 24%	<ul style="list-style-type: none"> <li>Market situation changes in demand and supply for money.</li> <li>Increase in inflation rate</li> </ul>
Capital cost	Three	Reduced by 50%–6%	<ul style="list-style-type: none"> <li>Market situation changes in demand and supply for money.</li> <li>Decrease in inflation rate</li> </ul>
		Increased by 50%	<ul style="list-style-type: none"> <li>Higher component prices</li> <li>Increased depreciation rates</li> </ul>
Operating cost	Four	Decreased by 50%	<ul style="list-style-type: none"> <li>Lower component prices</li> <li>Longer lifetime of the biogas plant</li> </ul>
		Increased by 50%	<ul style="list-style-type: none"> <li>High cowdung cost</li> <li>Higher labour wages</li> <li>Higher maintenance costs</li> <li>Lower component lifetime</li> </ul>
		Decreased by 50%	<ul style="list-style-type: none"> <li>Lower cowdung cost</li> <li>Lower labour wages</li> <li>Lower maintenance costs</li> <li>Higher component lifetime</li> </ul>

**Table 9b – Sensitivity analysis results for the economic parameters used.**

Capacity of biogas plant	NPVs for different discount rates with their respective IRR			
	6%	12%	24%	IRR
(i) Increase and decrease in discount rates from 12% to 24% and 6%, respectively				
8 m <sup>3</sup>	8399	4535	1280	35.96
12 m <sup>3</sup>	12,832	6998	2100	37.39
16 m <sup>3</sup>	17,369	9542	2977	38.6
(ii) 50% increase in capital costs				
8 m <sup>3</sup>	7789	3925	680	29.18
12 m <sup>3</sup>	6333	2469	775	19.81
16 m <sup>3</sup>	955	2091	–2153	14.77
(iii) 50% decrease in capital costs				
8 m <sup>3</sup>	9009	5145	1899	46.64
12 m <sup>3</sup>	9037	4173	928	31.62
16 m <sup>3</sup>	7091	3227	–18	23.89
(iv) 50% increase in operating and maintenance costs				
8 m <sup>3</sup>	1268	2031	–2671	0.96
12 m <sup>3</sup>	–243	–1920	–3329	5.40
16 m <sup>3</sup>	–1832	–3493	–4888	2.30
(v) 50% decrease in operating and maintenance costs				
8 m <sup>3</sup>	18,065	11100	5251	99.35
12 m <sup>3</sup>	26,115	15649	6869	67.19
16 m <sup>3</sup>	36,552	22577	10842	99.35

investment through the annual net cash revenues it generates than the other plants.

At the base case scenario discount rate of 12%, NPV turns out to be positive for all the three capacities of the biogas plants and increases with increase in plant capacity (Table 8). The slope of the change of NPV with the plant size largely depends on the discount rate. Lower rates depict a steeper change in NPV [17]. Hence, an 8 m<sup>3</sup> plant would be more sensitive to changes in economic parameters than the 16 m<sup>3</sup> plant. The positive NPV for the three plant capacities implies that all the three designs are economically viable. However, because smaller capacity designs are more sensitive to economic parameters, the 16 m<sup>3</sup> is more economically viable.

The IRR for the three capacities of the family-sized biogas plants (Table 8) shows that IRR increases with the increase in the capacity of the biogas plants. These results show the significance of scale on the economic viability of family-sized biogas plants. Based on the current stream of benefits and costs, the IRR results indicate that the NPV for the 8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup> plant designs would be equal to zero at discount rates of 36%, 37% and 39%, respectively. Interest rates above 36%, 37% and 39% for the respective plant designs will lead to negative NPVs, implying that the cost streams for the respective plant designs will exceed the benefits. Households should therefore refrain from borrowing at annual interest rates above 36% for the 8 m<sup>3</sup> plants, 37% for the 12 m<sup>3</sup> and 39% for the 16 m<sup>3</sup> plant designs. These results show that the 16 m<sup>3</sup> plant with the highest IRR is the most economically viable.

Sensitivity analysis parameters and scenarios used in the analysis are shown in Table 9a while the results of the analysis are presented in Table 9b. As expected, a reduction of the discount rate from 12% to 6% increases the NPV significantly.

Increasing the discount rate from 12% to 24% substantially decreases the NPVs of all the biogas plants. Thus while NPV remains positive for all the three plant capacity designs, a higher discount rate greatly decreases the profitability of biogas plants. It is important to note that the 12% discount rate used in this analysis is a standard rate conventionally used in evaluating economic projects. This shows that if the interest rates in Uganda were as low as the standard rate of 12%, the profitability of family-sized biogas plants would be as high as 4500\$ for the 8 m<sup>3</sup> plants, 7000\$ for the 12 m<sup>3</sup> and 9500\$ for 16 m<sup>3</sup> plants (Table 9b). However, the 24% discount rate which was the ongoing interest rate at the time of this study is more appropriate in portraying a realistic position of the economic performance of family-sized biogas systems. Thus the low NPV of 1300\$, 2100\$ and 3000\$ for the 8 m<sup>3</sup>, 12 m<sup>3</sup> and 16 m<sup>3</sup> plants, respectively, give a more realistic situation of the profitability of the plants (Table 9b).

Increase in the capital costs by 50% has a similar effect as the increase in the discount rate. Increase in capital costs increases the total cost of the biogas systems. When the capital costs are decreased by 50% with a discount rate of 6%; the NPV is greater than zero for all the three plant capacities. This reaffirms the fact that the biogas plants are economically viable at lower discount rates and lower capital costs. However, at a higher discount rate of 24% even when the capital costs are reduced by 50%, only the 8 m<sup>3</sup> biogas plants remain viable. This implies that capital costs significantly affect the economic viability of family-sized biogas energy production. The higher capacity plants register negative NPV implying that biogas plants are less viable at higher capital cost. It is thus noted that the 8 m<sup>3</sup> biogas plants (smaller capacity plants) register higher NPV compared to their larger counterparts because of the level of capital investments sunk in these plants. When capital costs are decreased by 50%, the higher capacity plants still register lower NPV than smaller ones.

The most important sensitivity parameter is the operation and maintenance costs. The greatest effect is registered when operation and maintenance costs are increased by 50% where for all discount rates (6–24%), all the three biogas plant capacities register negative NPV, making all of them not economically viable, of course with higher capacity plants registering even lower NPV. The corresponding IRR is lowest when the operation and maintenance costs are decreased compared to all the other scenarios (Table 9b). This highlights the effect of operation and maintenance cost on the viability of biogas plants. Attention needs to be paid to critical inputs required in the day-to-day operations of the biogas plants, such as fresh dung and labour for operating the plant, which can lead to sudden increase in operation and maintenance costs. This greatly affects the profitability of biogas energy production. Results show that when the operation and maintenance costs are decreased by 50%, NPV almost doubles (Table 9b). Households wishing to invest in biogas energy production should be very certain about the reliability of their source of raw materials especially cow dung if they are to ensure sustainable profitability of their biogas production systems.

Break-even sensitivity analysis results highlight critical levels and rates at which family-sized biogas systems in Uganda should operate and/or borrow if they are to remain

economically viable. These IRR results show that NPV of the biogas plants will remain positive at various interest rates below 35%, 37% and 39% for the respective plants, and beyond which the NPV become negative. Households should not borrow to invest in their biogas systems at interest higher than 36% per year for the 8 m<sup>3</sup> biogas plant, 37% for the 12 m<sup>3</sup> and 39% for the 16 m<sup>3</sup> plants. The cost structure of the biogas systems offers useful guidelines to households about which levels they should operate in order to remain economically viable. The break-even sensitivity results suggest that at 12% discount rate, total costs should not exceed 7200\$ for the 8 m<sup>3</sup> plants, 10,800\$ for the 12 m<sup>3</sup> and 14800\$ for 16 m<sup>3</sup> plants. Likewise, the total operation and maintenance costs should not exceed 2000\$ for the 8 m<sup>3</sup> plants, 3200\$ for the 12 m<sup>3</sup> and 4400\$ for 16 m<sup>3</sup> plants if the plants are to remain profitable. These expenditure levels reflect the break-even points (where the respective NPV are equal to zero) for the respective biogas plants at the discount rate of 12%. Beyond these levels, the biogas systems register losses; the NPV becomes negative.

At the discount rate of 24%, break-even sensitivity results reveal that total costs should not exceed 1300\$ for the 8 m<sup>3</sup> plants, 2100\$ for the 12 m<sup>3</sup> and 3000\$ for 16 m<sup>3</sup> plants (Table 9b). These results show that the break-even points for the biogas systems occur at relatively higher total and operation and maintenance costs with lower discount rates (12%) compared to the high rates (24%). Households should thus monitor the cost levels for the respective plants to avoid incurring losses.

#### 4. Policy recommendations

A number of policy options can be derived from this study. The study underscores the cost of capital for investment in biogas production. The interest rates at which households should borrow for investment in biogas energy must be reasonable enough if the biogas energy production is to be viable. This probably justifies some form of state support in the initial phase of dissemination of the technology.

Establishment of microfinance schemes (MFIs) specifically for the biogas program needs to be designed to facilitate the construction of new plants, and more importantly, provide incentives for sustained operation. The MFIs could diversify their exposure and ensure commercially viable returns on their portfolio, by balancing between low interest credit to individual households and commercial terms for business ventures promoting biogas technology on a commercial scale. The MFIs could use the group lending approach at closely monitored low interest rates to extend loans to households by directly engaging reliable local equipment vendors and service providers who can install and offer technical assistance to the households.

This study also reveals that it is important to ensure a reliable and low-cost source of raw materials if family-sized biogas plants are to remain economically viable. Increase in the O&M costs greatly affects the profitability of biogas systems as shown by the sensitivity analysis results. There is need for an efficient and effective way of collecting and utilizing cattle dung resource to ensure sustained biogas

sufficiency and reliability. One of the most feasible ways is to ensure that the prospective biogas producers possess a sufficient number of cattle.

Considerable R&D should continue to be undertaken in suitable and affordable construction materials such as bricks/blocks with good durable and high pressure resistance properties and low-cost sources of substrate. Such developments allow digesters to have a longer lifespan which reduces capital and depreciation costs. It also allows use of local materials which could cut down capital and installation costs considerably.

To increase household capacity building in biogas technology and increase self-sufficiency in basic repair and maintenance works, demonstration biogas projects should be revived and set up especially in places where the potential of the technology has been known to be high. The fixed-dome design, identified as the most suitable and common plant design [2] should consequently be considered for pilot projects and diffusion programmes in Uganda.

Another important policy issue regards to the monetary benefits from the use of slurry. This paper envisages that through sensitization and awareness campaigns, the economic benefits of slurry can be highlighted to households. Few households know the monetary benefits attributed to the use of slurry in agricultural production and in improving sanitation and health conditions. Households need to be convinced that biogas offers more benefits in terms of increased soil fertility. Furthermore, inadequately informed households fail to distinguish between raw animal residues and the digestate, thereby wasting the superior manurial value of the latter. Therefore the monetary benefits of this readily available source of rich low-cost fertilizer should be highly published in order to enable households appreciate the full economic potential of family-sized biogas plants. This will promote use of the local low-cost fertilizer (slurry) in agricultural production and also improve hygiene in the countryside. In this way, biogas plants will be more economically viable and have greater appeal to households than simply viewing them as a source of biogas for cooking and lighting only.

## Acknowledgement

The authors gratefully acknowledge the financial support from Swedish International Development Corporation (Sida) ([\\_100004441](#))/SAREC for funding this study under the Joint Makerere University and Swedish University of Agricultural Sciences (SLU) PhD training and capacity building project. We are also very grateful to the UK Department for International Development (DFID) ([\\_501100000278](#)) New and Emerging Technologies Research Call for the supplementary funding to complete this work.

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