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Portable Electrification using Biogas Systems

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Abstract

There is a strong correlation between electrification and rise in human development, but in developing countries access to electricity is often unreliable, unavailable, or unobtainable, especially from a centralized electric grid. Portable electrification using batteries provides an affordable energy source while sidestepping costs and regulations associated with physical transmission lines. In this paper, an anaerobic digestion system consumes organic waste and produces biogas that fuels an electric generator for battery charging. The paper presents a detailed approach for conducting an engineering economic analysis of the system. Two candidate business models to evaluate the potential of portable energy storage device distribution services of different sizes to return profit are proposed. The results offer a promising starting point for local entrepreneurs to implement similar business models, particularly at a small scale with a modest capital investment of about $1500, with revenue of about $100 per week, and a payback period of 18 months on the investment.

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1. Introduction

The nexus between availability of electricity and various human development indices has been established [1,2]. In this regard, initiatives such as the Power Africa program aim to increase the electrical generation in developing regions by a significant amount through the addition of various centralized hydro, solar, wind and geothermal power plants, as well as large-capacity power transmission lines [3,4]. However, this development has to be coupled with
appropriate retail distribution models that are compatible with the realities of sparseness in geography and undeveloped markets in order to ensure that the capacity additions reach the target populations [5]. In this regard, the newly initiated Sustainable Energy for All posits that, “Building out a national electricity grid has historically been a successful strategy for achieving high rates of energy access in many countries, but it is not as well suited to serving sparsely populated or remote areas. Such solutions require business models that are commercially viable, entrepreneurial supply chains that can reach remote areas, increased consumer acceptance, community-based service delivery models and innovative financing mechanisms” [6].

Presently, a significant amount of retail business models that take this approach are being explored in various markets. Such small-scale off-grid systems are diverse in their scope that range anywhere between rechargeable flashlights and multi-kilowatt home energy systems, primarily based on solar photovoltaic systems [7]. Microgrids and minigrids have been proposed to be one of the approaches for expanding the reach and scale of these systems across the developing countries to keep in step with access to mobile telephone and communication technologies [8]. However, significant hurdles remain in the form of market formation, regulatory framework, financing for preparatory, installation and operating costs. Development of regulatory framework requires progress across various dimensions that include: tariffs, competition, relationship with legacy utilities, future grid extension, expansion and integration uncertainties, right-of-way, ownership and land-use issues.

On the other hand, the portable electrification approaches that are based on rental and/or ownership models of batteries that are charged by a local business skirts the regulatory problems through a white-goods and service provider model. The BBOXX kit model for electrification has taken this approach [9]. Energy for charging the batteries is provided by solar panels, sold as part of the kit. While the cost of solar panels continues to go down, it still forms a significant portion of the cost of the kit. Furthermore, production technologies for solar panels are a highly sophisticated technology that requires silicon processing and handling that is beyond the scope of localization in developing economies. On the other hand, the BBOXX kit model, when integrated with an electrical source that is compatible with technologies that can be locally scaled further, and yield other benefits, would provide a more attractive solution for adoption. In this paper, the use of biogas generated from anaerobic digestion of waste as the prime energy source for electrification is presented.

| Nomenclature | Description |
|--------------|-------------|
| C_L          | Monthly cost of labor |
| C_M          | Monthly cost of biogas generator maintenance |
| C_T          | Monthly cost of transportation fuel |
| K_7          | Capital cost of BB7 PESD or similar |
| K_12         | Capital cost of BB12 PESD |
| K_G          | Capital cost of biogas generator |
| K_PESD       | Capital cost of sum of PESDs |
| K_T          | Capital cost of transportation fuel |
| P_7          | Price of BB7 PESD rental |
| P_12         | Price of BB12 PESD rental |
| P_BB         | Power required to charge one BBOXX PESD |
| PESD         | Portable energy storage device |
| P_G          | Power (rated) of biogas generator |
| P_W          | Power supplied by wall charger |
| r_mo        | Discount rate (monthly) for cost-revenue analysis |
| T_C          | Time each mobile phone charge drains from total PESD capacity |
| T_L          | Time PESD can supply for lighting and mobile phone charging |
| T_P          | Time PESD can supply for lighting |
| UGX          | Ugandan shilling (UGX 2,500 = US$1) |
Anaerobic digestion systems, also known as biogas recovery systems or biodigesters, use naturally-present bacteria in an oxygen-free environment to break down manure and other organic substrates such as food scraps and agricultural waste. One of the byproducts of anaerobic digestion is biogas, which contains about 60-70% methane, 30-40% carbon dioxide, and small amounts of other gases, including hydrogen sulfide. A solid-liquid effluent is also produced, which can be used as a crop fertilizer or dried and used for livestock bedding [10].

Biogas when used as a cooking fuel has the advantage of burning cleaner than any other fuel (e.g. wood-fuel, crop residue, animal dung), with the exception of electricity. It is also a carbon-negative fuel source, since burning the biogas releases less greenhouse gas than if the organic matter were to decompose naturally [11]. Combustion of biogas can be used for low-emission lighting, replacing kerosene lamps that are ubiquitous in developing countries and are well known to degrade human health [12]. Use of biogas to run internal combustion engine-driven generators is an established technology that can be refined and developed further; there is much more accessible information within the local technical knowledge in terms of maintenance and servicing locally. This paper further develops the approach of using a biogas digester to supply an internal combustion engine with fuel to generate electricity for portable energy storage devices (PESDs) for portable electrification. In the following section, the details of the biogas digester business model are presented. In Section 3 the function of the portable energy storage device PESD as an enabler for portable electrification is presented. Section 4 provides evaluation results from a BBOXX device. Section 5 provides an energy and cost analysis of a proposed W2E PESD distribution service with 840 PESDs rented per week, and Section 6 provides a similar analysis with a smaller, alternative service.

2. W2E in Uganda

W2E [13] is a Uganda-based company that has been operating a 30m³ biodigester system in the town of Mpiigi since December 2013. W2E sorts and collects organic waste—estimated at 1,000kg per week—from the local market and transports it 16 kilometers to the biodigester site. A two-stall latrine directly above the biodigester also provides ‘feed’ for the system. W2E is conducting research on effluent use for organic fertilizer. Transporting the biogas via pipeline is not practical because there are no residences on or near the site. Instead, a three-kilowatt biogas generator has been leased which uses the biogas for electricity generation.

The PESDs are charged by the biogas generator, transported to the local market, and distributed to customers for a fee. When the customer’s PESD has no charge remaining, the customer exchanges it for a charged PESD at the market. The transport returns the collection of discharged PESDs, along with organic waste from the market, to the W2E site. Due to the energy capacity of the PESDs, biweekly transport of charged and discharged units will be required. Figure 1 illustrates a flow diagram of the overall system.
3. Portable Energy Storage Device Functions

For low-end customers that do not have access to electricity, the major use for the PESD is expected to be for lighting and mobile phone charging.

3.1 Electrical lighting

Without reliable, available, and/or attainable electricity access from a central grid, people in developing countries must often rely on environmentally unsustainable fuel sources for lighting needs. One class of these fuels is wood-derived, such as firewood and charcoal, the second class is fossil fuels, such as kerosene and paraffin candles, and the third class is dried animal dung. Wood-derived fuels cause deforestation, fossil fuels (especially kerosene) are toxic if ingested, animal dung impairs hygiene, and all three classes emit pollution. Using electricity generated from biogas helps to offset the environmental and health hazards that accompany the aforementioned fuel sources.

3.2 Mobile phone charging

In Uganda, less than 10% of people have access to electricity, yet 50% own a mobile phone subscription [15]. This forces a great majority of the population to rely on mobile phone charging services, friends and family with electric grid connection, or off-grid solutions such as solar panels to charge their mobile phones. Aside from charging costs, the mobile service is not fully reliable. Long and frequent power outages elongate charging time periods, sometimes mobile phones are returned without a full charge, phone and battery theft is not uncommon, and vermin have been damaging wires.

The use of a PESD with a USB outlet would allow the user to charge mobile phones at a much lower cost with uninterrupted service. This would enable the user to charge mobile phones during any time of the day and within the safety of the customer’s home.

4. BBOXX as a PESD

BBOXX is a United Kingdom-based company offering off-grid solar solutions in fourteen countries throughout Africa and Asia. Their portable battery boxes range in capacity from 5Ah to 120Ah, and each kit includes at least a solar panel, two LED lamps, and a mobile phone charger accessory kit. Two such kits have been evaluated for preliminary studies, based on their weight and electrical capacity: the BB7 (7Ah, 3.68kg) and the BB12 (12Ah, 5.4kg) [9].

4.1. Initial charging and discharging experiments

From full-charge, both the BB7 and BB12 units were discharged using two 2W LED lamps, included in the kits, in three- to four-hour time periods to simulate customer use. This experiment was then repeated with the added loads of charging mobile phones. Charging times were measured and averaged for both units. The results are summarized in Table 1.

4.2. Electric Lighting

Electric lighting supplied by the BBOXX PESD is far superior to kerosene lamps. The LED lamps are brighter: each of the two LED lamps included in the BBOXX kit produce at least 128 lumens of light [9], while typical kerosene lamp produces only 37 lumens [18].

Unlike kerosene, the LED lamps produce zero emissions and pose no risk of fire or toxic ingestion. If the PESDs are used for lighting for 4 hours per day, Table 1 suggests that the BB7 PESD can supply lighting for 4-6 days per charge.
Table 1. Hourly interval for various charging and discharging experiments for BBOXXs

| Item                                           | BB7   | BB12   |
|------------------------------------------------|-------|--------|
| Average charging†                              | 9h50  | 9h50   |
| 2x 2W LED lamps ($T_L$)                        | 17h00 | 24h45  |
| 2x 2W LED lamps & phone charging ($T_P$)*      | 14h50 | 19h05  |

†3x charging average for BB7, 2x charging average for BB12
*2x phone charges for BB7, 3x phone charges for BB12

4.3. Mobile phone charging

By using these data from Table 1, it is possible to determine the number of mobile phone charges each unit can supply when charged every 3-4 days. This, then, will allow the weekly savings that the customer will experience by avoiding mobile phone charging stations to be computed. For each BBOXX PESD, $N_C$ is the number of mobile phone charges per number of days $N_D$, $T_p$ is the time duration that each PESD can supply power for lighting and phone charging, and $T_C$ is the time that each mobile phone charge drains from the PESD. To first determine $T_C$, the difference between $T_p$ and $T_L$—the time duration that each PESD can supply power for lighting only—is divided by the number of phone charges $N_M$ in the experiment above.

$$T_C = \frac{T_p - T_L}{N_M} = \begin{cases} \frac{17h00 - 14h50}{2} & \text{for BB7 PESD} \\ \frac{24h45 - 19h05}{3} & \text{for BB12 PESD} \end{cases}$$ (1)

Assuming 4 hours of lighting are used each day, the number of hours left that are not used for lighting is divided by $T_C$ to yield $N_C$.

$$N_C = \frac{T_p - 4N_D}{T_C} = \begin{cases} \frac{17h00 - (4h)N_D}{1h05} & \text{for BB7 PESD} \\ \frac{24h45 - (4h)N_D}{1h50} & \text{for BB12 PESD} \end{cases}$$ (2)

Note that the time variables must be converted to decimal numbers before computing Equation 2. For values of $N_D$ of 3 and 4 days, the results from the BBOXX experiments are summarized in Table 2. Based on these results, we may develop a revenue model for the system, described in the following section.

Table 2. Results from BBOXX experiments

| Item                                           | BB7   | BB12   |
|------------------------------------------------|-------|--------|
| Battery discharge interval used per mobile charge ($T_L$) | 1h05  | 1h50   |
| Number of mobile phone charges ($N_C$)          |       |        |
| Charged every 3 days ($N_D = 3$)                | 1.0   | 4.5    |
| Charged every 4 days ($N_D = 4$)                | 4.5   | 6.5    |
5. Scenario 1: Energy and Financial Analysis of W2E PESD Distribution Service

5.1. Market potential

According to the Uganda Bureau of Statistics, the latest census (2011) reveals the population for Mpigi town to be 38,800 [14]. Assuming Mpigi demographics follow those of the entire country of Uganda, 30% of the residents are aged 25 years or older and 91.5% lack access to electricity [15]. If perfect overlap exists, 27.4% (10,600) of the town’s population is at least 25 years of age with no access to electricity. Therefore, a 3% market share of this demographic—accounting for barriers of cost, location, awareness and utility—yields over 300 potential customers for the PESD rental service.

5.2. System and Service Characteristics

The volume of the W2E digester is 30m$^3$, and will produce approximately the same volume of biogas each day [16]. The 3kW biogas generator consumes 3.50m$^3$ per hour of operation [17], thus it can run for 8.5 hours daily. However, the biogas generator manufacturer recommends running the generator for only up to 8 hours per day. Since the BBOXXs require about 10 hours to charge, they cannot be fully charged in one day, so only 5.5 batches may be charged each week.

The internal BBOXX PESD charging circuitry efficiency $\eta_{BB}$ is 95% [9], the wall charger efficiency $\eta_W$ is assumed to be 85%, and the output power of the wall charger $P_W$ is the product of the output voltage (16V) and the output current (1A). The required power to charge one BBOXX PESD $P_{BB}$ is then $P_W$ divided by the produce of $\eta_{BB}$ and $\eta_W$ (see Equation 3).

$$P_{BB} = \frac{P_W}{\eta_{BB}\eta_W} = \frac{(16V)(1A)}{(0.95)(0.85)} = 20W$$

Now that the power required to charge each PESD is known, the number of PESDs that can be charged in one batch simultaneously by the biogas generator, $N_B$, can be determined. $N_B$ is found by dividing the power of the biogas generator $P_G$ by $P_{BB}$.

$$N_B = \frac{P_G}{P_{BB}} = \frac{3,000W}{20W} = 150 \text{ PESDs per batch}$$

Thus an average of 840 PESDs ($N_{PESD}$) could then be exchanged per week, requiring a market penetration of 4% of the appropriate village population for biweekly rental.

A scenario where the quantity of BB7 PESDs rented $N_7$ is twice the quantity of BB12 PESDs $N_{12}$ rented per week is analyzed ($N_7 = 560$, $N_{12} = 280$). Since the BB7 has a nominal amp-hour rating that is 60% of the BB12 rating, its rental price ($P_7$) will also be 60% of the BB12 rental price $P_{12}$.

$$P_7 = 0.6P_{12}$$

5.3. Costs

The PESD distribution service costs are divided into three monthly operating costs—transportation fuel, labor, and maintenance—and capital costs for the biogas generator and PESDs. Since the feed to the biodigester is considered waste, this ‘fuel’ is free of cost to W2E. Much of the operating costs will come from diesel fuel for transportation of the PESDs. Currently the company spends UGX60,000 per week on diesel fuel for transporting 1,000kg of waste weekly. The PESD distribution service will require two additional weekly trips to the market, so the net fuel cost for the service $C_T$ will be UGX120,000 monthly.
Labor costs for waste collection and transportation are currently UGX200,000 per month for 20 working days. The PESD distribution service will require an extra 8 days per month (twice per week), resulting in a net increased labor cost \( C_L \) of UGX80,000 per month.

The biogas generator requires an air filter cleaning every 50 working hours, oil change every 100 working hours, spark plug check or replacement every 200 working hours, and gas hose change every 18 months \[17\]. This cost, \( C_{O+M} \), will be estimated at UGX30,000 per month.

The biogas generator can be bought by W2E for a capital cost \( K_G \) of UGX3,750,000.

The BB7 retail cost is UGX387,000, and the BB12 is UGX723,000. The kits, however, include 15W (BB7) and 30W (BB12) solar panels, which will not be needed for this situation. Assuming the PESDs can be purchased without these panels, their costs may drop to UGX287,000 (K7) and UGX523,000 (K12), respectively. In this scenario, the sum of these estimates multiplied by their respective \( N \) values yield a total PESD capital cost \( K_{PESD} \) of UGX307,000,000.

\[
K_{PESD} = K_7 N_7 + K_{12} N_{12} = (UGX287,000)(560) + (UGX523,000)(280) = UGX307,000,000 \tag{6}
\]

5.4. Revenues

To determine the break-even rental price for the BB7 and BB12, \( P_7 \) and \( P_{12} \), revenue \( R \) will be the sum of these prices multiplied by their respective quantities of weekly rentals \( N_7 \) and \( N_{12} \). To adjust these quantities to a monthly revenue stream, we multiply \( R \) by 4 weeks. Recall from Equation 5 that \( P_7 = 0.6P_{12} \).

\[
R = 4(P_7 N_7 + P_{12} N_{12}) = 4[0.6(560)P_{12} + 280P_{12}] = P_{12}(2,464) \tag{7}
\]

In the following cost-revenue comparison, the revenues will be equated to the costs to determine \( P_{12} \) and \( P_7 \).

5.5. Cost-revenue comparison

The weekly operation and maintenance costs and revenue will be multiplied by appropriate \( P/A \) factors that bring annual streams of cost or revenue to a present value (Equation 9). These factors include a discount rate \( r \) and time duration \( n \) in years that the value is assumed to last. Because the \( P/A \) factor assumes yearly streams, \( r \) must be converted to a monthly discount rate (Equation 8) and \( n \) must be expressed in months. An annual discount rate of 5% is chosen for this scenario, yielding a monthly discount rate \( r_{mo} \) of 4.07\( \times \)10\(^{-3} \).

\[
r_{mo} = (1 + r)^{1/12} - 1 = (1.05)^{1/12} - 1 = 4.07 \times 10^{-3} \tag{8}
\]

\[
(P/A, r_{mo}, n) = \frac{(1 + r_{mo})^n - 1}{r_{mo}(1 + r_{mo})^n} = \frac{(1.00407)^{36} - 1}{0.00407(1.00407)^{36}} = 33.4 \tag{9}
\]

Analyzing this scenario for a 3-year period, 36 months will be used for \( n \). The BBOXX warranty is 18 months, so a new set of PESDs is purchased after this period. To bring these future costs to present value, a \( P/F \) factor with an \( n \) value of 18 months will be multiplied by this second \( K_{PESD} \) term.

\[
(P/F, r_{mo}, n) = (1 + r_{mo})^{-n} = (1.00407)^{-36} = 0.864 \tag{10}
\]

The final cost-revenue equation for determining \( P_{12} \) is shown in Equation 11.

\[
P_{12}(2,464)(P/A, r_{mo}, n) = (C_T + C_L + C_M)(P/A, r_{mo}, n) + K_G + K_{PESD}\left[1 + (P/F, r_{mo}, 18) \right] \tag{11}
\]
5.6. Customer savings

Kerosene lamps are very common in Uganda as an alternative to electric lighting. Each lamp typically consumes 3L of fuel per month for 4 hours of light per day [18]. From informal interviews, it was found that the typical end-user price for kerosene in Mpigi is UGX3,500 per liter, resulting in a UGX10,500 per month per lamp cost. From informal interviews, the typical cost of mobile phone charging is UGX500 per charge at charging stations, and phones must be charged every 2-3 days for many customers. Therefore the charging cost for a single mobile phone is about UGX6,000 per month.

Solving for \( P_{12} \) in Equation 11 and then \( P_7 \) in Equation 5, the rental prices for the BB7 and BB12 are UGX4,250 and UGX7,090, respectively. For a household with 2 mobile phones and 2 kerosene lamps providing light for 4 hours per day, the customer pays UGX8,250 per week in phone charging service and lamp fuel. The customer may rent a BB7 PESD twice per week for a total weekly cost of UGX8,500, using the break-even rental value, so there is no financial incentive for this customer. A larger household with 4 mobile phones and 2 kerosene lamps will be spending UGX11,300 per week, so the customer, again, will not find any financial incentive to rent a BB12 PESD biweekly for UGX14,200.

6. Scenario 2: Smaller, In-town System

While the first W2E scenario comes somewhat close to breaking even, the system setup needs improvement. First, the biogas generator imposes a large capital cost on the system, and requires charging a large number of PESDs to be fully utilized. Second, the long distance from the biodigester and biogas generator to the market generates significant fuel costs and requires large amounts of fossil fuel for transportation. Lastly, the PESDs used are incredibly expensive—totaling 100 times the cost of the biogas generator—and become even more expensive if they are unable to be purchased without accompanying solar panels. The following subsections address these issues in an alternative scenario.

6.1. Smaller biogas generator and biodigester

One way to reduce capital costs in the previous scenario, and get closer to making profit, is to reduce the size of the biogas generator. A smaller 600W biogas generator can be purchased for UGX1,000,000 ( $400) that is capable of charging 30 PESDs per week (see Equation 4 with \( P_G = 600W \)). This generator will also have much lower maintenance costs, now adjusted to UGX8,000 per month.

This smaller biogas generator consumes only 0.84m³ of biogas per hour [17], so a 7m³ biodigester will suffice (0.84m³/hr × 8hr/day = 6.7m³/day). Biodigesters of this size can be built closer to cities and many sources of organic waste, such as schools, restaurants and residential communities. Much less waste will be required (about 230kg per week if feed is assumed proportional to biodigester volume), allowing for alternative methods of transporting waste to the biodigester.

6.2. Alternative transportation

Since the biodigester will be located close to the sources of waste, and the amount of waste required is estimated to be less than 25% of the W2E biodigester requirement, alternative methods of waste transportation may be employed. Assuming the biodigester requires 230kg of waste per week, only 33kg needs to be transported per day—the weight of a primary school student. Such an amount can easily be moved by bicycle or handcart, requiring zero fossil fuel and zero fuel cost. Labor costs could even be dismissed if the biodigester is fed primarily with human waste via latrines, though these costs will still be considered nonzero in this scenario.

6.3. Alternative PESDs

Though the BBOXX PESDs appear fit for the PESD distribution service, they “are best suited to accommodate energy needs that range from small to medium households and are widely used to start and maintain a phone
charging business,” [9]. This is apparent in the inclusion of solar panels with every BBOXX kit, which are unnecessary for the PESD distribution service and drive up the cost. If BBOXX is used for this type of service, either the solar panels can be used for ancillary purposes or perhaps the distributor can be convinced to sell the PESDs without the solar panels. However, since the BBOXX charging inputs are easily accessible, customers may attempt to charge the PESDs themselves, thereby subjecting the PESDs to theft or damage.

Another option is to create custom PESDs for the sole purpose of a distribution service. Sealed lead-acid batteries similar to those used in the BB7 PESDs can typically be found for UGX25,000 (US$10) or less in bulk, and the remaining components (enclosure, charging and converter electronics, wall chargers) are estimated at UGX62,500 (US$25) per unit, for a total of UGX87,500 (US$35) per PESD. Due to the BB12 PESDs being much further from breaking even than the BB7 PESDs in Scenario 1, this scenario will assume only BB7-type PESDs. In this scenario, \( N_{PESD} \) is 30 and \( K_{P} \) is UGX87,500 (US$35; \( N_{12} \) and \( K_{12} \) are zero), yielding a \( K_{PESD} \) value of UGX2,630,000 (US$1,050). See Equation 6 for calculation method.

6.4. Costs

Since there are far fewer PESDs to transport and distribute, \( C_{T} \) in this scenario is (conservatively) estimated to be half of \( C_{T} \) in Scenario 1, for a monthly cost of UGX40,000 (US$16). Table 3 summarizes and compares the monthly and capital cost for Scenario 1 and Scenario 2.

| Cost description                  | Symbol | Scenario 1 value | Scenario 2 value | Scenario 1 value (US$) | Scenario 2 value (US$) |
|-----------------------------------|--------|------------------|------------------|-------------------------|------------------------|
| Monthly transportation fuel cost  | \( C_{T} \) | 120,000         | 0                | 48                      | 0                      |
| Monthly labor cost                | \( C_{L} \) | 80,000           | 40,000           | 32                      | 16                     |
| Monthly maintenance cost          | \( C_{M} \) | 30,000           | 8,000            | 12                      | 3                      |
| Capital biogas generator cost     | \( K_{G} \) | 3,750,000        | 1,000,000        | 1,500                   | 400                    |
| Capital PESDs cost               | \( K_{PESD} \) | 307,000,000     | 2,630,000        | 123,000                 | 1,050                  |

6.5. Revenues

Similar to Equation 7, the monthly revenues are the product of rental price of the PESD \( P_{PESD} \), the number of PESDs rented per week \( (N_{PESD}) \), and 4 weeks.

6.6. Cost-revenue comparison

Equation 11 is repeated with cost and revenue values from the second scenario. The program duration \( n \) and discount rate \( r_{mo} \) remain unchanged, and the PESDs are again assumed to require replacement after 18 months. Results from this scenario are presented in Table 4.

7. Conclusion

This paper has presented an approach to provide portable electrification systems that combine the features of battery rental business and a biogas digester operation. An outline of the system features are presented along with detailed engineering and revenue analysis of the system. Two scenarios for the system are considered. In Scenario 1, a rather large centralized biogas digester system with an aggressive penetration is studied. In the Scenario 2, a smaller system that is situated closer to customer locations and waste sources are considered. The results indicate that the per unit rental costs can be much lower for the Scenario 2, due to higher utilization factor and the elimination of transportation costs. Furthermore, Scenario 2 can be launched at a relatively modest cost of $1500/- for a rental business of 30 PESD devices per week, leading to a capital expense of about $50 per unit, in comparison
to a unit cost of about $150 per unit under Scenario 1. This is particularly interesting case of an inversion of the classical ‘economy of scale’ assumption that assumes ‘bigger is always better’.

Table 4. Weekly customer cost of mobile phone charging and kerosene lighting for Scenario 2.

| Item                                                      | UGX  | US$  |
|-----------------------------------------------------------|------|------|
| Current cost: 2 mobile phones, 2 lamps                    | 8,250| 3.30 |
| Equivalent weekly cost of PESD rental                     |      |      |
| Scenario 1                                                | 8,500| 3.40 |
| Scenario 2                                                | 3,740| 1.50 |
| Current cost: 4 mobile phones, 2 lamps                    | 11,300| 4.52 |
| Equivalent weekly cost of PESD rental                     |      |      |
| Scenario 1                                                | 14,200| 5.68 |
| Scenario 2                                                | 7,480| 3.00 |

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