Chapter 4
Integrating a Solar PV System with a Household Based Backup Generator for Hybrid Swarm Electrification: A Case Study of Nigeria

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Abstract Today most of the electrification grids in sub-Saharan Africa (SSA) are found in urban areas. However, these grids experience erratic and frequent power outages for long hours, on average 4.6 h in a day. Due to this problem, many of the African population rely on cheaper but unclean options like backup diesel/petrol generators for lighting, phone charging and other electrical appliances. In Nigeria, millions of people own power generators. These generators are not only noisy but the fuel they use is also costly and result into emissions that pollute the environment. In order to optimize fuel consumption and gradually reduce use of backup generators while increasing share of renewables, a strategy is proposed in this paper to interconnect the existing backup infrastructure to form a bottom-up swarm electrification grid with step by step integration of alternative storages and renewable energy sources. In the swarm-grid excess energy can be generated, sold among grid participants and even at later stage to the national grid. This study

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focused on a swarm grid hybrid node consisting of a solar PV system integrated with the existing individual backup generators for households and retail shop end users. The hybrid system designed was found to be a suitable system with fuel savings of 39%, excess energy of 27% and reduced cost of backup electricity by 34% for the household end user. For the retail shop end user, the hybrid system was found to be a suitable system with a fuel cost saving of 53%, excess energy generation of 28% and reduced cost of backup electricity by 45%. The study showed that integration of a solar PV system has a high potential to reduce fuel costs for backup generator end users and presents a great opportunity for hybrid swarm electrification approach.

Keywords National grid · Stand-alone system · Swarm grid · Renewable energy Excess energy

4.1 Introduction

Sub-Saharan Africa (SSA), a region in Africa where most of the population without access to electricity lives. The percentage population in SSA without access to electricity was about 63% in 2014 [1]. The main source of lighting continues to be kerosene lamps, firewood and candles, especially for regions off the main grid. Furthermore, even those with access to the central main grid often suffer from unpredictable power outages for long hours, on average 4.6 h per day, with 17 countries exceeding the average outage duration [2]. According to World Bank's enterprise surveys, last updated in October 2016, the average number of power outages in firms, in a typical month is 8.5 [3]. Many countries experience frequent outages in SSA with the worst scenario seen in Nigeria with 32.8 outages in a month. Other countries with high cases include; the Central African Republic with 29 outages, Congo 21.5, Chad 19.6, Niger 18.5, and Burundi with 16.6 outages [2]. This has led many people in peri-urban areas and trading centres in many countries in Africa to rely on unclean options like backup diesel/petrol generators for lighting, phone charging, and other electrical appliances.

Besides being noisy and producing emissions that are harmful to the environment, backup generators use fuel which makes them costly to maintain and use in the long run. Taking a case for Nigeria; private households spend over $13.35 million USD annually on alternate sources of energy [4]. This figure adds to over $21.8 billion USD per year if enterprises and manufacturers are also considered [4]. For small businesses, fuel costs account for 40% of their total overheads [5].

Owing to a pressing need to protect the environment, cut down fuels costs and promote energy efficiency, as expressed in the sub-goals of the Sustainable Development Goal (SDG) 7 with its main to ensure access to affordable, reliable, sustainable, and modern energy for all, a strategy is proposed to interconnect this existing backup power infrastructure in a swarm grid and to integrate alternative storage and renewable energy generators step by step. By doing so, it is anticipated

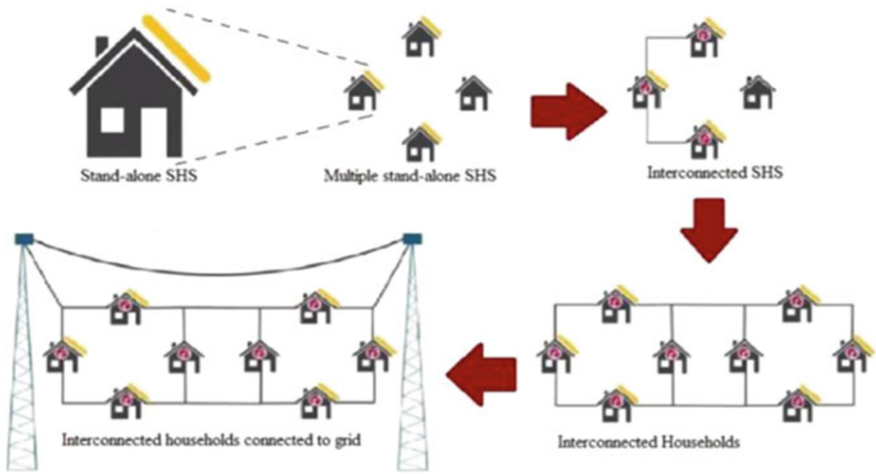

Fig. 4.1 Swarm electrification approach source [6]

that fuel consumption of backup generators could be optimized and gradually reduced, and the share of renewable energy could be increased too. The incremental development of such a grid does not require huge investments from the household or a small enterprise, but can be done using the savings realized on each step. Furthermore, a hypothesis is set up, that each generator in the swarm grid and the swarm grid as a unit can generate excess electricity which can be sold among grid participants and at a later stage even to the national grid. Figure 4.1 shows a representation of swarm electrification approach.

A swarm grid is a grid formed from interconnecting multiple households and small businesses with or without Solar Home Systems (SHS). The concept is known as Swarm Electrification (SE). This concept has been applied in Bangladesh. The end users forming the grid have the ability to share excess energy among themselves. SE allows the households and the small enterprises to become prosumers, i.e. producers and consumers at the same time. As a producer, a node can share or trade the excess energy with its neighbor or as a consumer, a node gets its unmet energy from the neighbors [6]. In a swarm grid a node represents a consumer and/or producer end user.

This paper proposes a strategy of forming a hybrid swarm grid with more than one source of energy in the grid as a whole, and at some nodes in particular. In the following steps, the proposed strategy is described one by one:

1. Integrating an existing generator into a swarm-grid and smart electricity management unit.

   - Excess energy is generated while operating a generator at an optimal point efficiency i.e. 80%.

- The energy can be shared and traded between swarm-grid participants, unlocking capital.

2. Using the capital to invest into batteries, excess energy generated from constantly operating the generators at an optimal point can be stored.
3. The electricity stored in the battery (ies) can be used instead of the generators.

   - This reduces the usage hours of a generator hence prolonging its lifespan.

4. Solar PV panels or other renewable energy sources can be integrated to the swarm-grid at the nodes. They can be used as a direct source of power and for charging the batteries.

   - Fuel can be saved; excess energy is generated from solar.
   - More energy can be shared and traded, unlocking capital for further investment.

5. Step by step, according to the needs, such a grid can grow by adding storage and generation capacities. More users can be integrated and trade with the electricity.
6. Generation and storage capacities might not only be used for backup during power outages but also for extended periods during the day, replacing step by step the power from the grid.
7. When the swarm-grid grows large enough and produces enough excess energy, interconnection with the national grid and a feed in-option can be considered.

This type of grids can grow organically. Each step is voluntary. The economic viability of each step still needs to be proven. The schematic representation of the hybrid swarm grid is shown in Fig. 4.2.

In Nigeria, according to a survey by [7] in the states of Delta, Bayelsa and Rivers, 43% of households with grid connection use backup generators for at least 4 h. Also 40% of the small enterprises with grid connection have less than four hours of electricity supply in a day. In a hybrid swarm grid, a prosumer can be a hybrid node (with more than one energy source at the node) and hence benefits from the merits of combined power sources. A household or small enterprise with a backup fossil-fuel generator could become such a hybrid node by integration of battery and solar PV generator as described in steps 3 and 4 above.

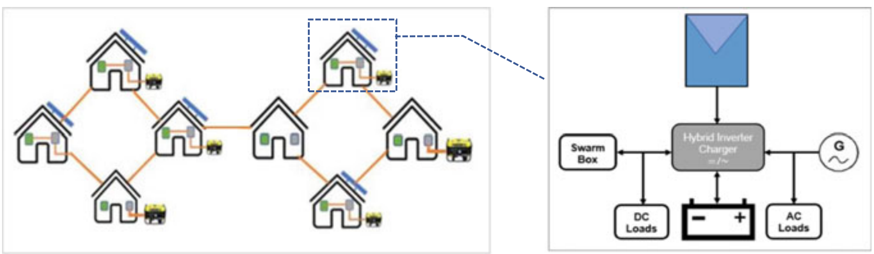

Fig. 4.2 Hybrid swarm grid and a hybrid node

This study focusses on the hybrid node of a swarm grid. With the main objective of contributing to a hybrid swarm grid, the study aimed at designing a hybrid node by integrating a solar PV system for a potential benefit of fossil-fuel savings. The focus was also to quantify excess energy production and determine its potential for sharing in a hybrid swarm grid.

4.2 Methodology

The three states of Bayelsa, Delta and Rivers in Nigeria were chosen as the study areas. The solar energy potential for the study area was determined based on the solar radiation database for PV performance estimation in Europe and Africa [8]. From the literature in [9–11], load profiles were developed for the household and a small enterprise end users as shown in Figs. 4.3 and 4.4.

From the load profiles, the energy demands were estimated, the hybrid units designed controlled by the technical and economic parameters. The energy production and use for the hybrid units designed was further assessed for potential excess energy generation.

4.2.1 *Solar Energy Demand*

The daily solar energy demand is the solar energy required to charge the battery and as a direct power source in the day [12].

$$W_{pv} = W_{pvbat} + W_{pvday} \tag{4.1}$$

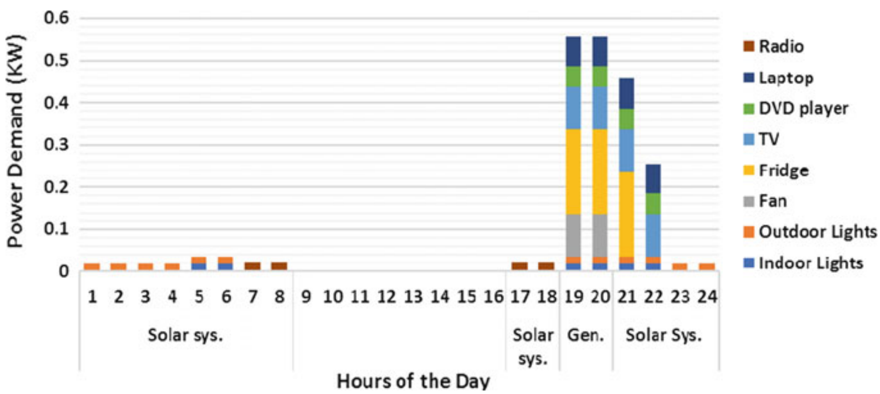

Fig. 4.3 Household end user load profile

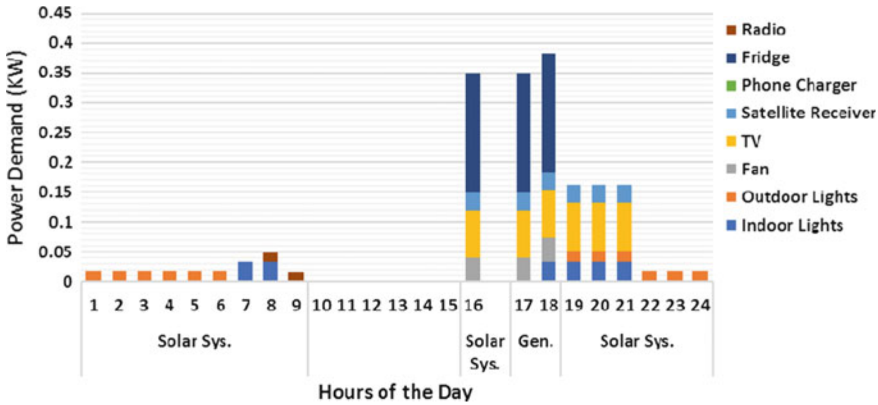

Fig. 4.4 Retail shop end user load profile

where W_{pvbat} is solar energy demand to charge the battery, W_{pvday} is solar energy demand for direct load supply during the day.

4.2.2 Battery Storage

The battery is considered like a pot used to store water during the day for later use at night. The method (7) [12] given below is used to size the battery storage;

$$B_B = \frac{E_{bat} \times AD}{V_s \times DOD \times \eta_{inv}} \tag{4.2}$$

where B_B is battery storage size in Ampere hours (Ah), E_{bat} is energy storage demand (Wh), AD is autonomous days, V_s is system voltage, DOD is depth of discharge (60%), η_{inv} is Inverter efficiency (90%).

$$E_{bat} = E_{bat\_night} + (E_d \times 10\%) \tag{4.3}$$

where E_{bat_night} is energy storage demand by loads at night, E_d is day time load energy demand.

In this study, 10% of the day time energy demand is stored to take care of abrupt changes in solar radiation due to swift movements of clouds.

4.2.3 Backup Fossil-Fuel Generator

The rated size of backup generator considered in this study is 1.0 kW each for the household and the small enterprise users, the size is big enough to power the peak demands in the load profiles of the users.

4.2.4 System Solar PV Production

The method applied for the daily estimation of the PV performance is given below [13];

$$P_{pv} = P_{wp} \times \frac{G}{G'} \times \left[1 + \alpha_t \left(T_a - T_{ref}\right)\right] \tag{4.4}$$

where P_{pv} is daily power output of the PV panels at a time, P_{wp} is total PV watt peak under reference conditions, G is daily solar irradiation (W/m^2) at optimal angle (11°), G' is the reference solar radiation (1000 W/m^2); T_a is the daily ambient temperature, and T_{ref} is the reference temperature (25 °C); α_t is the PV panel temperature coefficient; for mono and poly crystalline silicon materials.

4.2.5 Excess/Unmet Energy

Due to the day to day changes in weather, the daily energy production from solar is not the same. On brighter days, the solar irradiations are high and hence high energy production. This energy can be more than what is needed in a day resulting in excess energy and hence is put to waste if not utilized. By performing the solar energy production and consumption analysis, excess/unmet solar energy generation is assessed on daily basis. Excess energy is the energy that could be generated if the battery had not been fully charged or if there was an extra load to be supplied. In this study, the total daily solar energy demand is assumed to be constant in a year.

$$Excess/Unmet_{Energy} = P_{pv} - W_{pv} \tag{4.5}$$

If Eq. (4.5) gives a positive number, it is excess energy and if a negative number, it is unmet energy. During cloudy days or in the rainy season when the unmet energy is most generated, backup fossil-fuel is used to meet the unmet energy.

4.2.6 Economic Analysis

The Annualized Cost of the System (ACS) obtained from Eq. (4.6) is the cost of the system spread or discounted yearly over the whole system lifetime [14].

$$ACS = ACC + AOM + ARC + AFC \tag{4.6}$$

where ACC is the annualized capital cost, AOM is the annualized operation and maintenance cost, ARC is the annualized replacement cost, AFC is the annualized fuel consumption cost.

$$\begin{aligned} ACC &= C_c \times CRF(i', n) \\ CRF &= \frac{i'(1+i')^n}{(1+i')^n - 1} \\ i' &= \frac{i-f}{1+f} \end{aligned} \tag{4.7}$$

where C_c is the capital cost ($ USD), CRF is the capital recovery factor, n is the lifetime of the component in years, f is the inflation rate, i is the nominal interest rate.

$$\begin{aligned} ARC &= C_{rep} \times K - ASV \\ K &= N_{rep} \times SFF(i', n) \\ N_{rep} &= \frac{y}{n} - 1 \text{ if } y \text{ is divisible by } n \\ N_{rep} &= INT\left[\frac{y}{n}\right] \text{ if } y \text{ is not divisible by } n \\ SFF &= \frac{i'}{(1+i')^n - 1} \end{aligned} \tag{4.8}$$

where y is the lifetime of the system, N_{rep} is number of replacement, ASV is annualized salvage value, SFF is sinking fund factor.

$$ASV = S \times SFF(i', y) \tag{4.9}$$

If y is not divisible by n, the salvage value, S of the replaceable component is determined as in [9], with R_l being the remaining life of the component in years.

$$\begin{aligned} S &= C_{rep} \times \frac{R_l}{n} \\ R_l &= n - \left(y - \left(N_{rep} \times n\right)\right) \end{aligned} \tag{4.10}$$

The AOM and the AFC are determined as in [14]

$$AOM = \frac{C_c \times (1 - \mu)}{n}$$
$$AFC = C_f \times f_E \times \sum_{t=1}^{365} E_{gen} \tag{4.11}$$

where C_c is the capital cost, μ is the reliability of the component and n is the lifetime of the component.C_f is the fuel cost per litre in $ USD/l, f_E is the fuel consumption per unit energy (l/kWh), E_{gen} is the backup fossil-fuel generator daily energy output (kWh).

4.2.7 Levelized Cost of Backup Electricity (LCoE)

The cost of energy paid for the electricity produced and used in a year is computed using Eq. (4.12) where E_{year} is the electrical energy consumed in a year.

$$LCoE = \frac{ACS}{E_{year}} \tag{4.12}$$

4.3 Results and Discussion

A hybrid node is designed each for a household and a small enterprise. The results are discussed below in comparison to the baseline system of having a fossil-fuel backup generator.

4.3.1 Technical and Economic Analysis

The technical and economic results for the designed hybrid systems are as shown. From Table 4.1, the baseline system consists of the fossil-fuel backup generator as the main power source during power outage. The designed system is the hybrid system to be at a node of a swarm grid consisting of both a fossil-fuel backup generator and the PV system generator.

From Table 4.2, the designed hybrid systems are more cost effective than the baseline system by the end of their life time, as shown by lower values of the annualized costs of the systems. The levelized cost per unit of energy used is also lower for the designed system. The system costs are less due to reduced fuel consumption costs. The fuel costs reduced because of reduced usage hours of the fossil-fuel generators as more solar energy is used.

Table 4.1 Technical analysis for the end user systems

End users	System components	Generator (kW)	Battery (Ah)	Inverter (VA)	Solar PV (Wp)
Household	Baseline system	1.0	–	–	–
	Designed system	1.0	150	850	300
Retail shop	Baseline system	1.0	–	–	–
	Designed system	1.0	200	500	400

Table 4.2 Economic analysis for the end user systems

End users	Economic parameters	AFC ($ USD)	LCoE ($ USD/ kWh)	ACS ($ USD)	ICS ($ USD)
Household	Baseline system	349.12	0.574	381.89	137.3
	Designed system	213.48	0.447	357.81	932.1
Retail shop	Baseline system	299.74	0.582	332.51	137.3
	Designed system	140.96	0.403	320.01	1069.6

However, the Initial Cost of System (ICS) is higher for the designed hybrid systems as compared to the baseline systems. This could highly prevent the end users from integrating solar PV generator systems. Nevertheless, inclusive and flexible financial solutions could be used to make the systems more affordable as payment would only apply for the integrated solar PV system since the fossil-fuel generator as the baseline is already owned by the end users.

4.3.2 Energy Analysis

The production and consumption of different energy sources for the hybrid systems are analysed. Solar PV production and use in particular is also analysed. Excess energy potential is assessed and it is on that basis that recommendation for energy sharing in swarm grid is made.

From Fig. 4.5, fossil-fuel generator is still slightly used more throughout the year than the integrated solar energy for the household end user, however, its use has reduced to 51% with 49% integration of solar PV system as indicated in Fig. 4.6.

Figure 4.7 shows solar energy production is high at beginning and towards the end of the year. With the demand maintained constant, total excess solar energy of 27% is found for the household as illustrated in Fig. 4.8. The excess energy is

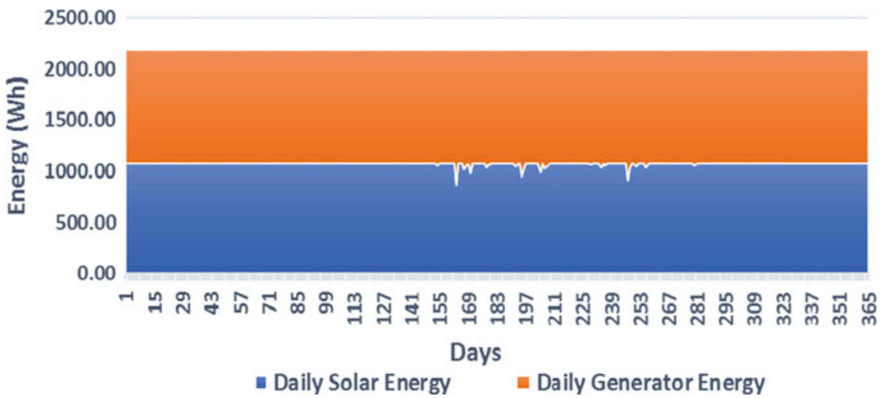

Fig. 4.5 Household end user energy consumption analysis

Fig. 4.6 Household energy mix

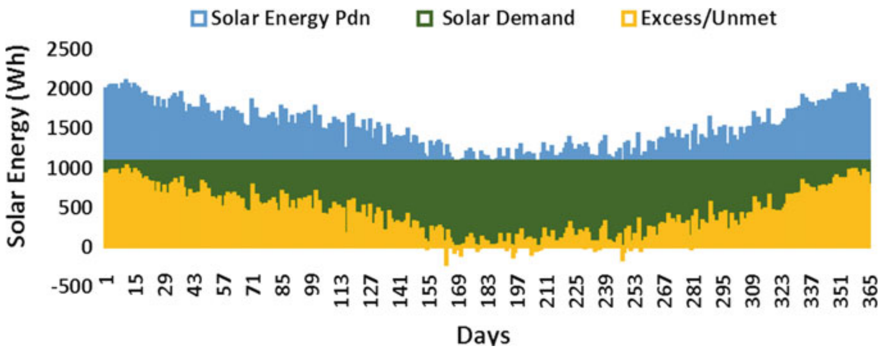

Fig. 4.7 Household end user solar energy production analysis

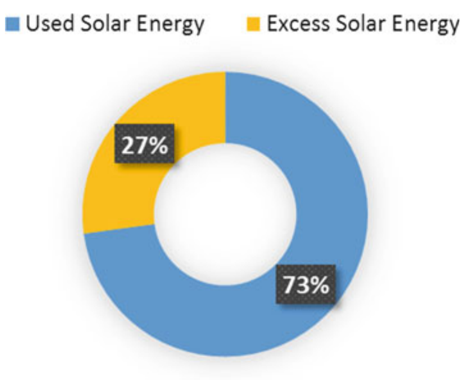

Fig. 4.8 Household end user ratio of excess solar energy

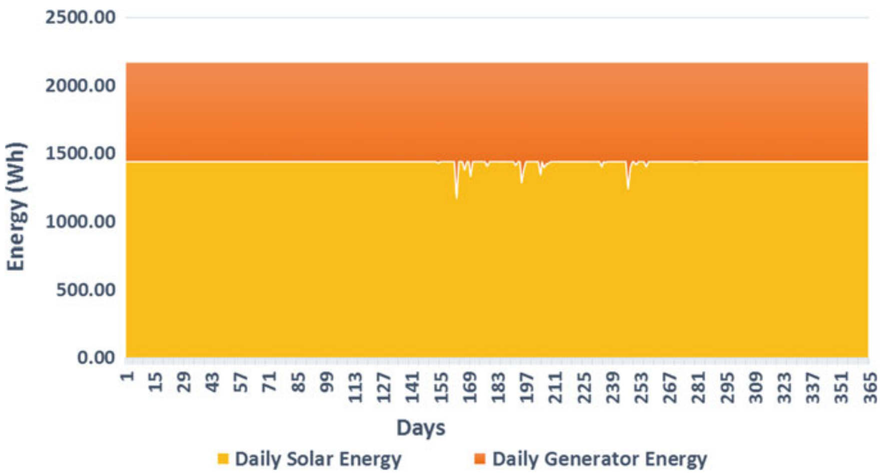

Fig. 4.9 Retail shop end user energy consumption analysis

generated on daily bases except in the middle of the year during rainy season when unmet energy is realized. The unmet energy is then supplied by the fossil-fuel generator as shown in Fig. 4.5.

For the retail shop enterprise, the integrated solar energy PV system becomes the main source throughout the year. Solar energy accounts for 66% of the daily use and fossil-fuel generator, 34%. See Figs. 4.9 and 4.10.

Figure 4.11 for the retail shop end user shows solar energy production is high at beginning and towards the end of the year similar to the household end user as they are of the same geographical location. The fossil-fuel generator is used to meet the unmet solar energy in the rainy days especially in the middle of the year, see Figs. 4.9 and 4.11. Like for the household, the excess energy for the retail shop end user is found to be 28% (Fig. 4.12) and is also generated on daily bases.

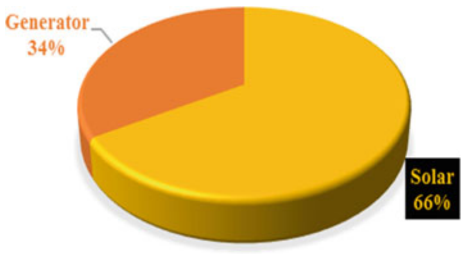

Fig. 4.10 Retail shop end user energy mix

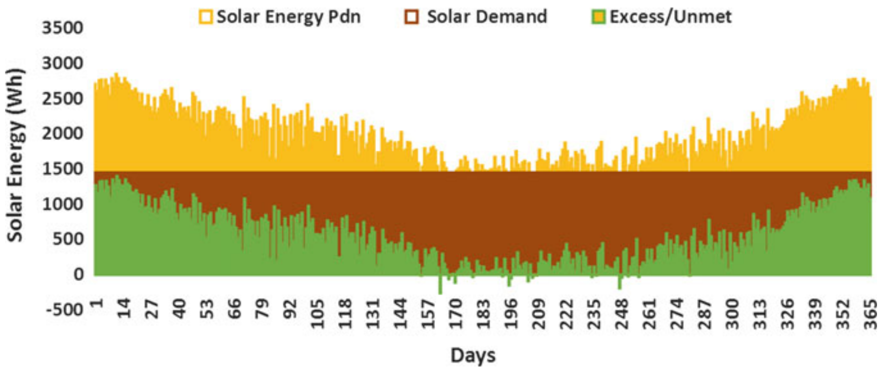

Fig. 4.11 Retail shop end user solar energy production analysis

Fig. 4.12 Retail shop end user ratio of excess solar energy

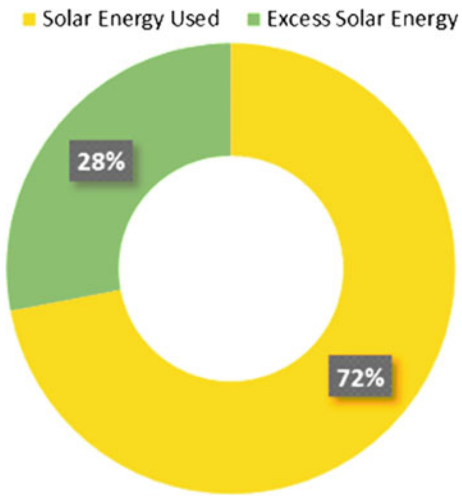

Table 4.3 Summary of results

End users	Systems	LCoE ($ USD/kWh)	Reduction in LCoE (%)	AFC ($ USD)	Reduction in AFC (%)	Excess energy (Solar) (%)
Household	Baseline	0.574	–	349.12		
	Designed system	0.447	22	213.48	39	27
	Designed system (Swarm grid)	0.378	34			
Retail shop	Baseline	0.582	–	299.74		
	Designed system	0.403	31	140.96	53	28
	Designed system (Swarm grid)	0.321	45			

4.3.3 Hybrid Swarm Grid Assessment

The result of excess solar energy found in this study is similar to that of Kirchhoff, in which he found an excess energy of 30% of the potential solar energy production from a single solar home system [15], a typical case of Bangladesh. In a swarm grid the excess energy can be utilized instead of being wasted. Also, the excess energy can be utilized by connecting more loads when swarm grid infrastructure is still missing.

In a swarm grid where excess solar energy can be traded, Table 4.3 shows that the LCoE could reduce by 34% for the household and 45% for the retail shop end users operating as hybrid nodes in a hybrid swarm grid. In comparison to Bangladesh, the reduction in LCoE in this study is higher. This is a result of reduced use of fossil fuel generators while the systems in Bangladesh are purely single source solar home systems. The reduction in LCoE would enable the end users to access reliable and a more affordable electricity while supporting neighbors by trading excess energy in a swarm grid.

4.4 Conclusion

Power outages in SSA occur at a high rate, the situation is more alarming in Nigeria. This has resulted into high reliance on fossil-fuel backup generators for most households and small enterprises. However, these generators are noisy and their fuel is costly. This study looked at a stepwise strategy of integrating solar PV system with a backup household-based generator interconnected in a swarm grid for a potential benefit of fuel savings and environmental protection in line with SDG 7. The study focussed on the hybrid node of the swarm grid. From the result, a potential fuel savings and overall system cost reduction is found. Integrating solar, hence increases the share of renewable energy mix for the end users, generates excess energy that can be shared in a swarm grid by the grid participants. The overall result is that swarm grid would enable the energy consumers to become prosumers capable of sharing or trading energy produced among themselves. However, for a successful implementation of this concept in SSA, the social-cultural aspects of sharing electricity in a swarm grid should be investigated.

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