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(Including Climate Change)

Integrating a Solar PV System with a Household based backup Generator for Hybrid Swarm Electrification in sub-Saharan Africa: case study of Nigeria

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PAUWES/343/15

Date: 4/09/2017

Master in ***Energy, Engineering track***

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Academic Year: 2016-2017

DECLARATION

I, *Muceka Rolex*, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

Electrification approaches in sub-Saharan Africa (SSA) has mainly been through centralized national grids besides mini-grids and other stand-alone systems. The existing grids are mainly found in urban areas, leaving many African population living in the rural areas without access to electricity. However, even some of those in peri-urban and urban areas who have access to electricity through connection to the centralized national grid suffer from erratic and frequent power outages for long hours, on average 4.6hours in the whole of SSA. Due to this problem, many of the population rely on 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; the fuel they use are also costly and result in greenhouse gas emissions like carbon dioxide polluting 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 thesis 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 focused on the integration of solar PV system to the existing individual backup generators for the household and the retail shop end users. Three systems are designed, and the hybrid system is found to be the preferred system for the household user with fuel savings of 39%, excess energy of 27% and reduced cost of backup electricity by 34%. The hybrid system for the retail shop is also found to be the most suitable system among others with fuel cost savings of 53%, excess energy generation of 28% and reduced cost of backup electricity by 45%. The study found that integration of a solar PV system has a high potential to reduce fuel costs for the backup generator end users and could contribute to a hybrid swarm electrification approach.

Key Words: National Grid; Stand-alone System; Swarm grid; Renewable Energy; Excess Energy

RESUME

Les approches d'électrification en Afrique subsaharienne (ASS) ont principalement été réalisées à travers des réseaux électrique nationaux centralisés, à côté des mini-réseaux décentralisés et d'autres systèmes autonomes. Les réseaux existants se retrouvent principalement dans les zones urbaines, laissant de nombreuses populations africaines vivant dans les zones rurales sans accès à l'électricité. Cependant, même certains de ceux qui vivent dans les zones urbaines et périurbaines ayant accès à l'électricité par le biais du réseau national centralisé souffrent de pannes d'électricité erratiques et fréquentes pendant de longues heures, en moyenne 4,6 heures dans toute l'Afrique subsaharienne. En raison de ce problème, plusieurs africains s'appuie maintenant sur des options d’énergie fossile, comme les groupes électrogènes de secours fonctionnant avec du diesel ou l’essence pour l'éclairage, la charge du téléphone et d'autres appareils électriques. Au Nigéria des millions de personne possèdent des groupes électrogènes. Ces groupes électrogènes produisent non seulement des bruits ; Le carburant qu'ils utilisent est également coûteux et entraîne des émissions de gaz à effet de serre, comme le dioxyde de carbone polluant l'environnement. Afin d'optimiser la consommation de carburant et de réduire progressivement l'utilisation des groupes électrogènes de secours tout en augmentant la part des énergies renouvelables, une stratégie est proposée dans cette thèse pour interconnecter l'infrastructure de secours existante pour former un réseau d'électrification ascendante en essieu avec intégration progressive d'entreposage alternatif et Sources d'énergie renouvelables. Dans l’ensemble du réseau, l'excès d'énergie peut être généré, vendu entre les abonnés du réseau et même plus tard au réseau national. Cette étude a porté sur l'intégration du système PV solaire aux groupes électrogènes de secours individuels existants pour les utilisateurs finaux et les détaillants. Trois systèmes sont conçus et le système hybride est le système préféré avec une économie de carburant de 39%, un excès d'énergie de 27% et un coût réduit de l'électricité de secours de 34% pour l'utilisateur du ménage. Le système hybride pour le magasin de détail est également considéré comme le système le plus approprié, entre autres, avec des économies de coûts de carburant de 53%, une production d'énergie excédentaire de 28% et un coût réduit de l'électricité de secours de 45%. L'étude a révélé que l’intégration d’un système solaire PV a un potentiel élevé pour réduire les coûts du carburant pour le groupe électrogène de secours des consommateurs et pourrait contribuer à l'approche hybride de l'électrification de l’ensemble du réseau électrique.

Mots Clés: Réseau électrique nationale; Système autonome; ensemble du réseau; Énergie renouvelable; Excès d'énergie.

ACKNOWLEDGEMENT

First and foremost, I am so grateful to the Almighty God for His abundant grace, knowledge and wisdom upon me which enabled this work to reach its completion.

I would like to extend my sincere thanks to Noara Kebir; the managing director of MicroEnergy International (MEI) for not only hosting me during my stay in German; for being more like a mother to me. I am grateful to her and her family including Henning Marxen, for their precious guidance, advice and physical exercise.

Furthermore, I want to thank my supervisor Dr. Sebastian Groh, and the team of MicroEnergy International including Daniel Phillip, Noara Kebir, Fredy Cañizares, Steffen Eyhorn, Setu Pelz, Hannes Kirchhoff and Raluca Dumitrescu. During the period of the work, they asked very important questions and gave vital advice for the structure and content of this master thesis. Also, I want to thank all my internship colleagues in MEI, they played a great role in the social part of my stay in Berlin.

Lastly but not the least, I thank PAUWES management for their support throughout the course of the two years master program in Energy Engineering in Algeria. I do appreciate the transport facilitated by PAUWES to go to German in the course of this master thesis work. Without forgetting the colleague students of PAUWES in my cohort, I am forever grateful to them for their support, knowledge, and fun shared during the two years of study.

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LIST OF ABBREVIATIONS

SSA	Sub-Saharan Africa
SME	Small and Medium Enterprises
SHS	Solar Home Systems
SE	Swarm Electrification
MTF	Multi-Tier Framework
USD	United States Dollars
PV	Photo-Voltaic
DC	Direct Current
AC	Alternating Current
TWh	Tera-Watt hours
KW	Kilo-Watts
$\mathbf{W_p}$	Watt peak
KWh	Kilo-Watt hours
VA	Volt Amperes
KVA	Kilo-Volt Amperes
Ah	Ampere hours
ACS	Annualized Cost of System
AOM	Annual Operation and Maintenance cost
ARC	Annualized Replacement Cost
AFC	Annual Fuel Cost
ICS	Initial Cost of System
LCoE	Levelized Cost of backup Electricity

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CHAPTER ONE: INTRODUCTION

1.1 Background

For many years electrification in sub-Saharan Africa (SSA) has been through centralized grids as it’s the case in most parts of the world. This has left many without access to electricity especially the majority of African population living in rural areas. According to World Bank, in 2015 about 62% of people in SSA live in rural areas [1]. The grid extension has taken too long and the timeline for an extension to reach very remote areas appears uncertain.

In addition, even those with access to electricity through centralized grid suffer from erratic and rampant power outages for long hours, on average 4.6 hours per every outage in the whole of SSA[2]. This has led many people in peri-urban areas and trading centers in many countries in Africa to rely on unclean options like backup diesel/petrol generators for lighting, phone charging, and other electrical appliances.

The backup generators are not only noisy; the fuel they use are costly and result in carbon dioxide emissions polluting the environment. Nigeria is a good example to show case this issue: According to [3], private households in Nigeria spend over $13.35 million USD annually on alternate sources of energy[3]. This figure adds to over $21.8 billion USD per year if enterprises and manufacturers are also considered [3]. For small businesses in Nigeria, fuel costs account for 40% of the total overheads [4].

Running diesel generator at low loading rate results in an ineffective fuel management as compared to a rate of at least 50% of its rated capacity [5]. In addition, synchronous speed generators running at low electrical load output power, are far from achieving their optimum efficiency. In some cases, in order to manage the variation in consumption pattern, some consumers own two generators (small and big). Small generators are turned on when the load is light and bigger generators are switched when the load increases [6].

For the reason of environmental protection, energy efficiency, and fossil fuel cost reduction, strategy is proposed to interconnect this existing infrastructure in a swarm grid and to integrate alternative storages and renewable energy generators step by step. Doing so, fuel consumption of backup generators could be optimized and gradually reduced and the share of renewable energies increased.

The incremental development of such a grid does not require huge investments from the household or the SME, 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.

The concept of interconnecting multiple households and Small businesses with or without Solar Home Systems (SHS) to form a grid with the ability to share excess energy among themselves is known as Swarm Electrification (SE)[7] as shown in Figure 1-1 below.

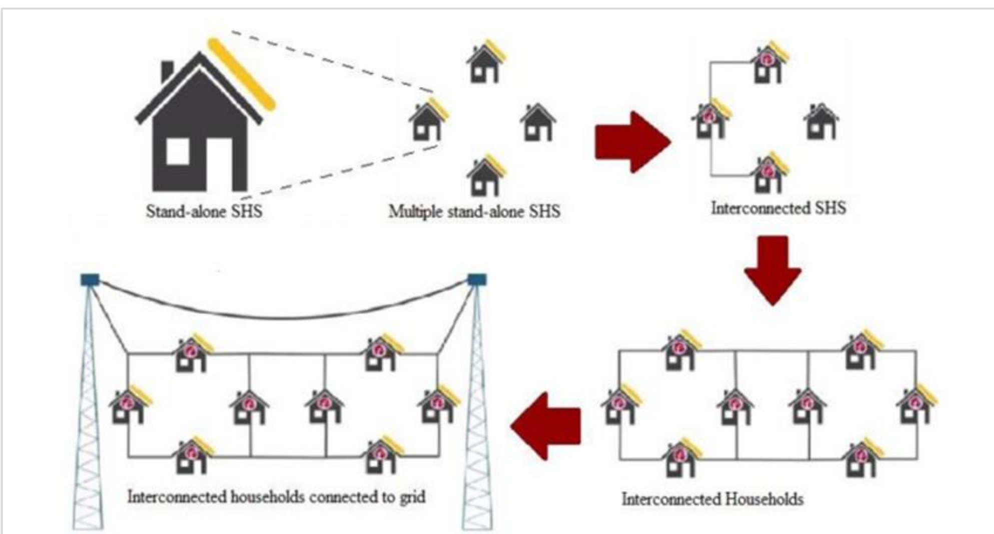

Figure 1-1. Swarm electrification approach [8]

The interconnection of solar/generator energy units into swarm-grids could be referred to as hybrid swarm electrification. A hybrid swarm electrification grid has at least a node (participating household or enterprise) with an alternative generator or another source of energy other than solar energy. With some nodes having hybrid energy systems, electricity duration of supply in hybrid swarm-grids could be prolonged at night or on cloudy days.

SE allows the households and the small enterprises to become prosumers, being both a producer and a consumer at the same time [7]. 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.

In the following, the steps are 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
    - 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 batterie(s) 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 be not only 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 structure and high costs of a backup infrastructure as it exists in Nigeria and other SSA countries with an insufficient power grid is a challenge and in the same time an opportunity for the integration of renewable energies. Solar energy resource is above 2000KWh/m^2/year in more than 39 African countries, and solar PV in a particular has experienced a tremendous reduction in cost over the past recent years [2].

The commonly used generators by the Nigerian households and small enterprises range from 650VA to 6.5KW. The generators are operated for 3-6 hours depending on the user [9]–[11]. A 2.6KW backup generator costs $137.25USD according to [10]. However, a replacing such a generator with a solar PV can result in a much higher initial investment for the same power capacity from a backup generator. In a hybrid swarm-grid, a prosumer with a hybrid or combined energy source can benefit from the merits of combined power sources.

Multi-Tier Framework (MTF) developed by Energy Sector Assistance Management Program (ESMAP) of World Bank defines different tiers for measuring the quality of electricity access for different type of endusers, such as households or businesses. According to the MTF for household electricity supply as shown in Table 1-1, the better the capacity, the availability, the reliability, the quality, the affordability, the legality and the safety of electricity access, the higher the tier. In this thesis, a system is considered, that integrates a solar PV alongside a backup generator operating in a hybrid swarm grid in order to ensure a consumer stays in the same tier or improves his situation by moving to a higher tier.

Table 1-1 MTF for measuring access to household electricity supply [12]

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

1.2 Problem Statement

Electrification rate remains low in Africa, over 485 and 105 million people in rural and urban Africa respectively, still lack access to affordable and sustainable energy [13]. Electrification is mainly through central grids, and over 50% of the transmission network in Africa is at least 30 years old. With the high need for investment in the grid infrastructure, which is often not done, maintenance challenges have led to common power blackouts seen on the African content. Other challenges to the central grid include drought related to climate change affecting hydropower stations, increased demand growth that the currently installed capacities cannot support [2].

The population in the urban and peri-urban areas are faced with unreliable supply of power. A frequent power outage that lasts for long hours with an average of about 4.6

hours is observed across SSA [2]. According to World Bank data [14], an average number of power outages across SSA in a typical month is 8.5, with the worst scenario seen in Nigeria with 32.8 outages in a month. As such many Nigerian households and businesses rely on backup generators. According to the Energy Commission of Nigeria, over 60 million Nigerians own power generators, implying high penetration of individually based generators [9].

High fuel cost is incurred by Nigerian households amounting to over $13.35 million USD every year [3]. For businesses, fuel expenses account for over 40% of the total overhead costs [4]. Generator fuel consumption also depends on the electrical load output. At low electrical load operating a generator results in a poor power and fuel efficiency. Some consumers have both small and big generators in order to manage the variation in electrical load output that changes with consumption pattern [6]. However, for consumers with a single backup generator, operating a generator at a time of low energy consumption can cause ineffective fuel management.

1.3 Justification and Practical Relevance

In this study, a unique and stepwise strategy is proposed to integrate a solar PV as a fuel saver, along with the backup generators operating in a hybrid swarm-grid. The underlining practical relevance could be the overall improvement in the tier of electricity access according to the MTF. This study attempts to increase the quality, reliability and the affordability of electricity access including the operating efficiency of the backup generators.

Different from other studies [15]–[18] which suggest standalone or hybrid systems to reduce dependence on backup generators, this study points out an innovative way to integrate solar PV and share excess electricity with neighbors by interconnecting in a swarm-grid enabling those without backup solutions to have electricity access during power outages. Hence, SE approach could serve to be a complement to avert the challenges faced with the existing electrification approaches of national grid and the individual backup generators.

1.4 Research Questions

- Considering the high penetration and frequent use of backup fossil-fuel generators in Nigerian households and SMEs, how can the fuel consumption of these individual energy systems be reduced step by step through the integration of Solar PV systems?
- Can the resulting hybrid systems produce excess energy for sharing in a swarm-grid? What could be the potential of the excess energy generated from these hybrid energy units?

1.5 Main Objective

Contribute to the development of a hybrid swarm-grid by designing a technical and economically feasible energy systems for end users through integration of solar PV systems with the existing backup generators.

1.6 Specific Objectives

1) Design separate energy systems for a household and retail shop end users
2) Determine annualized cost of these systems
3) Assess the daily energy generation and consumption of these systems
4) Determine the carbon dioxide emissions for the suitable systems

1.7 Scope

In this study, seven steps of a strategy to integrate solar PV system as fuel savers alongside a backup fossil-fuel generator interconnected in a hybrid swarm-grid is given as described in the background section 1.1. Out of the seven steps, the scope of this study covers some of the aspectes steps 1-4.

The study focuses on designing a technical and economic viable separate energy systems to assess the integration of a solar PV system as fuel saver. Step 4 is limited to finding excess energy to be shared in the proposed swarm-grid.

The geographical scope is limited to SSA, in particular, the Rivers state in Nigeria. The economic feasibility being assessed is focused on determining the annual cost of the systems as discounted over their lifetime, the initial cost, the levelized cost of their backup electricity, and the annual fuel cost savings. The design and analysis of the systems are limited to a fixed period of power outage in the evening.

1.8 Structure of the Thesis

This thesis report consists five chapters as described in a structure below

Chapter One: Introduction

Includes the background overview of the main insights of the study, the problem statement, the research question, the objectives and the scope.

Chapter Two: Literature Review

Here, the magnitude of power outages and the use of backup generators in SSA and Nigeria, in particular, is reviewed. A critical comparison is done for conventional electrifications approaches of central grid extension, mini-grids, and stand-alone solar home systems with swarm electrification approach. The working principle of swarm electrification and field experience in Bangladesh is also given.

Chapter Three: Methodology

This chapter gives the description of the study area, required data, the design criteria and the main methods used. The methods for calculating the energy demand, the solar PV size, the battery storage and the daily solar PV energy production are described. Also, the equations for calculating the annual cost of the systems, levelized cost of electricity are presented. Lastly, in this chapter, the calculation of the carbon dioxide emissions is given.

Chapter Four: Results and Discussion

In this chapter, the main results are given and discussed. The results include the sizes of the designed battery, solar PV to be integrated. The fuel cost savings, saving on the annual cost of the designed system, the proportion of excess energy generated in a year for swam electrification. The carbon dioxide emission reduction for the designed hybrid systems of the prosumers.

Chapter Five: Conclusion and Recommendation

It includes the conclusion and the recommendations for future research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Usage of Backup Diesel/Petrol Generators in Sub-Saharan Africa

Sub-Saharan Africa (SSA), a region in Africa where most of the population without access to electricity lives. The population in SSA without access to electricity is about 63% in 2014 [13]. They rely on kerosene, firewood, candles, and fuel based generators especially for regions off the main the grid. Meanwhile, even those with access to the central or mini-grids often suffer from unpredictable power outages for long hours, on average 4.6 hours 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 [14]. Many countries experience frequent outages in SSA with worst scenario seen in Nigeria with 32.8 outages in a month. Other countries include; the Central African Republic with 29 outages, Congo 21.5, Chad 19.6, Niger 18.5, and Burundi with 16.6 outages [2] as shown in Figure 2-1 below.

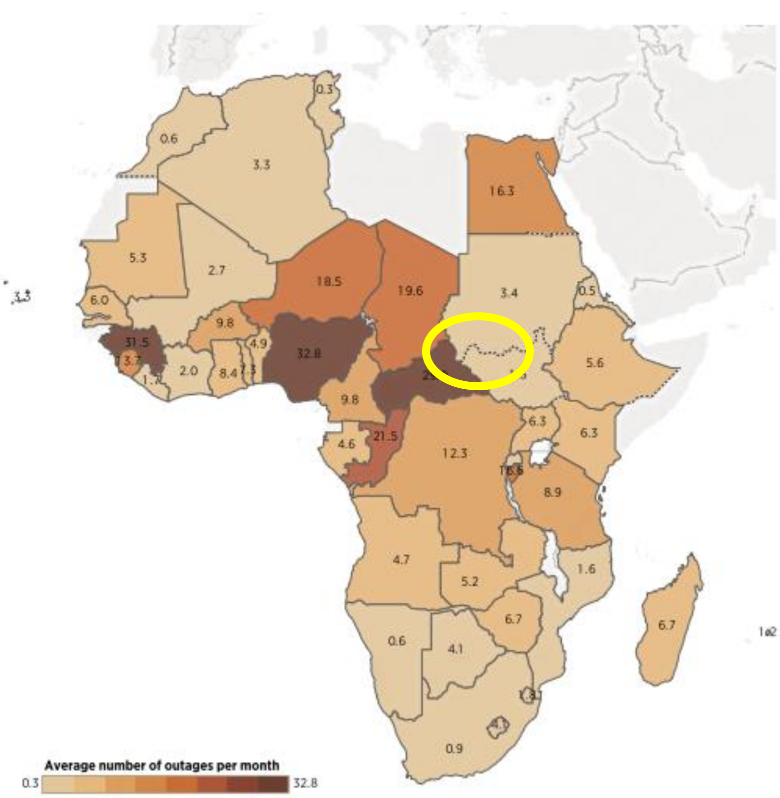

Figure 2-1. Map of Africa showing number of power outages in a month [2]

As a result of the frequent power cuts, many of the electricity consumers rely on small fossil-fuel based backup generators. Using these backup generators can be expensive due to continues expenses incurred for fuel. Those without backup source suffer from the problems of not having access to electricity during power outages. The generators are not environmentally friendly; they cause pollution through comparably high greenhouse gases including carbon dioxide emissions.

The Figure 2-2 below shows the energy produced from small backup generators from the different regions in SSA. From the figure, across SSA, the total electrical energy generated from the backup generators in 2012, was about 16TWh, and Nigeria accounts for three-quarters of this energy [19]. Other regions like Central, East and Southern Africa have low contributions.

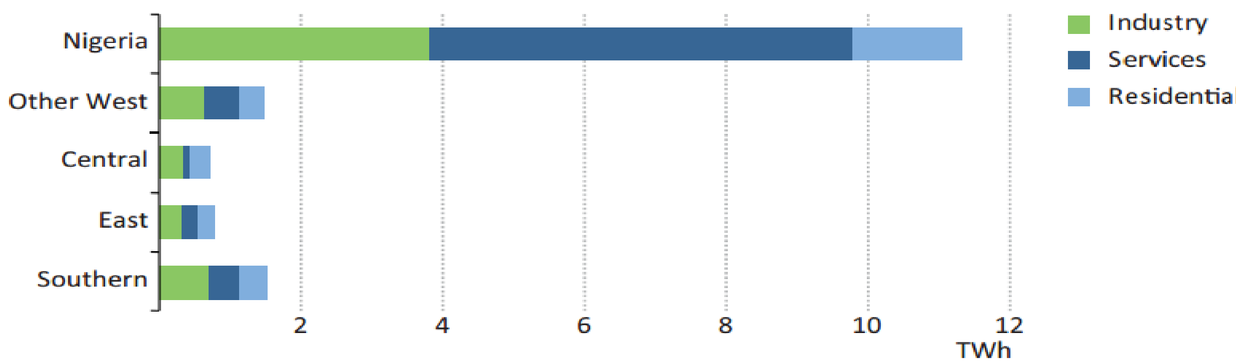

Figure 2-2. Electricity Demand met by backup generators, 2012 [19]

The number of firms in the different countries in SSA rely on backup generators due to high unreliability and inadequacy of grid connected power. Sierra Leone, Nigeria, and Chad have the highest use of backup generators. Meanwhile, Mauritius, Botswana, Senegal, and Gabon are among the countries with low dependence on backup generators as shown in Figure 2-3 below further indicates.

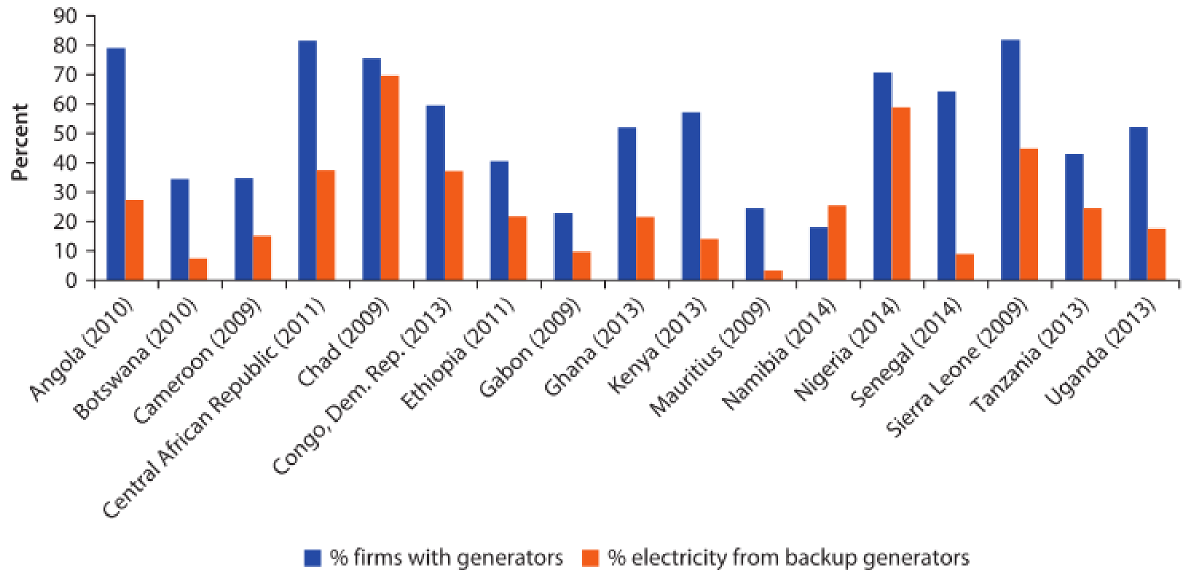

Figure 2-3. Percentage of firms relying on generators; various years [20]

2.2 Case Study of Nigeria

Nigeria has an estimated population of 184 million in 2017 [21], and electrification rate of 58% in 2014 [13]. This makes it the highest African population without access to electricity and the second highest population after India in the whole world [13]. The rural population constitutes about 51% of the total population and of whom only 39% have access to electricity [13], [21].

Nigeria has 23-grid connected generating plants with installed capacity of 10.4GW and available capacity of 6.1GW. As shown in Figure 2-4 below, thermal (oil and gas) generating plants dominates the electricity generation energy mix in Nigeria with 82.5% of the total available capacity. The remaining 17.25% of the available generation capacity comes from Hydropower (17.5%) [22]. The low generation capacity with the increasing population results in low electricity per capita of about of 230KWh.

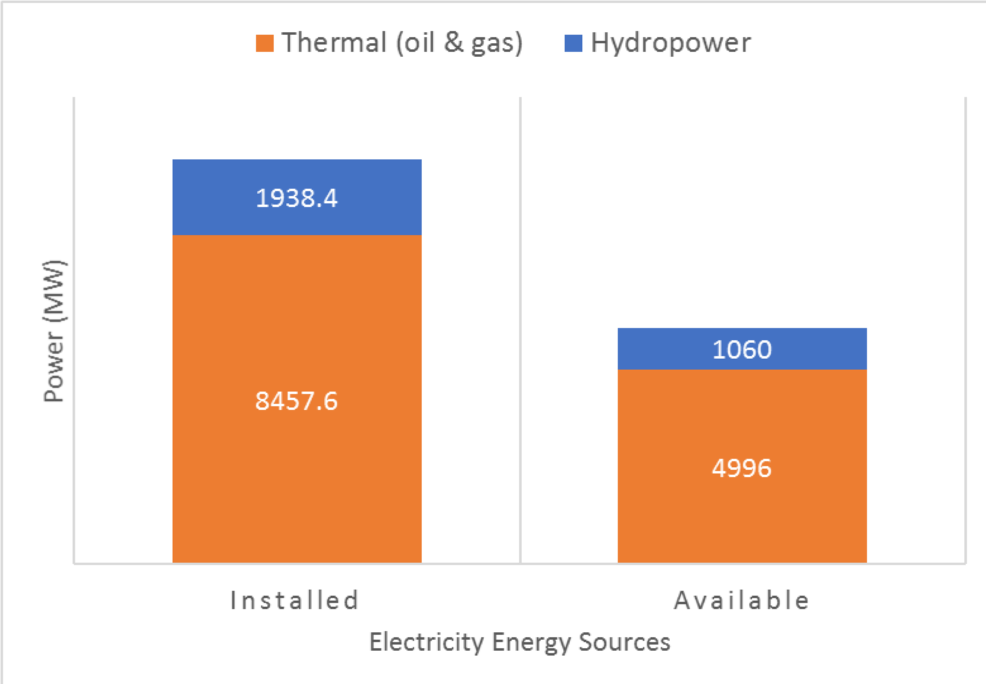

Figure 2-4. Showing electricity generation energy mix for Nigeria

In 2016, 14 solar power companies were issued licenses to generate 1,125MW but only one of the firms has reached a financial close. There is high vandalism of the gas pipeline in Nigeria. Also, the installed capacity outpaces the transmission capacity, which can only transmit 5,300MW of power. Upgrade of the transmission network is needed, which is estimated to require an investment of about $10billion USD per annum for ten consecutive years [23].

With high unlikelihood of this upgrade due to high investment cost needed, it is therefore prudent for the country to think of new energy sources like solar, wind, and biomass to take advantage of the geographical location otherwise power shortage and blackouts are liquidly to continue in the coming years for the whole country.

The economy of Nigeria grew by 2.7% in 2015, dropping from 6.3% in 2014. The drop in oil prices in mid-2014 significantly affected the economy of Nigeria, causing an economic recession. In 2016 Nigeria experienced a strong shortage of power, fuel, the decline in oil output and foreign exchange. Inflation rate doubled from 9.6% at the end of 2015 to 18.8% at the end of 2016 as a result of increased prices of electricity and end-user fuel price, and depreciation of Nigerian naira in 2016. The economy of Nigeria is anticipated to grow by 1% in 2017 and 2.5% in 2018 [21].

With the ongoing economic problems facing Nigeria, the question is whether Vision 2020 of 2009 set by the National Planning Commission (NPC) will be achieved. The target was to become one of the top 20 economies of the world and generate at least 40,000MW of electricity by 2020, with a mix of 5:3:2 [23] for thermal, hydro and solar respectively. Through the National Energy Policy (NEP) of 2003, implemented by the Energy Commission of Nigeria (ECN), the country has a target to achieve 75% electrification rate by 2020 [24].

2.2.1 Household based diesel/petrol generator usage in Nigeria

With an estimated capacity of over 2.6GW of decentralized diesel generators installed in Nigeria, over 80% of the Nigerians rely on generators as an alternative source of electricity supply. Nigeria is the leading African Nation in importing generators since no local production takes place [3, p. 38].

Over 60 million Nigerians own power generators according to the Energy Commission of Nigeria, implying high penetration of individually based generators. This result in a combined expense of over ₦3.5trillion ($21.8billion USD) per year spent by the Nigerian Families, SMEs and Manufacturers to power their alternative sources due to unstable power supply. Private households alone spend over ₦1.56 trillion ($13.35 million USD annually [3], [9]

With the continuous depreciation of Nigerian naira, causing high inflation rates, the end-user price for diesel and petrol continue to increase in Nigeria as shown in Figure 2-5 and Figure 2-6 below for the year of 2016.

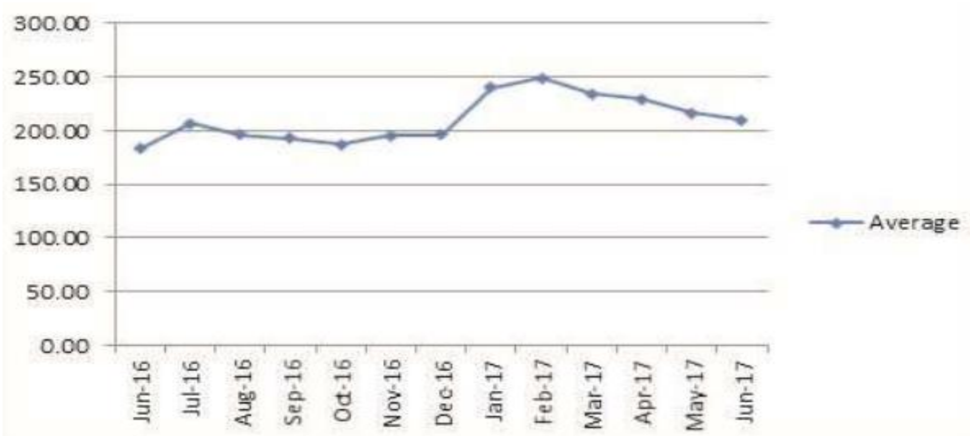

Figure 2-5. Average Diesel Prices (₦) June 2016 to June 2017[25]

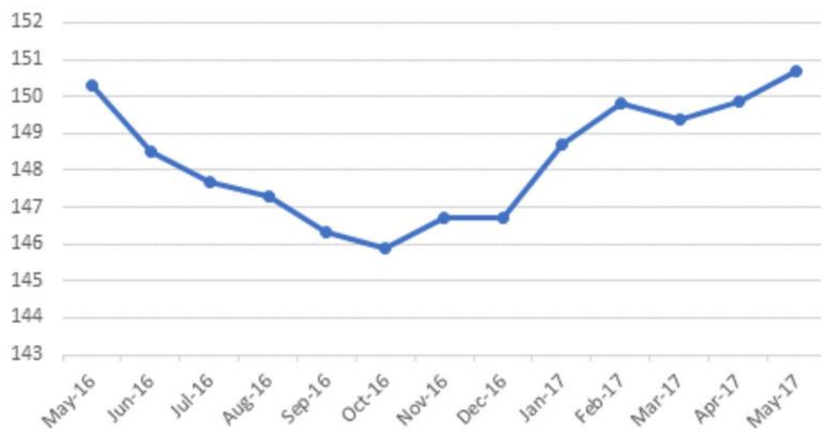

Figure 2-6. Average Petrol Price (₦) from May 2016-May 2017[26]

For the 36 states in Nigeria, the average price of diesel in June 2017 is ₦210.42 ($0.69 USD) with a year-on-year increase of 14.73% and the price of petrol in May 2017 was ₦150.7 ($0.49 USD) with 0.3% year-on-year increase [25],[26].

High fuel prices can cause a barrier for backup power electricity usage from the fossil-fuel generators. Different fuels; diesel and petrol are used for the small fossil-fuel based backup generators. However, in the subsequent analysis of this study, more focus is given to the petrol generators since they are assumed to exist in smaller sizes more common than the diesel generators.

2.2.2 Generator use in the focus states of Bayelsa, Delta and River State

A household, small and medium enterprise survey was done jointly by All On and Dalberg in the three focus states of Bayelsa, Delta, and River State. In the survey, households and the SME's were divided into three sectors; off-grid, on-grid (with >4 hours of electricity supply) and bad-grid (with <4 hours) [10]. Some of the findings of the survey are described as follows;

- The percentage of households in the bad-grid sector in the three states is 45%. Out of which 55% have 2-4 hours and 45% have < 2 hours of electricity supply.
- In the three focus states, a total of 1.8 million households and 0.9 million SMEs have either bad-grid connectivity or are found in off-grid areas.
- The off-grid and bad-grid households and SMEs in the three focus states, consume about 4.4TWh and spend $420 million USD yearly on energy sources (excluding the national grid).

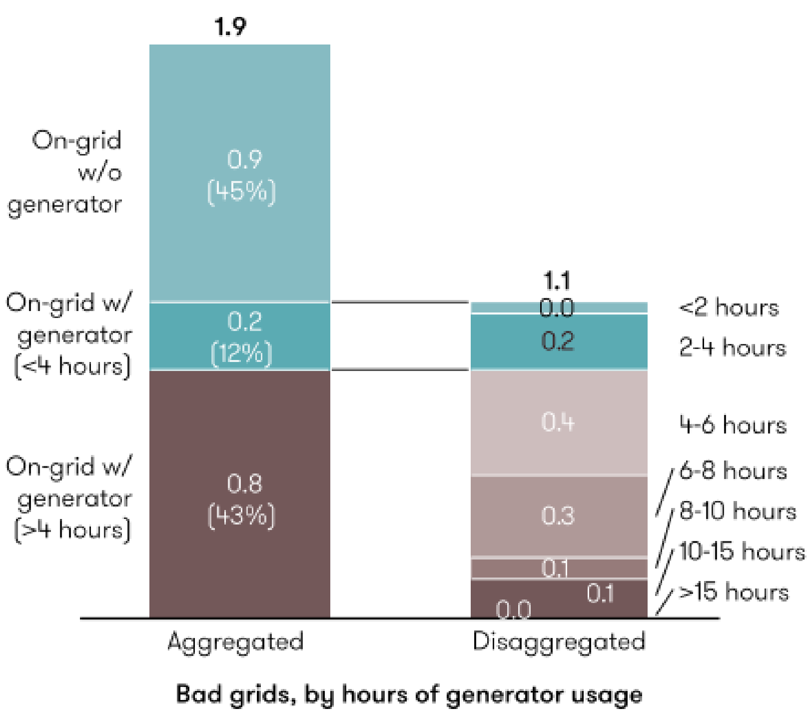

Figure 2-7. Number of households in three focus states by generator hours [10]

From Figure 2-7 above, 43% of the combined number of households in the three focus states connected to the grid, and use backup generator for at least four hours. And, about 50% of these households use generators for 4-6 hours.

The number of SMEs in the three focus states with less than four hours of electricity supply (bad-grid) is about 40% as shown in Figure 2-8 below. Implying some of the SMEs rely on backup generators or other standby sources or stay without electricity for the rest of the day.

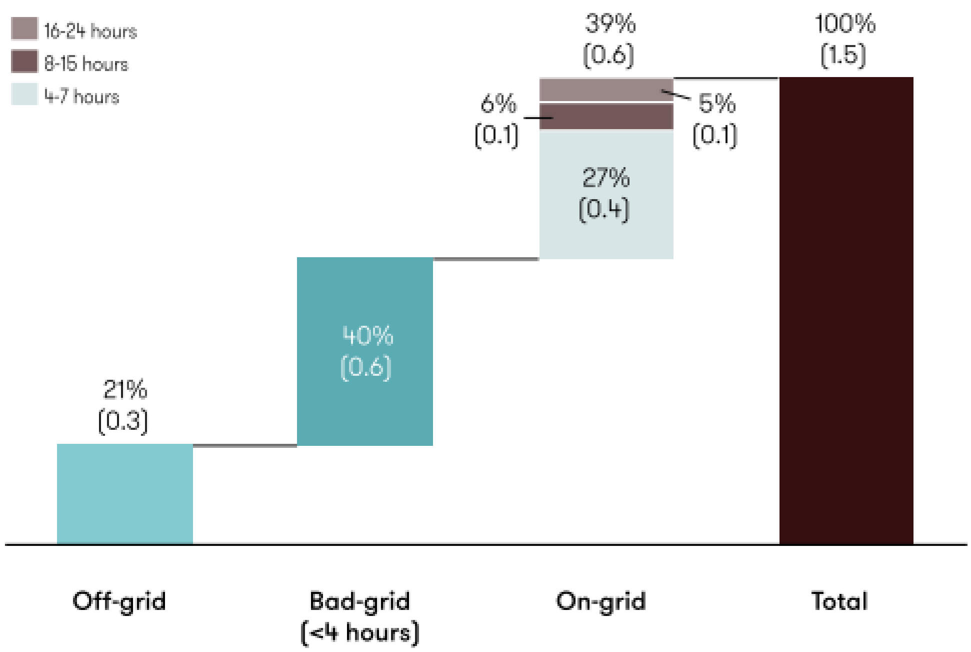

Figure 2-8. Number of SMEs in the three states by connectivity to the grid [10]

From the survey in this three focus states [10], it is found that there is a high willingness-to-pay for a solution that can provide a reliable electricity supply and is less costly than the current spend on grid and generator usage. Also, in [27] and [18], due to unstable supply from the national grid, and high expenditure on fuel for backup generators, the households and the SMEs are motivated to adopt or add up systems that are affordable, and reliable. This shows great opportunity for the integration of solar PV system, as way to save fuel costs from the fossil-fuel based backup generators.

a).

b).

Figure 2-9. Generators in Nigeria, a). Starting [28] **and b) Refuelling a generator** [29]

2.3 Electrification Approaches in sub-Saharan Africa

In the whole world, about 1.06 billion people still lack access to clean, affordable and reliable electricity [13]. Most of these people come from the Global South (developing countries) in particular, sub-Saharan Africa and developing Asia, with most living in the rural areas.

In an effort to increase access to electricity, many electrification approaches are being applied. According to the literature, these approaches can be summarized majorly into three including; individual or stand-alone systems (including solar home systems, diesel generators), hybrid or single energy source mini-grids and main (national) grid extension and densification [30]. A critical review of these three main approaches is done in this section starting with main grid extension, mini-grids and the individual or stand-alone systems.

2.3.1 Main national grid extension

The main national grid is normally the most preferred approach of electrification since it supplies power which is large enough for productive purposes. However, the grid extension to very remote areas faces a lot of challenges. Some of the challenges include large capital costs required for transmission infrastructure which can be hard to recover due to relatively low consumption in the remote areas.

Cost recovery can be difficult with the implementation of fixed low tariffs as such subsidies from the government or donation from international funding agencies are needed. In 2012, an annual subsidy amounting to $50-90 million USD is reported in Nigeria to under price gas used for electricity generation [31]. The government pays subsidies to the power companies to buy gas at low-price to maintain a low electricity tariff.

Due to long distances to be covered to reach very remote areas, the timeline remains indefinite and hence some remote areas might never get electricity by grid extension. Even though some areas get connected with grid extension, power supply reliability still remains an issue as the grid is susceptible to maintenance challenges, vandalism of gas pipeline, and natural disaster like drought, heavy winds causing power cuts [32]

2.3.2 Hybrid or single energy source mini-grids

Mini-grid is one of the off-grid electrification approaches, with centralized generation from single or a combination of energy sources (diesel, hydro, solar, wind). Some mini-grids have installed capacity between 5-500KW, even though bigger systems exist. It is designed to provide power enough to accommodate productive uses [32][33].

Micro-grids as compared to mini-grids are smaller in size. Micro-grids are semi or fully autonomous grids with interconnected loads and distributed energy sources working on or off the main grid. Mini-grids are seen as a second preferred option for electrification with more unlikeliness of main grid extension [32][8].

A study reported by International Energy Agency (IEA) shows that in order to achieve the universal energy access by 2030, rural electrification through the main grid can only contribute 30%, and the rest of the 70% connection can be either with mini-grids or other stand-alone off-grid solutions [34].

Many benefits are attached to mini-grid electrification as it can provide electricity access at high tier enough to support the household, small and medium-sized enterprises energy demands. Mini-grids utilize the locally available energy resources mostly renewable, it provides for its own generation, storage, distribution, and consumption.

Mini-grids can utilize many different energy resources simultaneously known as hybrid systems, this ensures the reliability of its power supply. Although, mini-grids have many benefits it also does face a number of challenges making it not the most suitable approaches, as discussed below.

Mini-grid Challenges

Generally, mini-grids require intensive planning and preparation work to enable sustainability of the system’s operation and maintenance. Mini-grid electrification can only thrive best with stable policies and financial solutions. Most times, an external source of financial support as international donation or grant is needed to meet the initial capital cost. This is seen in the case study of a hybrid mini-grid system in rural Lao as reported by Alliance for Rural Electrification (ARE). For the case of Lao, the project would not have been possible without initial financial support by the public sector for the grid infrastructure [33].

Mini-grid sizes are designed once, and it can be oversized or undersized during the design. In the case of oversized design, the system might not be economically viable for the overseeing company. In a way that the company's revenue collection can be too low to meet their operation and maintenance costs. This is because the area being supplied has too low demand [33].

Whereas in the case of an under-sized system, the total demand might not be sufficiently met, affecting the social acceptance and economic development [8], [30], [33]. As stated in a study by Groh and Koepke [8], the growth of demand never follows any rule and it remains unpredictable. As observed in a case study of the solar home systems in Zambia by Gustavsson [35], household energy demand grows with time, resulting into overstress in the system. As such, the one-time design of mini-grid systems fails to cater for growth in demand and over design hinders the financial sustainability of the whole system.

Challenges to both main national grid extension and mini-grids

The main national-grid extension and mini-grids are both not user centered with a minimum level of ownership given to the users hence affecting the sustainability of the system. This is evident where a private sector is involved in selling electricity to the users [30].

The communities are only seen as customers or beneficiaries but not drivers of their own destiny. This kind of scenario is problematic and should change according to Groh and Philipp in their study [7]. Organized people or communities should be treated as partners of development. In contradiction, where mini-grids are even owned by the community or the users, it experiences the problem of insufficient training on demand side management, system operation and usage [30][33].

Both grid extension and mini-grids require subsidies from the government or international donor funding to meet initial capital cost and for cost recovery to be possible [32]. Also, seen common with grid extension and mini-grids is a top-down approach where the provision of electricity is done by the utility companies owned by the state or central grid operators. This kind of approach neglects the end users in decision making and leads to an interaction that is unidirectional [32].

2.3.3 Individual or stand-alone systems

The final of the three electrification approaches critically reviewed in this section is the individual or stand-alone systems which include solar home systems, and individual generators. Solar home systems are more common in remote and off-grid areas, compared to generators commonly owned as backups in the peri-urban areas.

Solar Homes Systems (SHS) are electrical systems which range from 20-250 Wp [33]. SHS consist of a solar panel, charge controller, battery, and the appliances mostly in DC systems. SHS as another approach of electrification provides electricity enough to supply the basic services, what is referred to as a fitting approach to meet the initial demand without driving up costs [30].

Individually owned generators can supply enough power for the basics services as well as for productive uses. It’s mostly used as backup during power outages from the national grid. Generators can provide electricity at any time of the day whenever there is fuel in their tank.

There is strong ownership with most individually owned systems except in some few cases of SHS distributed by governments and utility companies to reach customers far from the grid. SHS has low initial cost and minimum operation and maintenance costs as compared to mini-grids [33] and fuel based generators.

Challenges of individual or stand-alone systems

The individual electrification approach such as SHS is limited in scaling up their capacity in the long run. Only suitable for the low tier (1,2) electricity supply with limited likeliness for the higher tier (3,4, and 5) energy services [8],[36]. Kirchhoff, in his study, found that households for the case of Bangladesh can achieve a full battery state by midday, leading into excess energy generation of 30% [37].

Individual diesel systems have high operation and maintenance cost due to high fuel costs involved. And for bigger SHS, their initial cost is still high even though inclusive-finance schemes could be used to reduce the cost.

Different from the electrification approaches discussed above, swarm electrification as another approach of electrification is given focus in this thesis, as it is still a new concept to fully understand. The approach involves interconnection of different SHS to form a micro-grid system with distributed energy sources.

The operation of the micro-grid system formed in swarm electrification approach is equated to the concept of swarm intelligence where household or nodes interlinked contribute to creating a conglomerate of value which is greater than the sum of its separate parts [7]. The details of swarm electrification concept as a new electrification approach is discussed in the following section.

2.4 Swarm Electrification (SE) Approach

In this section, the definition of swarm electrification concept is outlined and as one of the electrification approaches, the concept is further discussed.

2.4.1 Definition of swarm electrification

Swarm Electrification is a concept introduced by a group of researchers from Technische Universität Berlin with a focus on Microenergy Systems [7]. SE is an approach where many households with or without SHS are interconnected to form a micro-grid in a low voltage DC system.

The interconnected individual systems form a micro-grid that enables the possibility to sell and buy electricity from the neighbors. Hence, the interconnected participants can both be producers and consumers of electricity, a state that can be referred to as prosumers [7] [8].

2.4.2 Swarm electrification application to on-grid areas

SE concept is formerly developed to improve the electrification means of off-grid areas with stand-alone electrification systems, mostly SHS. Through a peer-to-peer interconnection, many households are interlinked as shown in Figure 2-10

Figure 2-10. Stepwise development of swarm electrification approach below, forming clusters and sharing excess energy.

Furthermore, interlinking the clusters, SE grid is set to expand and interconnect to neighboring mini-grids or nearby main national grid extension. Thereby, reaching its highest level of development. In this way SE approach acts as a vehicle for off-grid areas to achieve higher tier of MTF for better energy services.

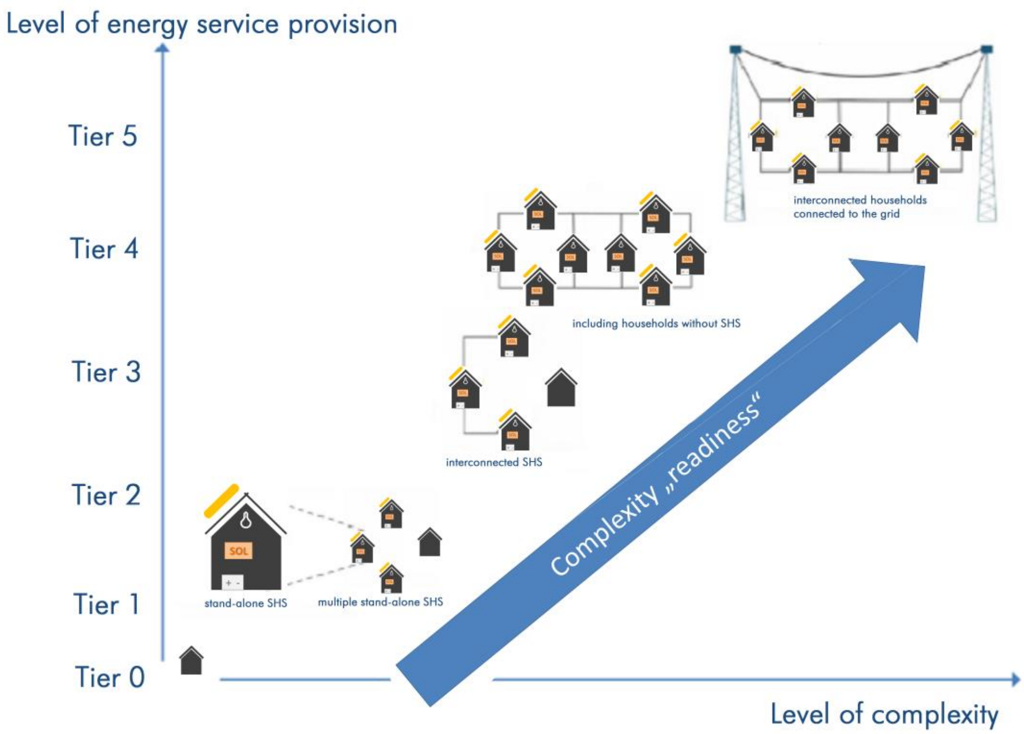

Figure 2-10. Stepwise development of swarm electrification approach [38]

However, in the context of this thesis, the application of SE is different. This thesis proposes a systematic strategy to apply SE approach to improve the electrification of on-grid areas. Mainly on-grid areas with a poor supply of electricity from the national grid characterized by long hours of power outages.

SE builds on existing stand-alone systems like SHS, and diesel generators [30]. Similarly, during power outages, many households and small businesses use individually owned backup generators for the case of Nigeria, which forms the basis of SE application to an on-grid area. SE application in this context could contribute in improving energy services in all aspects of the MTF.

In the following subsection, the phase development of SE grid is further described in the context of off-grid areas, to be better understand its application in on-grid areas.

2.4.3 Phase developments of swarm electrification grids

In swarm electrification approach, many households with or without existing energy infrastructures are interlinked to share electricity among each other. The interconnection grows organically in order to link more households forming clusters of systems. The micro-grid cluster while operating autonomously can then be interconnected to nearby micro-grids or regional or central main grid.

This stepwise approach to expansion is possible with recent developments in Information and Communication Technology (ICT) [39]. The development of swarm electrification approach can be summarized into three phases shown in Figure 2-11 below.

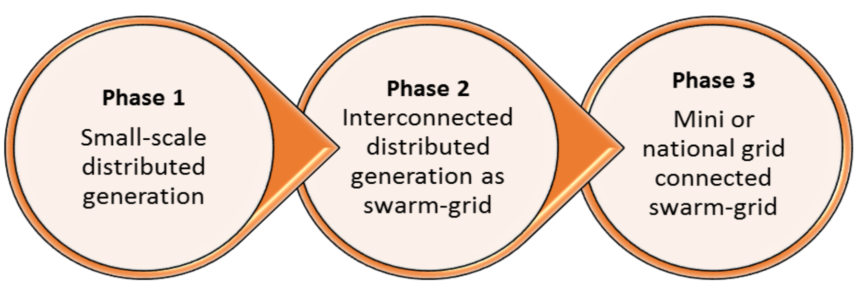

Figure 2-11. The three-phase development of grid-connected autonomous swarm-grid [32]

Phase 1

As shown from Figure 2-11, and Figure 2-11 above, the first phase begins with multiple households and SMEs installing efficient SHS or small individual energy systems, with integrated storage and intelligent control devices. The acquisition of the energy system devices is done through inclusive-finance support with provision of long term locally available technical services. This phase gives the people their first experience of using electricity. It helps to achieve the initial electrification level (tier 1 and 2) for basic services. In this phase, a household energy system capacity is limited and cannot handle growth in demand hence, productive use of electricity remains a challenge [32].

Phase 2

The second phase of swarm electrification approach is the interconnection of the multiple households to form clusters. This allows sharing of excess power with the neighbors as a result of a swarm of generation capacity. Also in this phase, the people organized in a community including interested small businesses can seek for community-based financing to make this phase possible. The interconnection can necessitate connection of more distributed generation sources, and support productive use of electricity given the efficient use of maximum generation capacity from the individual nodes.

This phase results into a swarm-grid that can grow organically and is implemented in Direct Current (DC) system. The DC system eliminates losses from the use of DC/AC inverters, making use of efficient DC appliances hence improving the efficiency of the whole system. Recent developments in DC motors make it possible for productive use of electricity in a DC micro-grid swarm electrification approach [32].

Phase 3

This phase involves connection of phase two swarm-grid clusters to other nearby mini-grid or regional or national-grid networks. This connection may have many benefits in that it gives a more balancing effect.

The expansion until connection to the national-grid network demonstrates a bottom-up approach. The expansion brings reduced cost benefits since the major cost involves only putting up transmission lines given the already existing swarm-grid distribution lines.

In SE approach, the different nodes are able to island and operate autonomously even if natural disasters, one of the reasons for power outages, occurs in the neighboring grid network. In this third and final phase, the swarm-grid can both feed and consume from the main grid system. The active nature of the swarm-grid favors the main grid operators not to think about increased generation in a bid to extend. Also, micro-grid at this level due to its storage capability can act as a buffer to the main grid in case of excess generation [32] [8].

2.4.4 Swarm Electrification as a complement to the existing approaches

SE as a new concept has the potential to complement the existing approaches such as the national grid, the mini-grids, and the individual systems. There are a number of challenges with some of the existing approaches. Some of these include long and frequent power outages, planning and operational challenge, insufficient capacity for the case of SHS, high fuel cost for individually owned diesel generators.

The national grid among other centralized grid systems is a top-down approach in its operational management. The management is from the top-level. Electricity flows from a single entity to the lowest level in a unidirectional way. According to a study by Groh and Koepke [8], the main difference between SE and centralized systems is that SE is a bottom-up approach other than a top-down approach. This makes SE stronger and flexible approach with management from below.

As seen in the third phase of SE stepwise development process in section 2.4.3 above, through SE approach, electricity could be exchanged between the grid and the users in a bidirectional manner. The exchange also occurs between the users, and as such in an on-grid area faced with power outage challenges, complementing the national grid with the existing backup infrastructure through SE approach could be of great relevance.

Through SE, some of the users without backup means could get electricity from their neighbor at a time when the national grid is off. SE approach interconnects the individually owned system with the publicly owned grid infrastructure in an active interaction. This could increase the participation level of the people in decision-making procedure for the management of the electrification system. When the user participation is enhanced, the system could become more user-centered and cause impacts like increased share of renewables in the grid system. This was seen as the case for the communities in Germany which lead to increased renewable energy integration in the grid according to Kirchhoff et al. [40].

Through SE approach, the electricity consumers become prosumers (a producer and consumer). They can sell excess electricity which gives them a unique scenario of economic benefit according to Koepke and Groh [30]. This kind of economic benefit could result in some significant earnings to offset the high fuel costs in running an individually owned backup generator.

2.5 Swarm Electrification DC Micro-grid Experience in Bangladesh

Bangladesh has 4 million installed SHS, the highest in the world according to REN21 renewables global status report [41]. The systems mainly installed through microcredit schemes are however, limited in capacity for higher loads and productive uses.

Swarm electrification in Bangladesh is based on the integration of these existing SHS implemented at pilot level by ME SOLshare a start-up company. In Bangladesh, trading of energy through the SOLbox is done using the mobile banking network. Through the mobile banking one can buy or sell electricity by switching the SOLbox to 'buy' or 'sell' mode respectively. The SOLbox costs about USD $30, which is payable on an installment basis for 24-36 months [42].

2.5.1 Swarm-grid SOLbox

The SOLbox is bi-directional hardware that enables a peer-to-peer interconnection between households and small businesses. It is integrated to an existing solar home system or battery only system, interconnecting one SOLbox to other SOLboxes creates a smart low-voltage DC Swarm-grid as shown in the Figure 2-12 below [43].

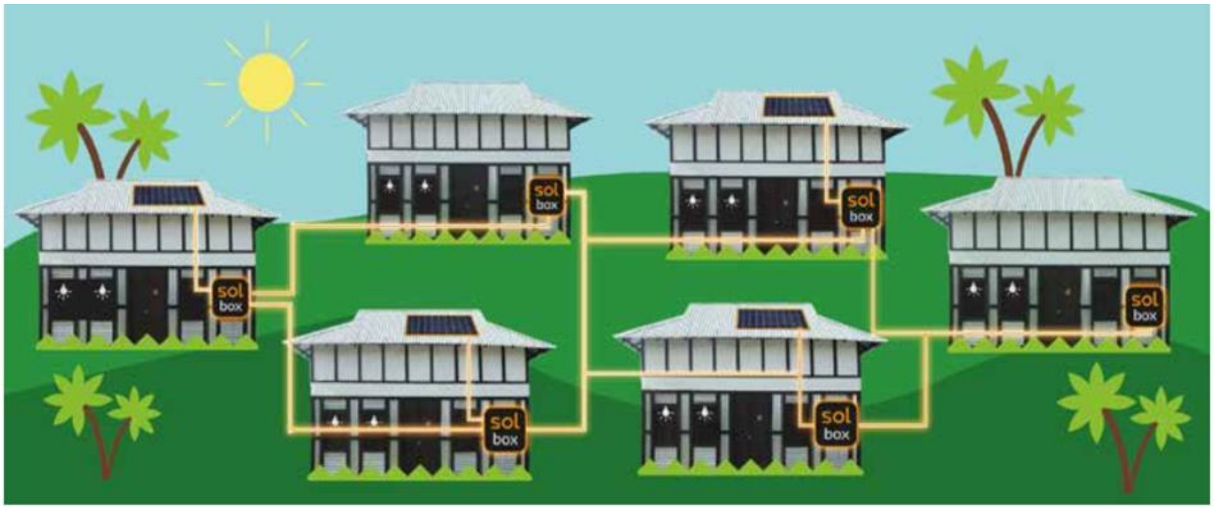

Figure 2-12. Swarm-grid Network [43]

With many more SOLboxes installed, the grid has the potential to grow hence integrating more households and productive uses as result of increased excess electricity. One of the version of the SOLbox used in Bangladesh has 120W rated capacity with a rated current of 10A and 12V DC

Figure 2-13. The SOLbox with three outlets to interconnect neighboring households [43]

SOLbox is also linked to an information processing system called SOLcloud, a software that process data obtained from the SOLbox on the cloud. With a device within the SOLbox, data such as amount of electricity generated and consumed, battery capacity, electricity taken/supplied to the swarm-grid at each home is transmitted to SOLcloud in real time. The data is transmitted through the mobile phone communication network[44]. This enables automatic computation of the quantity of electricity sold or consumed at each household, and the credit balance of electricity purchased. In this way, the system is automatically controlled and optimized.

2.5.2 Shakimali Matborkandi village

The first swarm-grid project in the world is found in Shakimali Matborkandi village in Shariatpur region about 50km South of Dhaka, the capital City of Bangladesh. In this village, about seven households approximately 20 meters a part form a cluster neighboring other clusters [45].

The main economic activity for men is either farming or being a local driver with women mostly involved in household activities. Per household average monthly income range from 10,000-20,000 Taka ($125-250USD). Six of the seven households have SHS [45].

The swarm-grid specification

The SOLbox is installed every household, and are then interconnected to form swarm-grid. The swarm-grid distribution voltage is 12V DC, and the longest single cable length between houses is limited to 20 meters. The installed generation specification of the swarm-grid includes the following [45];

- Five households have a 20Wp, 30Ah SHS and one SOLbox each
- One household has a 50Wp, 80Ah SHS and one SOLbox
- One household has a10Ah battery and one SOLbox
- SOLshare installed a buffer (over-sized) 100Wp, 80Ah SHS to simulate network effects

The orientation of these households is shown in Figure 2-14 below. The total installed decentralized Solar PV is 250Wp with 320Ah battery storage. The total nominal per-household installed Solar PV and storage capacity equates to an average of 35.71Wp and 45.71Ah.

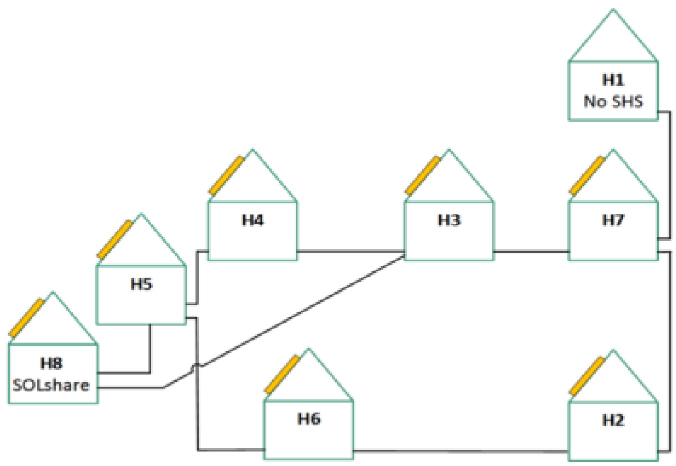

Figure 2-14 Shariatpur Swarm-grid layout [46]

Some of the appliances being powered in the swarm-grid include household lights, phone chargers, and community street lights installed by SOLshare in the formal village center. Households use 1-3 LED lights depending on the size of their own SHS before the formation of the grid. With the excess energy generation, households have added new devices such as TV, and DVDs. They also added irrigation pump and rice husker.

2.6 DC Micro-grid system in comparison to AC Micro-grid

Towards the end of 19th century, there was a dispute in the sector of electricity on which system to commercialize. The struggle was between adopting either Direct Current (DC) system or Alternating Current (AC) system for electricity transmission and distribution.

American innovator and entrepreneur, Thomas Edison was the first to commercialize DC system electricity transmission and distribution [47]. However, Edison faced a big challenge from the invention of AC system by Tesla which was financially supported by George Westinghouse [48]. AC system won the dispute to dominate the electricity market since it could be transmitted over longer distances than DC systems with minimum losses [47]. And other reasons as presented in [49] include:

- Large power plants were more economical than many small distributed ones
- Incandescent bulbs by then the major load could work on either AC or DC
- Semiconductors were not yet discovered

In reference to these reasons above, a lot has changed today. Now with the invention of semiconductors, small distributed power systems have become possible and cost-effective, even though transmission through AC system is still dominant. Also, many electrical appliances today operate on DC (including laptops, mobile phones, and LED lights). For the SE approach proposed in this thesis, DC supply voltage is chosen. DC microgrid supports an efficient integration of technologies such as solar PV, battery storage, small wind turbines directly without the need for DC/AC conversion for these energy sources [50]–[52].

Furthermore, in order to eliminate the complexity of synchronizing distributed backup generators in swarm-grid, DC supply voltage is preferred. The backup generators through AC/DC conversion can easily be integrated into a DC swarm-grid. Although AC voltage supply is better over long distances of electricity supply, energy generation sources and storage units installed close to the users can reduce the losses in DC grid system.

2.7 Excess Energy for Swarm-grid

As one of the main objectives of swarm electrification, the excess energy generated from single standalone systems should be put to use through sharing with the neighbors. This excess energy is the potential electricity that could be generated by a power source if the battery had not been fully charged or if there had been a load to be powered [53]. The excess energy is a virtual value determined by the charge controller.

The charge controller of a solar PV system is designed to control the output current for charging the battery. The controller also protects the battery from over charging and deep-charging. The voltage level of the battery is detected by the controller, at a certain voltage level, the controller gradually reduces the charging current, and eventually disconnects the power source circuit in order to protect the battery from overcharging [53]. Once the battery is fully charged without being utilized, excess energy that would have been generated is then wasted. This thesis aims to quantity this excess energy from the solar PV system in the proposed swarm-grid.

CHAPTER THREE: METHODOLOGY

3.1 Description of The Study Area

The area chosen for this study is Elele, located in Rivers state, Nigeria. The geographical location is 5°6'6" North and 6°49'8" East [54]. The state is located in the Southern region of Nigeria bordered by the Atlantic Ocean in the South, Delta, Anambra, and the Imo States in the North as shown in Figure 3-1 below with an indication of a blue circle. Rivers state is one of the 36 states in Nigeria. It has a total area of 11,077 Km^2. It is the sixth populous state in Nigeria according to the 2006 census, with a population density in the range of 400-600 people per square km [55].

In 2014, the population with access to electricity in Nigeria is about 58%. The urban and rural populations have 78% and 39% access to electricity respectively [13]. The number of household in Nigeria by connectivity to the national grid is 62% out of which 60% have electricity for less than four hours in a day [10]. The Rivers state has 71% of its households connected to the grid.

Usage of diesel/petrol generators is generally high in Rivers state. According to All-On and Shell in a research conducted in the states of Bayelsa, Delta and Rivers, 38% of households and 98% of SMEs in Rivers state use generators. The research also shows that 43% of the households connected to the grid in the three states, use generators for more than four hours in a day. And about 50% of these households use generators for 4-6 hours (refer to Figure 2-7 on page 18). The three states including Rivers state, in total have 45% and 40% of their households and SMEs with electricity supply from the grid for less than four hours in a day (bad-grid connection) [10].

Figure 3-1. Map of Nigeria showing its States [56]

3.2 Data Collection and Data Analysis

The various data necessary for the execution of the methodology is described in this section. These include solar resource data, the energy consumption, and the economic parameters.

3.2.1 Solar resource data for the chosen study area

The data for the solar potential of the selected area for this study is obtained from the European Commission, a new solar radiation database for PV performance estimation in Europe and Africa [54].

Hourly data for both irradiance and temperature is obtained for a period of ten years from 2007 to 2016. Average of hourly data for a day, in a month over the ten-year period is computed in Excel spread sheet. The hourly data is summed on daily basis to obtain the daily irradiation and temperature data in a year as is presented in Figure 3-2 below, and Appendix 8. The solar PV performance is determined on daily basis for 365 days in a year using this excel based daily irradiation and temperature data.

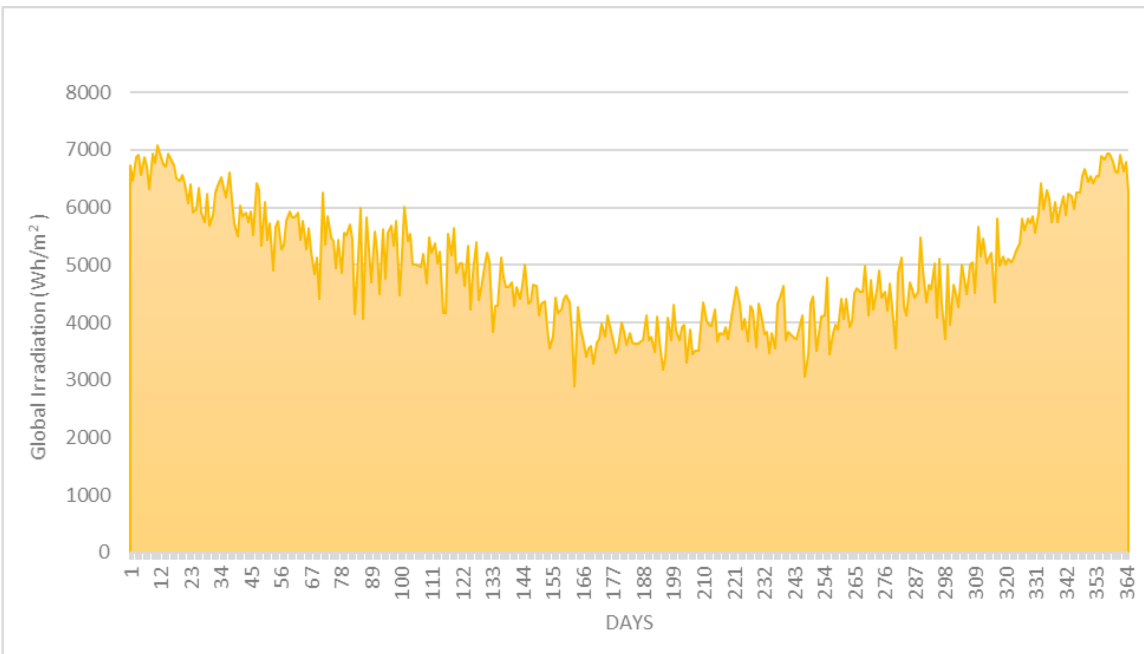

Figure 3-2. Daily global horizontal solar irradiation on optimal tilt angle for a year

The solar irradiation potential is averagely good in the whole year. The average irradiation is 5.0KWh/m^2, with a maximum of 7.1KWh/m^2 and a minimum of 2.9KWh/m^2. The maximum irradiation for the ten years data occurs on the eleventh day of the year in January, and the minimum occurs on the 163rd day of the year in the month of July.

Generally, as seen from Figure 3-2 above, high global horizontal solar irradiation is measured at the beginning of the year. The values reduce gradually with time until the middle of the year before it starts to rise again as it approaches December towards the end of the year. This trend is as result of the geographical location of Nigeria with tropical climate. Generally, Nigeria has two seasons, the wet (rainy) season from April to October, and dry season from November to March [57].

A monthly average daily global solar irradiation for Elele study area is shown in Figure 3-3 below. The month of January has the highest average daily irradiation of 6.5KWh/m^2. The month of January is closely followed by December with 6.4KWh/m^2, and the month with the lowest average daily irradiation is July with only 3.8KWh/m^2.

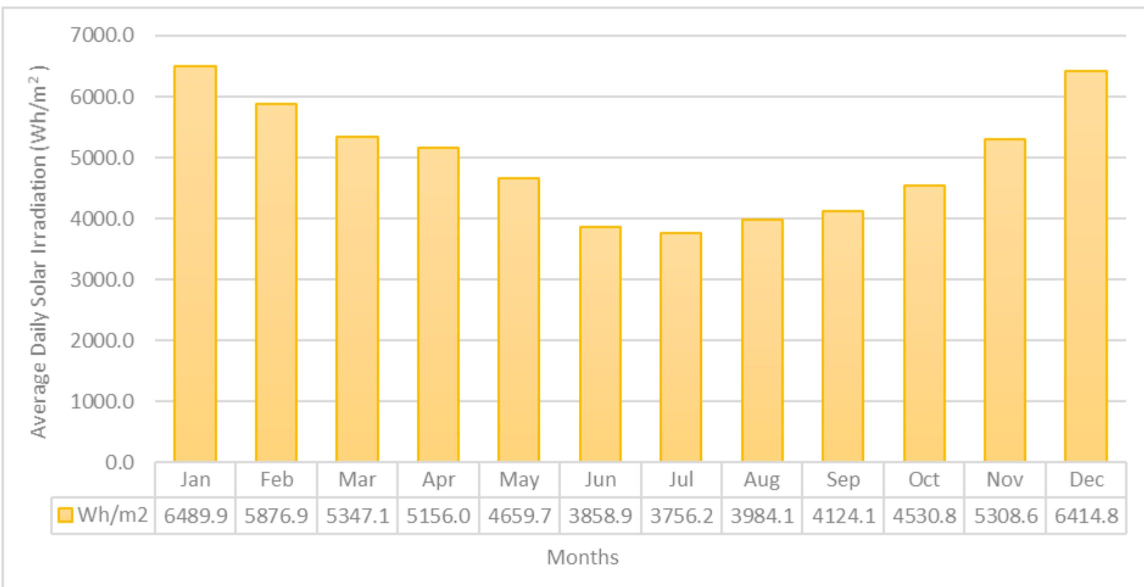

Figure 3-3. Monthly average daily global solar irradiation

In a day, the sun averagely shines for 12 hours, from 6 am (06.00 hours) in the morning to 6 pm (18.00 hours) in the evening. And within this time of the day, the solar irradiance rises steadily until the solar noon which occurs at about 12 pm (12.00 hours). At the solar noon, the irradiation is maximum. After the solar noon, the irradiation starts to reduce until 18.00 hours when the sunset sets. The solar irradiation pattern during a typical day in Elele is as shown in Figure 3-4 below for the month of July.

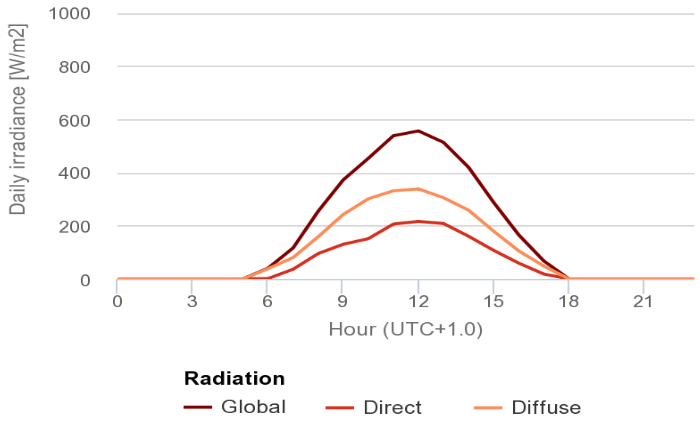

Figure 3-4. Daily average irradiance profile on optimal inclined plane [54]

3.3 Estimation of the Daily Energy Demand

The daily energy demand is estimated for a household and a small retail shop enterprise to represent a business scenario. The load profiles of the household and the retail shop are created based on some of the load profiles described in literature [16], [18], [58].

Daily energy demand is dependent on the hourly energy consumption by the various electric loads in the course of the day. Energy consumed by a load is determined by multiplying its unit power with the number of hours of use in a day. Total daily energy demand was then determined from the sum of energy consumed by all the loads in a day.

The household load profile

The load profile for the household is estimated based on the assumption of electrical appliances shown in Table 3-1 below.

Table 3-1. Electrical appliances for the household

Items	Qty	Unit (W)	Total (W)
Indoor lights	3	6	18
Outdoor lights	2	9	18
Electric fan	2	50	100
Refrigerator	1	200	200
TV 21”	1	100	100
DVD player	1	50	50
Laptop	1	70	70
Radio	1	20	20
			556

The household electricity consumption is assumed to peak during the day and at night from 19.00-21.00 hours. Consumption during the rest of the day is assumed as presented in the Appendix 6, resulting in the household load profile as shown in Figure 3-5 below.

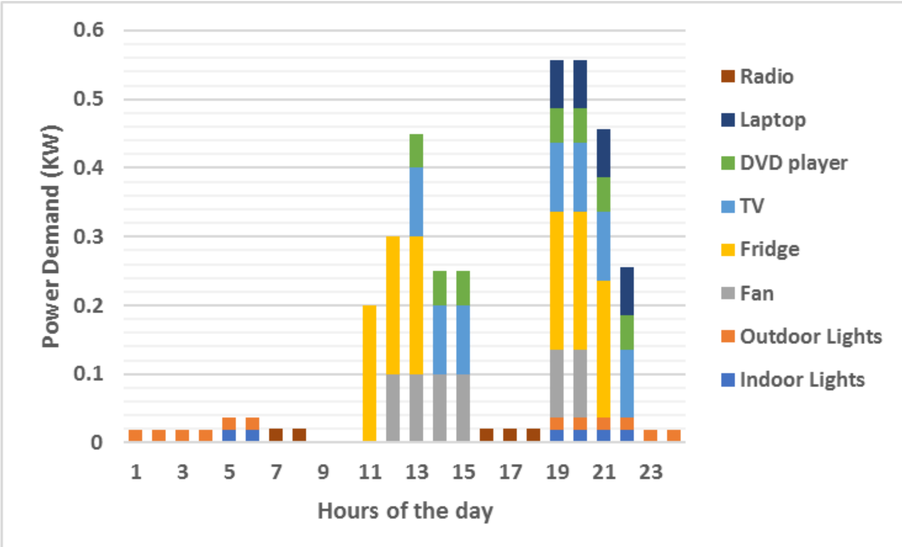

Figure 3-5. Household consumer estimated electricity load profile

The retail shop business load profile

The load profile developed for retail shop business is based on the assumption made for the use of electrical appliances given in the table below.

Table 3-2. Electrical Appliances for the retail shop

Items	Qty	Unit (W)	Total (W)
Indoor lights	2	11	22
Outdoor lights	2	9	18
Phone charger	5	3	15
TV19”	1	80	80
Satellite Receiver	1	30	30
Refrigerator	1	200	200
Ceiling fan	1	40	40
Radio	1	15	15
			420

Assuming pick hours in the morning between 10.00-11.00 hours and in the evening from 15.00-18.00 hours, and other appliances usage as shown in Appendix 7, a load profile for the retail shop would look as shown in Figure 3-6 below.

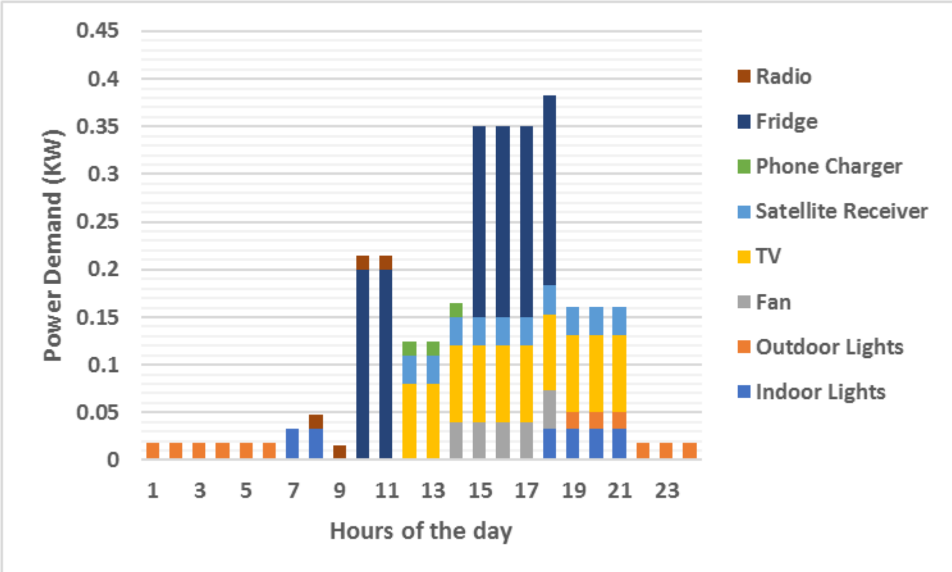

Figure 3-6. Small retail shop consumer estimated electricity load profile

From the figure above, the peak consumption for the retail shop is in the evening between 15.00hours and 18.00hours. The fridge is assumed to take much of the energy for cooling drinks besides entertainment, phone charging and lighting.

3.4 Designing an Energy System for the Household and the Retail shop

As described in subsection 2.2.2 on page 18, the households and the retail shop (SME) are connected to a national grid but the grid is only available for four hours. They then rely on backup generators. The use of generators can be expensive due to high fuel costs involved.

In this thesis, as described in chapter one, a stepwise strategy is proposed to interconnect the existing back infrastructure to form a swarm-grid with integration of renewable energy generation. The aim is to reduce fuel costs and have an overall improvement of quality of electricity access. Seven steps are described however, this thesis focuses on the first four steps.

In this section, new systems are developed by integrating a battery and a solar PV generator step by step to an existing household and retail shop backup power system (baseline system). The technical and economic impacts of these systems are then assessed.

Baseline system (Backup Generator only)

In this system, the electricity consumers are assumed to use only their backup generators, mainly in the evening. Other assumptions made for this system include the following;

- Electricity from the national grid is only available for four hours in a day
- Power outage is assumed to occur every day in the evening
- The households use their backup generators in the evening for about four hours every day
- The retail shops use their backup generators for six hours every day in the evening
- During power outage in the daytime the households and the retail shops are assumed to stay without electricity. The generators are assumed to be used only in the evening when it's getting dark.

In the baseline system, during a power outage from national grid, the load profiles of electricity consumption from the backup generators of the household and the retail shop would look as follows;

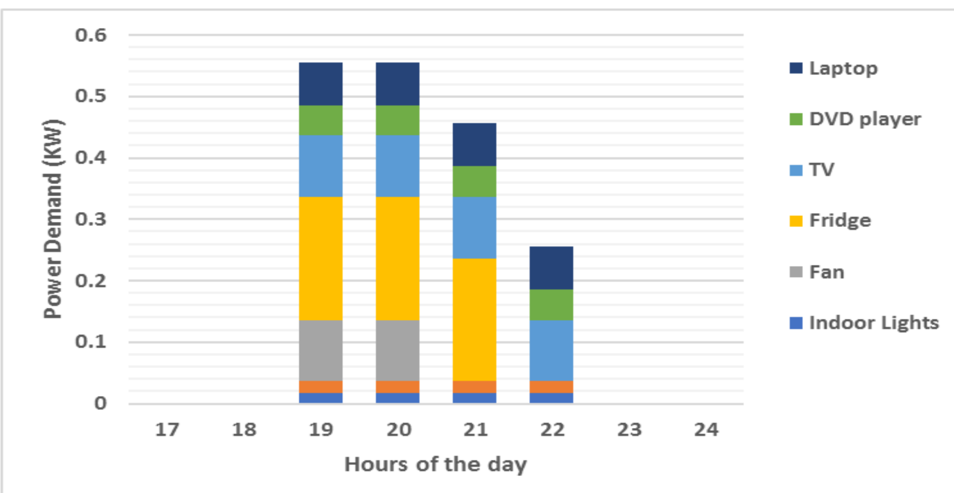

Figure 3-7. Household load profile in the baseline system

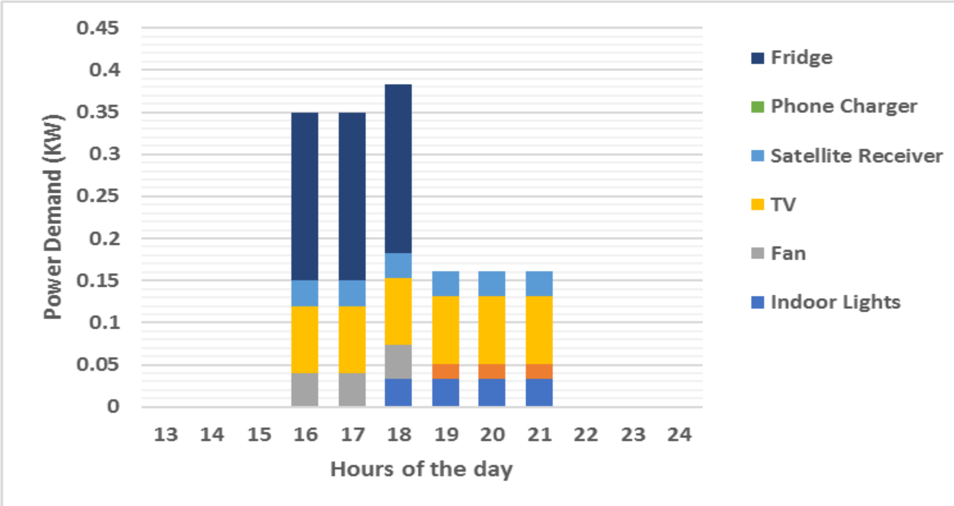

Figure 3-8. Retail Shop load profile in the baseline system

As seen from the load profiles above in the figures above, it is assumed that during power outage, electrical usage for the households and the retail shops from the backup power sources is mainly for lighting, entertainment and using fridge for mainly cooling the drinks

System-I (Generator +Battery)

In this system, the battery is integrated to the baseline system. The battery is charged by the generator, in order to have a high electrical load output for optimal generator efficiency. The generator operating hours are reduced since the battery integrated is later used instead of the generator.

An AC/DC hybrid bidirectional converter is used to charge and discharge the battery, since the battery loads are AC loads. Replacing the AC loads for the battery with DC loads for direct battery discharge could have significant effect but was not considered in this thesis. The economic viability of this system for the household and the retail shop under described conditions is assessed and presented in the next chapter.

The load profiles for the household and the retail shop in system-I are as shown below.

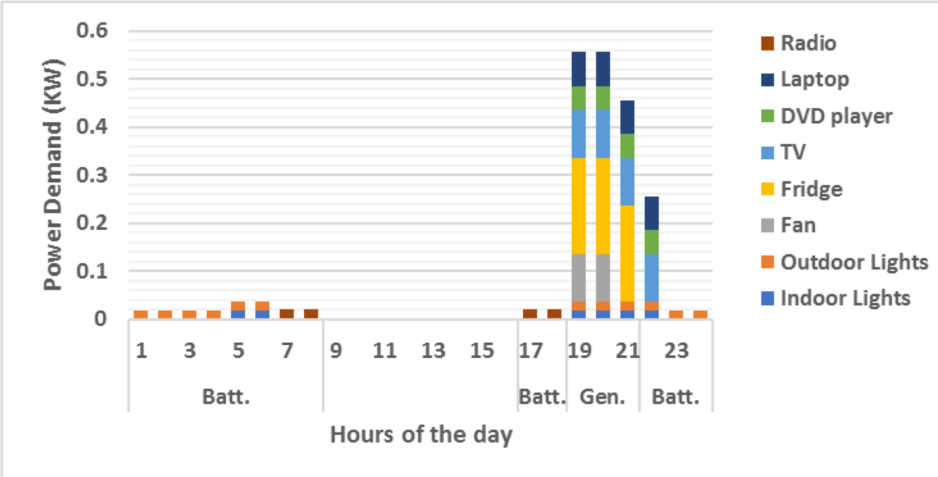

Figure 3-9. Household load profile in system-I

Due to the integration of the battery to the baseline system, generator hours for the household are reduced from four hours in the baseline system to three hours in system-I1 as observed from Figure 3-9 above. Also, the battery is integrated for longer electricity availability duration. Powering more loads including the outdoor lights, the indoor light in the dawn, and listening to radio in the morning.

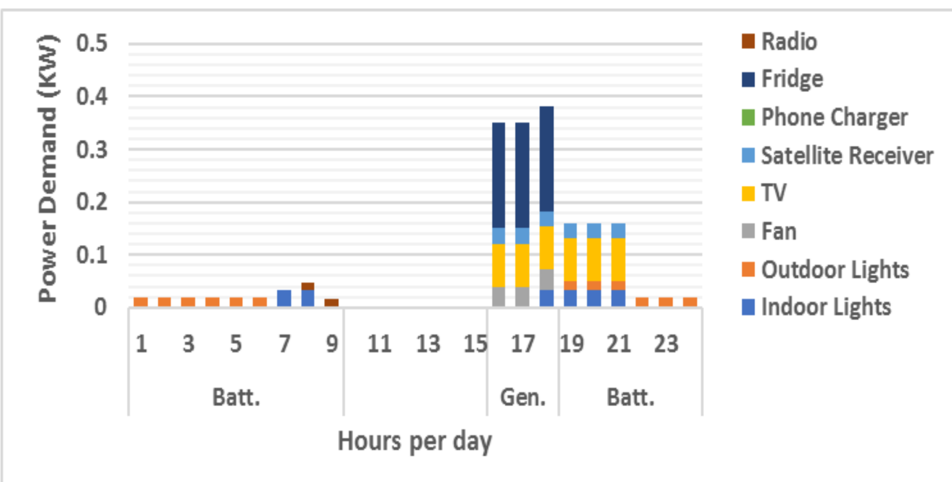

Figure 3-10. The retail shop load profile in System-I

By adding a battery to the baseline system, the generator hours for the retail shop from Figure 3-10 above, are reduced from six hours in the baseline system to three hours in system-I. In addition, electricity from the battery is used instead of the generator throughout the night.

System-II (Generator + Battery + solar PV)

Different from system-I, in system-II a solar PV is separately added as a fuel saver to the household and the retail shop systems. In this system, solar PV is mainly used instead of the generator to charge the batteries and as a direct power source. An AC/DC hybrid bidirectional converter is used to charge and discharge the batteries. The operation of the generators is limited to the peak hours in order to run the generators at optimal point. The technical and economic impacts are assessed and presented in the next chapter.

Further in this system, a postulation is made for excess energy generation. The generation happens through two ways. Excess energy from solar PV after fully charging the battery, and excess energy from the diesel/petrol generator when running at optimal point. The assessment of the excess energy that can be generated to share with neighbors a swarm-grid is done and also presented in the next chapter of results and discussion. The analysis for using excess energy as direct power during the day is considered out of scope for this study.

The load profiles for the household and the retail shop in system-II are presented as follows;

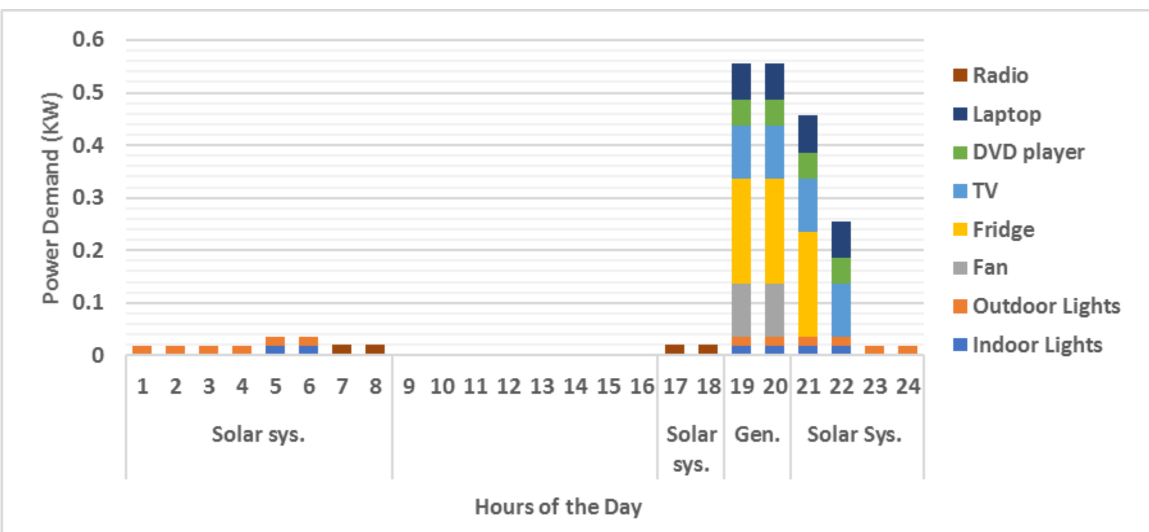

Figure 3-11. Household load profile in system-II

From Figure 3-11 above, the generator hours for the household in system-II are reduced to two hours from three hours in system-I, and four hours in the baseline system. In addition, the battery mainly charged by the solar PV during the day, is later used as power source throughout the night hence increasing electricity availability.

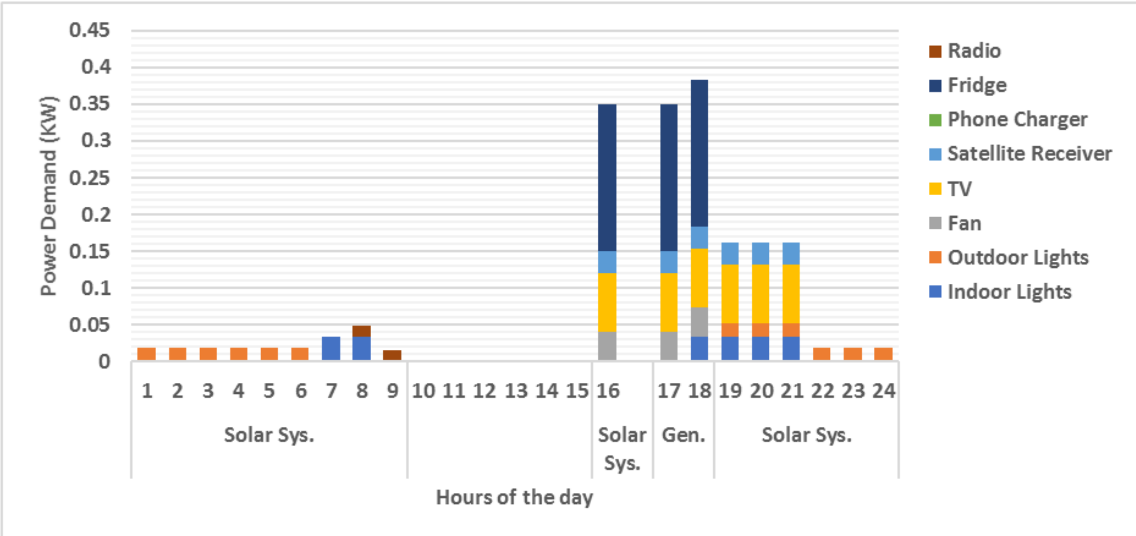

Figure 3-12. Retail shop load profile in System-II

From Figure 3-12 above, the generator hours for the retail shop in system-II are reduced to two hours from three hours in system-I, and six hours in the baseline system. In addition, with system-II, the retail shop has electricity at night all the time hence increasing electricity reliability and availability.

System-III (Solar PV + Battery only)

In this system, the fossil-fuel based backup generator is completely replaces with a renewable energy source. The system consists of a solar PV and a battery only. The solar charges the battery during the day when sun is shining and the battery is discharged in the evening. There is need for an AC/DC bidirectional converter since the existing appliances are AC appliances. The economic viability of this system is assessed and discussed in the next chapter.

The load profile of the household in this system is as shown in the figure below.

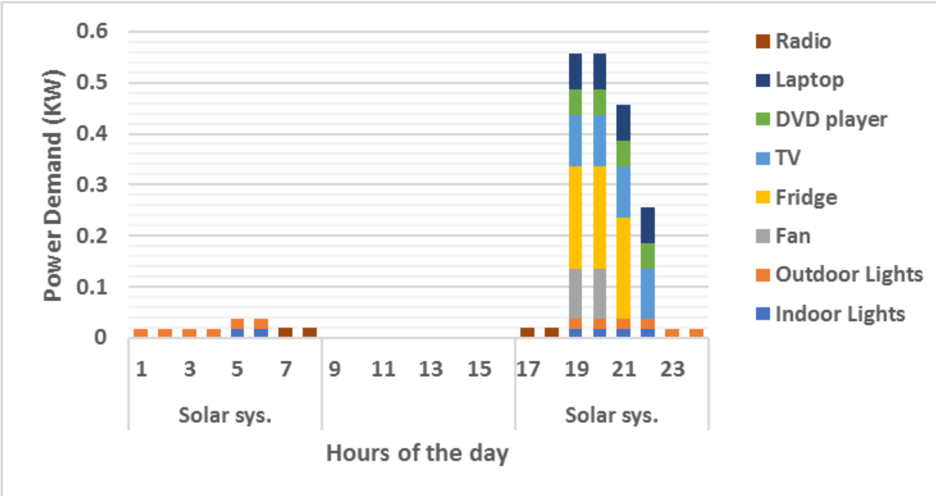

Figure 3-13. Household load profile in system-III

The load profile of the retail shop consumer in system-III is as shown in the figure below.

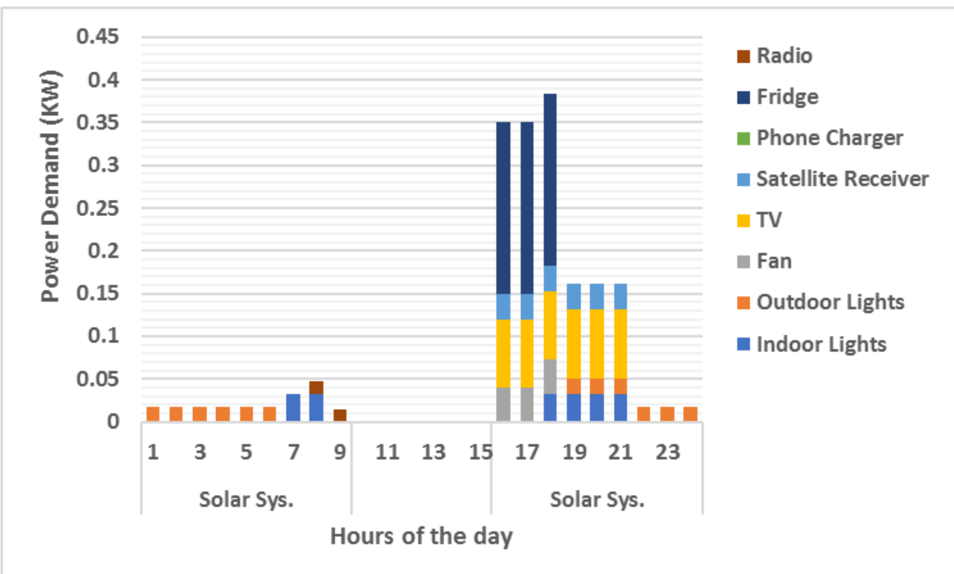

Figure 3-14. Retail shop load profile in system-III

3.4.1 Proposed swarm-grid operation

Considering integration of batteries and solar PV generators as way to save fuel from the existing backup infrastructures, the proposed swarm-grid would consist of hybrid energy systems at its nodes. A schematic drawing in Figure 3-15 below is used to show the hybrid swarm-grid node.

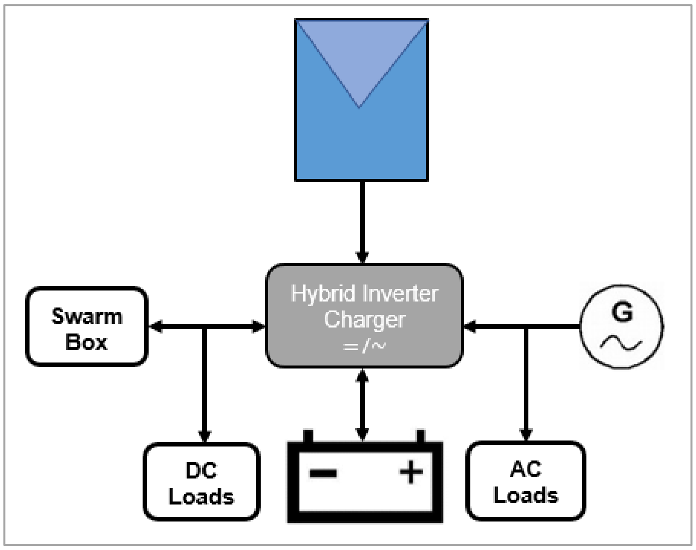

Figure 3-15. Hybrid energy system connection in a household (system-II)

The system consists of a swarm box, a DC/DC bidirectional device used to interconnect with two or three neighboring households or enterprises in a swarm-grid. The device can include a DC/DC converter to step up or step down the DC Swarm-grid voltage. During the day, excess energy from solar is shared or traded with the swarm-grid participants through the swarm box.

From Figure 3-15 above, the hybrid energy system also consists of a hybrid inverter charger (AC/DC bidirectional converter) through which the battery is charged and discharged. Both solar and diesel/petrol generators can be used to charge the batteries. Also, the battery could be charged by the national grid in case available but this was considered out of scope for this thesis.

Both AC and DC appliances can be connected to the system. Changing some of the AC loads to DC loads could have a big impact on the efficiency and overall system size. However, in thesis the analysis is limited to the existing AC loads.

The swarm-grid formed from a proposal of interconnecting the backup infrastructure, with an integration storage and renewable energies would look as schematically shown in the figure below;

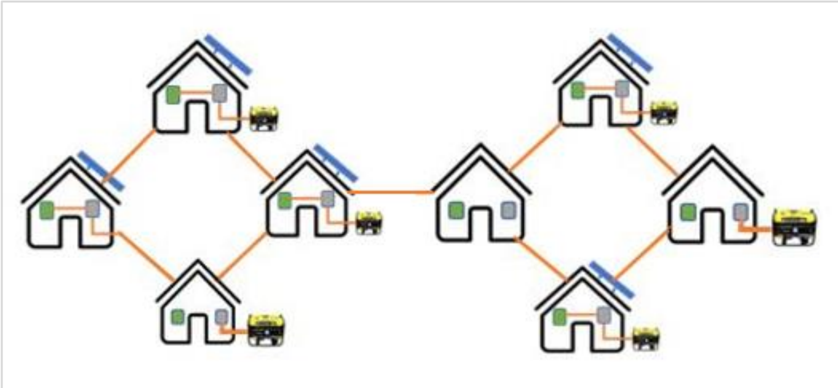

Figure 3-16. A schematic drawing of a hybrid swarm-grid

From the figure above, the hybrid swarm-grid has some nodes consisting of both a fossil-fuel generator, and a solar PV system. Other nodes have only fossil-fuel generators or solar PV systems or completely lack energy generating sources and depend on neighbors.

3.4.2 Operation decision strategy of nodes in the hybrid swarm-grid

Solar energy would be the preferred source of energy production with a backup generator as a standby. One of the advantages of hybrid swarm-grid would be that the energy can be shared or traded at night when the sun is not shining, by operating backup AC generators as an alternative source. The operation decision strategy could run as follows;

- During the daytime, the energy from solar PV for a node in the swarm-grid is first used to charge the battery and supply its loads.
- If the solar energy generated is more than the demand to charge the battery and supply the loads, then the excess energy is shared or traded among neighbors in the swarm-grid.
- If there is any unmet power demand for a node, the local battery can be discharged first and then the remaining unmet demand is taken from the swarm-grid.
- In the case of the night or cloudy days, if there is no available power in the swarm-grid, the local backup generators can be switched on, to first supply the loads and if efficient enough then load batteries to be charged.

- If the battery reaches a certain minimum sharing state of charge, and there is demand for energy to be shared, the feed into the swarm-grid can be started.

3.4.3 Sizing for the solar PV panels

The total PV size (Watt peak, Wp) for the solar system needed is calculated in excel spread sheet using the method shown below according to a book section of Mini-grids for Rural Electrification in Developing Countries [59];

$$P_{wp} = \frac{W_{pv}}{H_p \times PR} \tag{1}$$

Where: P_{wp}= Total watt peak of the solar component

W_{pv} = Daily solar energy demand

H_p= Peak sunshine hours

PR= Performance Ratio (80%)

The daily solar energy demand is the solar energy required to charge the battery and as a direct power source in the day [59].

$$W_{pv} = W_{pvbat} + W_{pvday} \tag{2}$$

Where: W_{pvbat} = solar energy demand to charge the battery

W_{pvday} = solar energy demand for direct load supply during the day

The peak sunshine hours (H_p) is determined from design month (with minimum average daily irradiation) and the solar irradiation at standard test conditions given as below [59];

$$H_p = \frac{G}{G'} \tag{3}$$

Where: G = minimum monthly average daily irradiation at optimal angle (11°)

G'= solar irradiance at standard test condition ($G' = 1000$W/m^2)

Solar panels in parallel

Depending the solar PV size calculated using equation (1) above and the size of panels in the market, the number of panels to be connected in parallel is calculated using equation (4) [60] given below.

$$P_p = \frac{P_{wp}}{P_m} \tag{4}$$

Where: P_p= Number of panels in parallel

P_{wp}= Total watt peak of the household or Small enterprise

P_m= Power rating at standard test condition of one module/panel

Solar panels in series

Depending on the system voltage, and the voltage of a single module/panel, the number of panels in series is determined using the equation (5) [60] given below;

$$P_s = \frac{V_s}{V_m} \tag{5}$$

Where: P_s= Number of panels in series

V_s= System voltage

V_m= Voltage of a module

Total number of panels

The total number of panels is determined from the product of number of panels in series and that in parallel as shown below [60];

$$P_T = P_p \times P_s \tag{6}$$

Where: P_T = The total number of panels for an individual system

3.4.4 Sizing for the battery storage

The size of the battery depends on the total energy demand from the battery in the evening and at night. The battery is considered like a pot used to store water during the day for later use at night. The method (7) [59] given below is used to size the battery storage;

$$B_B = \frac{E_{bat} \times AD}{V_s \times DOD \times \eta_{inv}} \quad (7)$$

Where: B_B= Battery storage size in Ampere hours (Ah)

E_{bat} = Energy storage demand (Wh)

AD = Autonomous Days

V_s = System voltage

DOD =Depth of Discharge (60%)

η_{inv} = Inverter efficiency (90%)

The energy storage demand is determined from the sum of the energy needed from the battery for the loads at night and the energy stored to take care of unexpected fluctuations of solar irradiation caused by swift movements of clouds during the day [59].

$$E_{bat} = E_{bat\_night} + \ (E_d \times 10\%) \quad (8)$$

Where: E_{bat_night} = energy storage demand by loads at night

E_d = day time load energy demand

In this thesis, 10% of the day time energy demand is stored to take care of abrupt changes in solar radiation.

Batteries in parallel

According to the battery storage size determined using equation (7) above, and the capacity of a single battery, the number of batteries in parallel for a system is calculated using equation (9) [60] given below.

$$B_p = \frac{B_B}{B_c} \quad (9)$$

Where: B_p= The number of batteries in parallel

B_c = The capacity of a single battery in Ah

Batteries in series

The number of batteries in series depending on the system voltage and the battery voltage is obtained using equation (10) [60] given below.

$$B_s = \frac{V_s}{V_b} \qquad (10)$$

Where: B_s= The number of batteries in series for a prosumer energy system

Total number of batteries

The total number of batteries is found from the product of batteries in parallel and in series using equation (11) shown below [60];

$$B_T = B_p \times B_s \qquad (11)$$

Where: B_T = Total number of batteries

3.4.5 Backup generator sizes

In this thesis, hybrid system is individually designed for a household and a retail shop business assumed to be owning backup petrol generators already. The sizes of the generators are assumed to be big enough to power the peak demand. From the load profile presented in Figure 3-5 and Figure 3-6 in section 3.3, a backup generator rated size of 1.0KW is separately used for the households and the retail shop electricity consumers.

This assumption is also in line with research done by All On and Shell [10] which reported popular sizes of generators used in Rives state as 1.0KW, 2.5KW and 6.5KW. The different fuels; diesel and petrol generators but the focus of this study focused on a petrol generator assumed to exist more in smaller sizes than the diesel generators.

3.5 Determining Energy Output of the designed energy systems

This section describes the methodology used to determine the output energy of the designed energy systems for the household and the retail shop. The estimation of PV performance, the backup petrol generator energy outputs are here described as follows;

3.5.1 Determining the solar PV daily energy output

The energy output of the solar PV generator is determined on daily basis depending on the daily solar irradiation data given in Appendix 8.

The method applied for the daily estimation of the PV performance is given below [61];

$$P_{pv} = P_{wp} \times \frac{G}{G'} \times \left[1 + \alpha_t\left(T_a - T_{ref}\right)\right] \quad (12)$$

Where: P_{pv}= Daily power output of the PV panels at time,

P_{wp} = Total PV watt peak under reference conditions;

G = daily solar irradiation (W/m^2) at optimal angle (11°)

G' = the reference solar radiation (1000W/m^2);

T_a = the daily ambient temperature, and T_{ref} is the reference temperature (25°C);

α_t = the PV panel temperature coefficient; for mono and poly crystalline silicon materials.

3.5.2 Determining the generator daily energy output

Daily energy output from the generators depends on the daily energy demand supplied by the generators during the period of a power outage in the evening. Energy output in a day from a generator is then added up in excel spread sheet to get the annual contribution of energy from the generators.

3.5.3 Determining the Excess/Unmet energy from the Solar System

Due to the day to day change 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 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 had to be an extra load to be supplied.

The total daily solar energy demand (sum of battery charging demand and the daytime direct solar power demand) as in equation (2) is assumed to remain constant for a year. Daily energy production from solar PV system is computed using equation (12).

The daily solar energy produced is compared to the daily solar energy demand to obtain any daily excess or unmet energy from solar. The calculations are done in excel spread sheet to obtain total daily excess energy in a year.

3.6 Determining the Annualized Cost of System for an end user

The annualized cost of a system (ACS) is the cost of the system spread or discounted yearly or annually over the whole project lifetime. It takes into account all costs involved in the life cycle of the system. A system with lower annualized cost becomes the most cost-effective system. The annualized cost of a system (ACS) is the summation of all yearly costs on all the components of the system. This includes the annualized capital cost (ACC), the annualized operation and maintenance cost (AOM), the annualized replacement cost (ARC), the annualized fuel consumption cost (AFC) [62].

$$ACS = ACC + AOM + ARC + AFC \quad (13)$$

The ACC of the irreplaceable components (solar panels, inverter) over the lifespan of project is determined as follows;

$$ACC = C_c \times CRF(i', n) \quad (14)$$

Where; C_c = the capital cost of a component expressed in $USD,

CRF= the Capital Recovery Factor.

n = the lifetime of the system in years.

$$CRF = \frac{i'(1+i')^n}{(1+i')^n - 1} \quad (15)$$

$$i' = \frac{i - f}{1 + f} \quad (16)$$

Where; i' = the real or effective annual interest rate

f = the inflation rate

i = the nominal interest rate

For components that get replaced before the end of the lifetime of the PV panel like the battery, and the backup generator, the CRF in ACC is calculated based on the lifetime of the component, y, in years as follows [62];

$$CRF = \frac{i'(1+i')^y}{(1+i')^y - 1} \tag{17}$$

And the ARC, of the replaceable components are calculated based on the replacement cost, C_{rep}, and the lifetime of the component, shown as follows [18];

$$ARC = C_{rep} \times K - ASV \tag{18}$$

$$K = N_{rep} \times SFF(i', y) \tag{19}$$

Where; $N_{rep} = \frac{n}{y} - 1$ if n is divisible by y

$N_{rep} = INT\left[\frac{n}{y}\right]$ if n is not divisible by y. INT returns the integer of the real value.

N_{rep}= number of replacement

SFF = Sinking Fund Factor

ASV= Annualized Salvage Value

$$SFF = \frac{i'}{(1+i')^y - 1} \tag{20}$$

If n is not divisible by y, the salvage value of the replaceable component is determined as [18];

$$S = C_{rep} \times \frac{R_l}{y} \tag{21}$$

Where: R_l = remaining life of the replaceable components at the end of the project determined as shown below [18];

$$R_l = y - \left(n - \left(N_{rep} \times y\right)\right) \tag{22}$$

The method gives salvage value of zero, for the number of replacement when the project lifetime is divisible by the component lifetime.

Annualized Salvage Value (ASV) of a component is found from equation (23) as follows [18];

$$ASV = S \times SFF(i', n) \tag{23}$$

The AOM is determined as a function of capital cost (C_c), reliability of components (μ) and their lifetime (y) [62].

$$AOM = \frac{C_c \times (1 - \mu)}{y} \tag{24}$$

The annualized fuel cost (AFC) depends on the amount of energy obtained from the backup petrol generator. The household and the retail shop have both petrol backup generators. And their fuel consumption is determined using the following method.

$$AFC = C_f \times f_E \times \sum_{t=1}^{365} E_{gen} \tag{25}$$

Where; C_f = the fuel cost per liter in \$ USD/l,

f_E = fuel consumption per unit energy (l/KWh),

E_{gen} = backup petrol generator daily energy output (KWh)

The fuel consumed per unit energy depends on the size, electric load and the operation of the petrol generator. The amount of fuel consumed per unit energy is obtained from the manufacturer’s product description information of each of the generators as shown in Appendix 2 and Appendix 3.

3.6.1 Determining the Levelized Cost of backup Electricity (LCoE)

The cost of energy paid for the electricity produced and used in a year is computed using equation (26) given below.

$$LCoE = \frac{ACS}{E_{year}} \tag{26}$$

Where; E_{year} = Electrical energy consumed in a year

3.7 Determining Carbon Dioxide Emissions

The carbon dioxide emissions from the hybrid system depend on the amount of energy used from the backup petrol generator, and the emission factor. The carbon dioxide emission in a year is determined from equation (27) given below. The result is presented and discussed in the next chapter.

$$CE = E_f \times \sum_{t=1}^{365} E_{gen} \tag{27}$$

Where; CE = Total Carbon dioxide emission in a year

E_f = Carbon dioxide Emission factor, (0.27kg/KWh for petrol fuel, [63])

E_{gen}= Generator daily energy output (KWh)

The results for all the calculations in this chapter are all presented and discussed in chapter four (next chapter) of this thesis report.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Designed Backup Energy System Units

Three different systems are designed for the household and the retail shop respectively and the results are discussed here in this section in comparison to the baseline system.

4.1.1 Designed backup energy system unit for the household

The result of the systems designed for the household is shown in Table 4-1 below.

Table 4-1. Technical analysis for the household systems

System Components	Generator (KVA)	Battery (Ah)	Inverter (VA)	Solar PV (Wp)
Baseline System	1.0	-	-	-
System-I	1.0	100	500	-
System-II	1.0	150	850	300
System-III	-	200	850	900

Table 4-2. The household battery and solar PV connections details

Component Connections	Battery Connection				Solar PV Connections				
	B_C (Ah)	B_s	B_p	B_T	P_{wp} (W_p)	P_m(W_p)	P_s	P_P	P_T
System-I	100	1	1	1	-	-	-	-	-
System-II	150	1	1	1	300	150	1	2	2
System-III	200	2	1	1	900	300	1	3	3

From Table 4-1 above, the baseline system and system-I consist of the backup generator as the main power source during power outage. System-II is a hybrid energy system consisting of both a backup petrol generator and solar PV as the energy sources during power outage. System-III is 100% renewable with solar PV as the main power source during power outage. The capacity of the generators is the same since it is considered an existing component, high enough to power the loads during peak hours.

System-I has a single battery with a 12V DC system voltage. The battery storage and the inverter size are bigger in System-II than in system-I. This is because for the same household electricity demand from the battery in system-II is higher than in system-I. System-II also has a battery system voltage of 12V DC.

In system-III, the household entirely depends on the electricity stored in the battery. This results into a bigger battery capacity and the solar PV size than those in system-II. There are two 150Ah batteries of 12V DC connected in series in system-III, forming a battery system voltage of 24V DC as indicated in Table 4-2 above. The solar panels of System-II and III, are all connected in parallel.

From the Table 4-1 above, the solar PV size for system-III is three times bigger than that of system-II. This implies that a bigger capacity of solar PV is required for complete replacement of the generator while maintaining the same types of electric loads for the same duration of time.

4.1.2 Designed backup energy system unit for the retail shop

The result of the energy systems designed for the retail shop is presented in Table 4-3 and Table 4-4 below.

Table 4-3. Technical analysis for the retail shop Systems

System Components	Generator (KVA)	Battery (Ah)	Inverter (VA)	Solar PV (Wp)
Baseline System	1.0	-	-	-
System-I	1.0	120	300	-
System-II	1.0	200	500	405
System-III	-	150	850	600

Table 4-4. The battery and solar PV connections details for the retail shop consumer

Component Connections	Battery Connection				Solar PV Connections				
	B_C (Ah)	B_s	B_p	B_T	P_{wp} (W_p)	P_m(W)	P_s	P_P	P_T
System-I	120	1	1	1	-	-	-	-	-
System-II	200	1	1	1	405	135	1	3	3
System-III	150	2	1	2	600	300	1	2	2

Generally, from Table 4-3 above the battery capacity, the inverter and the panel sizes increase from system-I to system-III. This is as result of shift of power supply from the backup petrol generator in the baseline system to the battery in system-II and III.

In system-I, much of the electricity demand is directly supplied by the generator hence a smaller battery size of 120Ah. The system has only one battery with 12V DC voltage.

System-II, with solar PV integrated, has 200Ah battery capacity bigger than the battery size in system-I. This is for the reason of more energy consumed from the battery in system-II than in system-I. System-II also consists of one battery of 12V DC voltage.

System-III is purely renewable designed as a replacement for the backup petrol generator. The battery system voltage in system-III is 24V DC resulting from two batteries of each 150Ah, 12V DC connected in series.

For systems-II and -III, the solar panels are all connected in parallel since they have the same module voltage as their system voltage.

4.2 Economic Analysis for the designed backup energy systems

The main economic parameters applied in this study to show the benefit of integrating solar PV with existing generators include, the Initial Cost of the System (ICS), the Annualized Cost of the system (ACS), the Levelized Cost of Energy (LCoE), and the Annual Fuel Cost (AFC). These parameters are calculated in excel spread sheet and their results are summarized in a table as further discussed in the following sub-sections.

4.2.1 Economic analysis for the household systems.

The economic viability of the systems is assessed in order to see suitable means of saving fuel from the backup generators for the household. The result is summarized in Table 4-5 below.

Table 4-5. Economic analysis for the household systems

Economic Parameters	AFC ($ USD)	LCoE ($ USD/KWh)	ACS ($ USD)	ICS ($ USD)
Baseline System	349.12	0.574	381.89	137.3
System-I	437.94	0.642	535.52	421.6
System-II	213.48	0.447	357.81	932.1
System-III	—	0.282	296.04	1939.1

From Table 4-5 above, integrating a battery to be charged by the backup generator is not recommendable. Since the generator consumes more fuel to run the additional load of charging the battery. It also increases the cost of backup power and the system cost over the lifetime, which is the case seen with system-I in comparison to the baseline system.

The economic analysis for system-II reveals that charging the battery added to the backup generator by solar PV during the day and using the stored energy at night alongside a generator is more economically effective. This is in comparison to system-I where the generator is used to charge the battery and the baseline system where the generator is the only backup power source. With system-II, the household spending on fuel is reduced, reducing the system cost by the end of the lifetime. However, the household has to pay high initial cost than in system-I in order to integrate both the battery and the solar PV to the existing system.

System-III designed to replace the backup generators, is the most economical by the end of its lifetime, reducing the fuel cost to zero and cost of electricity to the minimum. However, in comparison to other systems, the initial cost is too high (more than fourteen times higher than the initial cost of baseline system) which can be challenging for the household to implement.

From Table 4-5 above, the fuel cost is reduced by about 39%, the levelized cost of backup electricity by about 22% in system-II from the baseline system. System-II is also slighlty cheaper than baseline system by 6.3% at the end of their lifetime. From the load profile of system-II (Figure 3-11) electricity is supplied for longer period than the baseline system increasing electrcity availability duration and reliability. Therefore, developing a smart financial meachnism that helps to overcome the high barrierr of the initial investment cost of system-II, the integration of a solar PV system as a fuel saver for a backup generator is highly potential.

4.2.2 Economic analysis for the retail shop systems

The systems designed for the retail shop are also economically assessed. The result of the assessment done in excel is summarized in Table 4-6 below and is further discussed.

Table 4-6. Economic analysis for the retail shop systems

Economic Parameters	AFC ($ USD)	LCOE ($ USD/KWh)	ACS ($ USD)	ICS ($ USD)
Baseline System	299.74	0.582	332.51	137.3
System-I	372.67	0.683	485.04	431.4
System-II	140.96	0.403	320.01	1069.6
System-III	—	0.271	214.05	1393.6

Adding a battery to the baseline system to be charged by the existing generator as in system-I is less economically viable in comparison to the baseline system (a generator without a battery). It results in an increased fuel price, high cost of backup electricity, and making the system more costly than other systems by the end of their lifetime.

Charging the battery added to the baseline system by solar PV is more economically viable than charging it with the generator. This is seen from Table 4-6 above on comparing system-II with system-I. In system-II, the fuel cost, the cost of backup electricity and the cost of the system at the end of its lifetime are all reduced compared to system-1 and the baseline system.

Completely replacing the generator by a solar PV system in system-III is highly economical over the system lifetime. It also results in a reduced fuel cost to zero, and a very low cost of backup electricity in comparison to other systems.

However, system-III has the highest initial cost among all other systems, more than ten times the initial cost of the baseline system. And this high initial cost can be discouraging for the retail shop owner to adopt such a system.

Reducing fuel cost by about 53%, levelized cost of backup electricity by about 31% and moderately lower annualized cost of the system by 3.8%, integrating solar PV (in system-II) to charge a battery added to an existing backup system of only petrol generator (baseline system) is taken to be a more suitable system for the start as a way to save fuel costs and replace the fossil-fuel generator with a cleaner energy source.

Even though system-II has a higher initial cost than the baseline system, it provides electricity for a longer period (see Figure 3-12). And an adapted-financing mechanism could be applied to overcome the barrier.

4.3 Energy Analysis of the Selected Systems

System-II is separately selected for the household and the retail shop. In this system, solar PV is integrated to charge the batteries added to the baseline system. This section covers the energy production and consumption analysis of this system separately selected for the household and the retail shop as described in the sub-sections below.

4.3.1 The energy analysis for the selected household system

The energy supplied by the household system throughout the year is illustrated using Figure 4-1 below,

According to the figure, the share of the generator in a day is always 1.11KWh throughout the year except in the rainy seasons (months June, July and August) when the solar irradiation is insufficient resulting in unmet energy from solar PV to charge the battery. The unmet energy is alternatively supplied by the fossil-fuel generator in hybrid connection with the solar PV. The national grid could as well be used to supply the unmet energy on rainy days whenever power from grid is available.

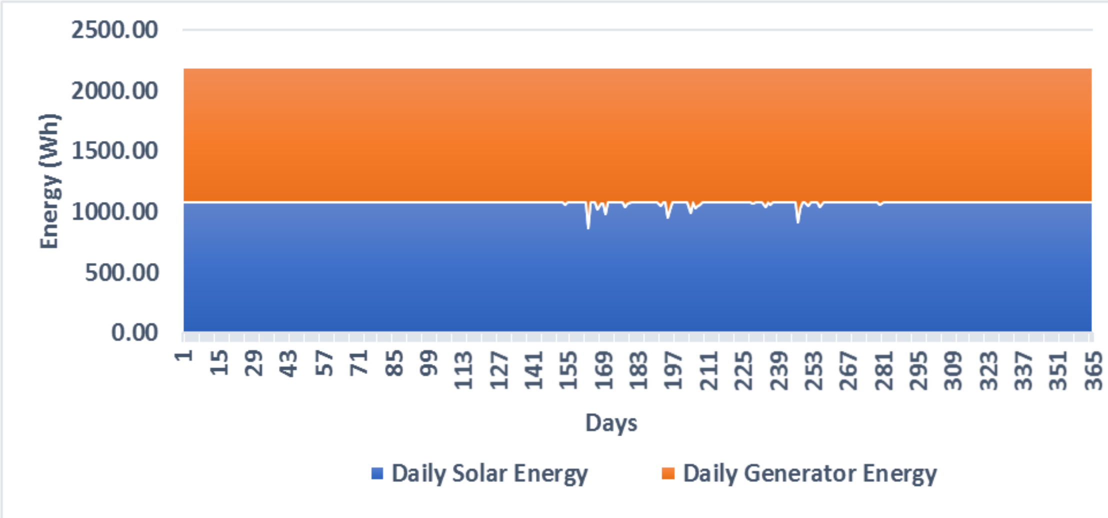

Figure 4-1. Household energy consumed from solar and petrol generator in a year

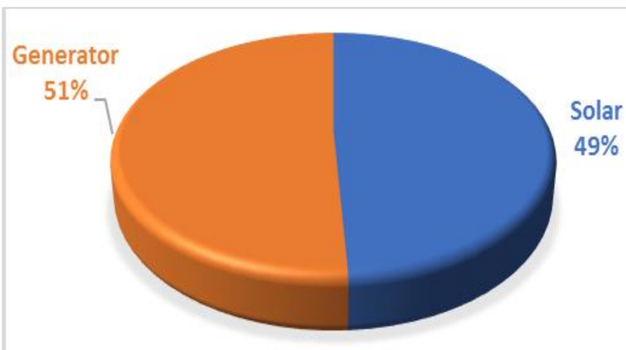

Figure 4-2. Household's backup energy mix

The household fossil-fuel generator contributes slightly the largest share of the energy consumed by the household. From Figure 4-2 above, the share of energy utilized from the generator is 51% (407.1KWh/year) and from solar is 49% (393KWh/year).

The untapped excess energy from the household backup generator

At the daily energy demand of 1.11KWh from the fossil-fuel generator, the hourly peak power demand of the generator is 0.56KW as shown in system-II load profile for the household in Figure 3-11 and Appendix 6. The fossil-fuel generator has a rated capacity of 1.0KW. Assuming the generator is operated at 80% of its rated capacity, an untapped excess (virtual) energy of about 0.24KWh in an hour could be potentially produced in system-II. This would result in about 0.48KWh excess energy in a day of two hours of operating the backup generator for the selected household system.

4.3.2 The household's solar PV system energy analysis

The designed system selected for the household provides electricity during the assumed time of power outage in the evening, throughout the night until the dawn. Within this time the household total daily energy demand is about 2.1KWh. The share of the solar energy system in system-II for the household is 0.97KWh about 49% of the total demand. See the Figure 4-2, and Appendix 6. This energy is mainly supplied through the battery.

Taking the depth of discharge, the efficiency of the inverter and the autonomy days into consideration, a battery storage of 150Ah (1800Wh) is calculated using equation (7). With a 60% depth of discharge, a daily energy needed to charge the battery is found to be 1.1KWh. As solar PV is mainly used to charge the battery, the daily energy demand of 1.1KWh for charging the battery is depicted by the green color, in Figure 4-3 below as solar energy demand.

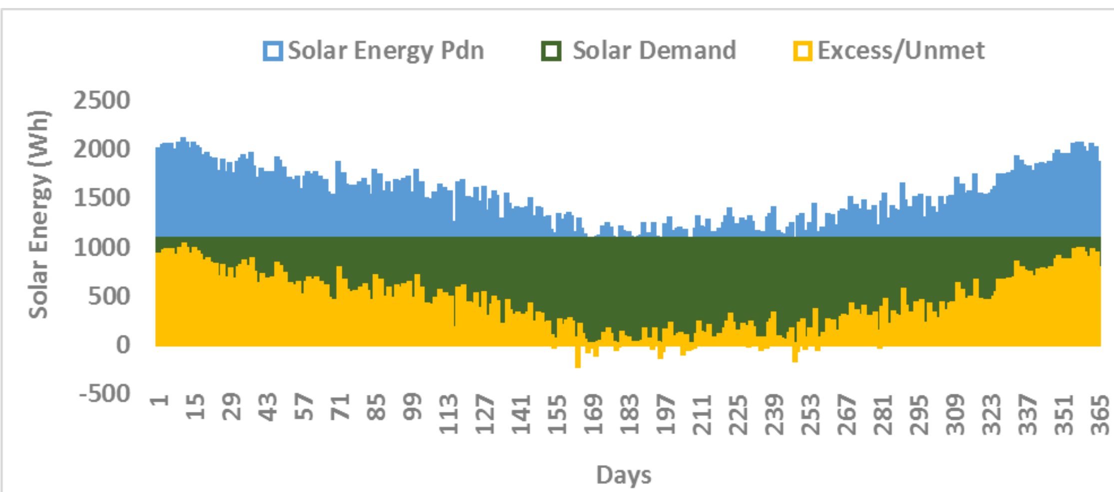

Figure 4-3. Household's solar energy production and consumption analysis

The result of the household solar energy analysis is as shown in Figure 4-3 above. From the figure, it is seen that the production of solar energy is maximum at the beginning and towards the end of the year. In the rain season in the months of June, July and August, the solar energy production is minimum.

The daily energy from solar is assumed to be constant throughout the year. The excess energy is highest at the beginning and towards the end of the year. In the rainy season, in the months of June, July and August, energy from solar is insufficient to charge the batteries. This results in an unmet energy from solar as shown by the yellow bars below the zero mark of the solar energy axis in Figure 4-3 above. In these months, the battery could be charged with power from the national grid at the time when its available. This would increase the electricity bills but analysis for this is considered out of scope in this study.

The daily excess energy is summed for a year and is found to be 27% of the total solar energy to be potentially produced in a year, as represented in Table 4-7, and Figure 4-4 below.

Table 4-7. Household's solar system energy analysis

Parameter	Value	Units
Total potential solar energy	540	KWh/year
Used solar energy	393	KWh/year
Excess energy generation	147	KWh/year
Ratio of excess generation	27.2	%
Average daily excess energy	428.64	Wh/day

The excess solar energy not utilized is 147KWh/year about 27% of the total potential solar energy production of 540KWh/year. The maximum daily excess energy is about 1KWh, and the average daily excess energy in a period of a year is 428.64Wh (0.43KWh).

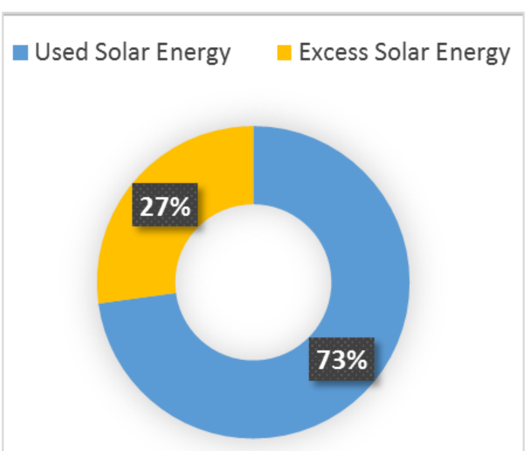

Figure 4-4. Household’s ratio of excess solar energy

4.3.3 The energy analysis for the selected retail shop system

The retail shop consumer is more dependent on solar energy. The total daily energy demand for the retail shop system-II is about 1.8KWh according to the load profile in Figure 3-12 and Appendix 7. The share of energy from the fossil-fuel generator is about 0.73KWh and from solar PV system is about 1.1KWh except on some days in rainy season when solar irradiation is insufficient. The generator is used to supply the unmet energy from solar to charge the battery in the rainy seasons, as seen from Figure 4-5 below. The retail shop energy mix is further illustrated in Figure 4-6 below.

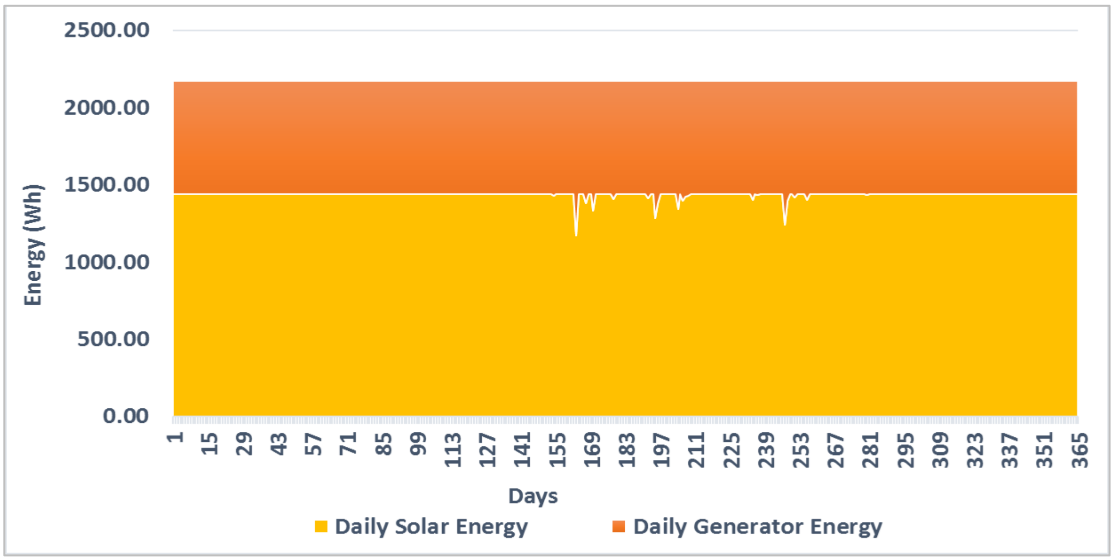

Figure 4-5. Retail shop energy consumed from solar and petrol generator in a year

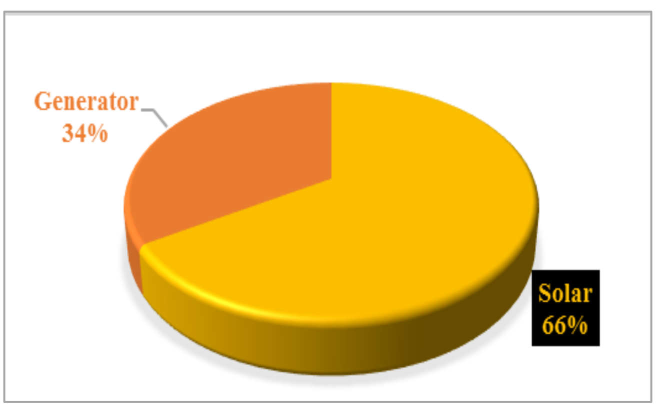

Figure 4-6. Retail shop backup energy mix

From Figure 4-6 above, it can be deduced that reducing the usage hours of the backup generator from six hours in the baseline system to two hours in the system-II results in about 66% adoption of solar energy for the retail shop. The total amount of energy from the backup petrol generator is 268.8KWh/year and from solar PV is 524.3KWh/year.

The retail shop backup generator untapped excess energy in system-II

The energy supplied by the retail shop backup generator in a day is 0.73kWh. The hourly peak power demand of the generator is 0.4KW as shown in the load profile for the retail shop system-II in Figure 3-12 and Appendix 7. The rated capacity of the backup generator is 1.0KW. Assuming the backup generator is operated at about 80% of its rated capacity, an untapped excess (virtual) energy of about 0.4KWh in an hour could be potentially produced. This would result in about 0.8KWh excess energy in a day of two hours of operating the backup generator in system-II for the retail shop.

4.3.4 The retail shop's solar PV system energy analysis

The retail shop total daily energy demand is about 1.8KWh. The share of solar PV system is 1.1KWh, and the energy is supplied through the battery since the energy is needed in the evening and at night. Considering the depth of discharge, the efficiency of the inverter and the autonomy days, a battery storage of 200Ah (2400Wh) is calculated using equation (7). With a depth of discharge of 60%, a daily battery charging energy demand of 1.44KWh is determined. Solar PV is mainly used to charge the battery with backup support from the petrol generator on cloudy days.

The daily storage demand of 1.44KWh forms the daily solar energy demand as depicted by the brown color in Figure 4.7 below, and the daily solar energy generated is represented by the yellow color, and the excess energy is green.

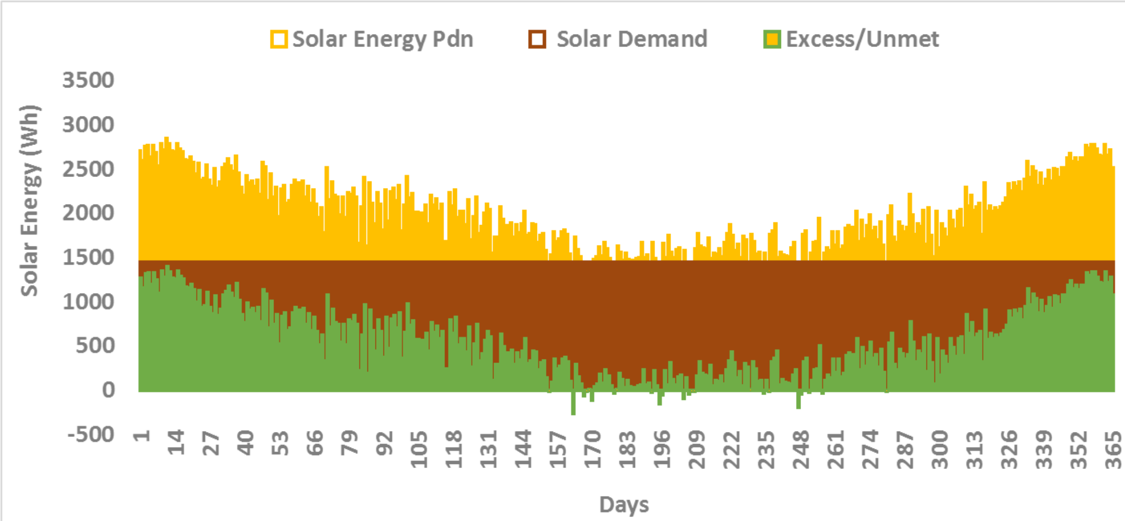

Figure 4-7. The retail shop's solar PV system energy analysis

The solar energy production is highest in the beginning and towards the end of the year similar to excess solar energy generation. The excess energy varies per day and is available on most of the days in a year with exception of some days in the rainy season year with very low solar irradiation. In the rain season which occurs in the months of June, July and August, unmet energy from solar PV to charge the battery can be realized. In this time, the backup petrol generator is used to charge the battery.

For the retail shop's designed hybrid energy system, the excess solar energy production is approximately 28% of the total solar energy production in a year as shown in the table 4.11 below and figure 4.6 below.

Table 4-8. Retail shop's solar system energy analysis

Parameter	Value	Units
Potential solar energy	728.4	KWh/year
Used solar energy	524.3	KWh/year
Excess energy generation	204.1	KWh/year
Ratio of excess generation	28	%
Average daily excess energy	591.6	Wh/day

The potential solar energy production in a year is 728.4KWh, the used solar PV energy is 524.3KWh, and the total excess solar energy produced in a year is 204.1KWh. The daily maximum excess solar PV energy is about 1.4KWh, which occurs in the first month of the year. The average of the daily excess solar energy is approximately 591.6Wh (0.59KWh).

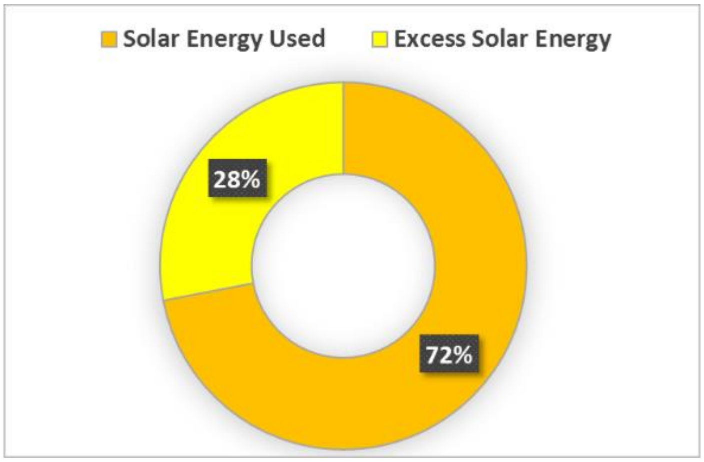

Figure 4-8. Retail shop excess solar energy as a percentage of the total solar production

4.4 Carbon dioxide Emission Analysis for the Selected Systems

The carbon dioxide emission is analyzed for the selected systems in comparison to the baseline systems for the household and the retail shop. The baseline system consists of only the backup petrol generator being used for fours for the household and six hours for the retail shop in in the evening during power outage. Meanwhile the selected systems are hybrid systems consisting of a solar PV, a backup petrol generator, and a battery. In the selected systems due to the integration of a solar PV system, the usage hours of the backup petrol generators reduced to two for both the household and retail shop systems, and the carbon dioxide emissions are assessed with the result given below.

The carbon dioxide emission reduction is found to be more for the retail shop than household consumer because the electricity supply share from solar in the hybrid system is much higher for the retail shop consumer compared to the household consumer.

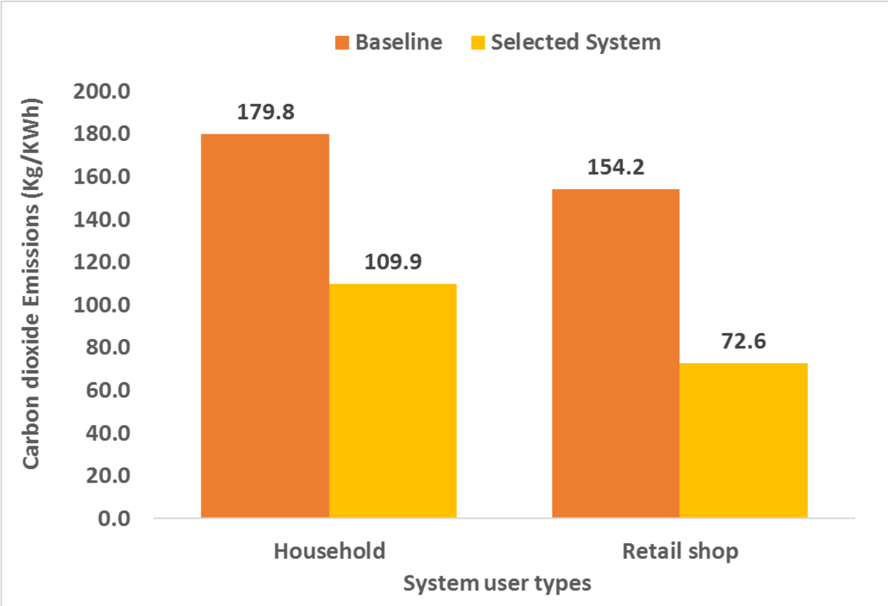

Figure 4-9. Showing the carbon dioxide emission savings for a consumer

Solar PV system supplies 49% of the household electricity demand resulting in carbon dioxide emissions savings of about 70kg/KWh in a year, and 1.4tons/KWh by the end of the lifetime of the solar PV panels. Whereas with 66% of the retail shop electricity demand supplied by the solar PV system, the carbon dioxide emissions reduction is found to be 82kg/KWh in a year, and 1.64tons/KWh by the end of lifetime of the PV panels.

4.5 Hybrid Swarm Electrification Assessment

This section describes the assessment for the potential for a hybrid swarm electrification concept as proposed in this study. The assessment is limited to the excess energy that could be generated as discussed in the section 4.3 of this report.

With the high penetration of individually owned generators in Nigeria, as seen in section 2.2, this study assessed the technical and economic impacts of integrating as a fuel saver, a solar PV system with a backup generator operating in a swarm-grid. From the economic assessment of integrating solar PV system as discussed in section 4.2, the following summary of the result is made:

- The household system with 49% energy share from integrated solar PV system attained a fuel cost savings of 39%, a reduction in the levelized cost of backup electricity by 22%, and a reduction in the annualized cost of the system by 6.3% over the lifetime of the system in comparison to the baseline system.
- The retail shop system with 66% energy share from solar PV system results in a fuel costs savings of 53%, a reduction in levelized cost of backup electricity by 31%, and a reduced annualized cost of the system by 3.8% over the lifetime in comparison to the baseline system.

Based on these results for the economic analysis, integrating a solar PV system alongside an existing backup generator operating in a swarm-grid is has a high potential to reduce fuel costs.

From the technical analysis done as discussed in section 4.3 for the energy production and consumption in the hybrid systems containing a battery and solar PV generator the following summary of the results is made:

- If the backup petrol generator had to be operated at 80% of its rated capacity, it would result in more energy conversion into electrical energy
- Energy production from solar PV system varies in a year depending on the weather, resulting in excess energy generation
- The household system backup petrol generator (rated 1.0KW) would have about 0.48KWh untapped excess energy in a day if it had to be operated at 80% of its rated capacity for two hours
- The integrated solar PV system for the household generates a total excess energy of about 147KWh in a year and a daily average of 0.43KWh in a period of a year
- The retail system backup petrol generator (also rated 1.0KW) would have about 0.8KWh untapped excess energy in a day if it had to be operated at 80% of its rated capacity for two hours

- The solar PV system integrated in the baseline system of the retail shop generates a total excess energy of 204.1KWh in year and a daily average of 0.59KWh in a period of a year

The solar PV excess energy is found to be 27% of the total potential solar energy production in a year for the household system and 28% for the retail shop system. This result is found to be similar to a study by Kirchhoff, in which he found out that a single solar home system also generates slightly over 30% of the total potential energy [37].

This kind of excess energy is normally wasted if not utilized. Swarm electrification provides a unique approach to share excess energy from a hybrid energy system for a household or retail shop end user. Therefore, the proposed strategy to interconnect the existing backup infrastructure in a swarm electrification grid would complement the integration of the solar PV systems for an end user. The excess energy from the solar PV would be shared through the swarm-grid.

An integration of solar PV would on one hand reduce the energy shared in the swarm-grid from the backup generators, and on the other hand increase energy shared from the solar PV system. The reduction in energy shared from backup generators would mean lowering fuel costs due to reduced hours of running a backup fossil fuel generator.

Utilizing the excess energy through SE approach would further reduce the levelized cost of backup electricity for the ender users due to increased use of available energy. Hence, cost of backup electricity becomes cheaper in swarm-grid than in baseline & system-II.

Table 4-9. LCoE for systems operating in a swarm-grid

End users	Systems	LCoE	Reduction in LCoE
Household	Baseline	0.574	—
	System-II	0.447	22%
	System-II (Swarm-grid)	0.378	34%
Retail shop	Baseline	0.582	—
	System-II	0.403	31%
	System-II (Swarm-grid)	0.321	45%

From the table above, the levelized cost of the backup electricity in swarm-grid reduces by 34% for the households and 45% for the retail shop from the baseline system since the individual users can sell electricity to their neighbors in a swarm-grid.

This study, therefore, highly recommend that hybrid SE approach is suitable and highly potential for areas with high penetration of backup fossil-fuel generators. It asserts that both technical and economic benefits can be realized from running fossil-fuel generators close to the optimal point while trading energy from the backup generators with neighbors in swarm-grid.

Not limited to strategy of SE being proposed in this study, the excess energy from solar PV system can as well be utilized by powering more loads during the day. The household or the retail shop users could for longer period watch TV, listen to radio, charge mobile phones and other solar system batteries during the day in order to maximize the excess solar energy.

4.6 Limitation of the study

One major limitation was encountered in the course of carrying out the study. And this was majorly in the methodology concerned with the load profile estimations for the household and the retail shop enterprise. The load profiles used in this study were purely estimations after reviewing the literature since no real data was collected.

In the load profile estimation, little knowledge is known about the energy use pattern during power outage in the case of Nigeria. Also lacking is the user behavior in regards to the use of backup generators, their electrical appliances and the willingness to integrate solar PV system.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main idea described in this thesis is the hybrid swarm electrification approach for areas with an existing high penetration of backup generators. The idea is an extension of the concept of swarm electrification developed for the case of Bangladesh. In the review of the literature, the study found that there is high penetration of household based backup generators in Nigeria as a result of unpredictable and rampant power outages.

It is reported that 60 million Nigerians own generators, and they are the biggest importers of generators in Africa. Generally, generator usage in Nigeria was found to be at least three to four hours for households and up to six hours for small businesses on daily basis. This has led to high expenses for the families and small businesses. With increasing fuel prices, fuels costs are reported to be as high as 40% of the total overhead costs for small and medium enterprises.

For the reason of environmental protection, energy efficiency, and fossil fuel cost reduction, this study proposed a strategy to interconnect the existing infrastructure in a swarm grid and to integrate alternative storages and renewable energy generators step by step. Doing so, fuel consumption of backup generators could be optimized and gradually reduced and the share of renewable energies increased.

The study focused on integrating solar PV system step by step with the existing backup infrastructure operating in a swarm-grid. Three major steps resulting into three systems are applied for the technical and economic assessment of the integration of a battery and solar PV generator in comparison to the baseline system. The baseline system consists of the backup petrol generator only. The analyses were done for a household and retail shop enterprise.

System-I included adding a battery to be charged by the backup generator. The battery would be later used instead of a generator reducing the usage hours of the generator from the backup system. System-II included a solar PV integrated to charge the battery instead of using a backup generator, further reducing the generator usage hours. System-III included completing replacing the backup generator with a solar PV system.

The study found that integrating a battery to be charged by the backup generator while reducing its usage hours is not viable option. It results into higher fuel costs arising from the additional load of charging the battery. However, the study also found that integrating a solar PV to charge the battery while limiting the generator usage to the peak hours is a more viable option resulting in a hybrid system.

The hybrid system for the household had 49% of solar energy share resulting in 39% fuel cost saving, 22% reduction in levelized cost of backup electricity, 6.3% reduction in annualized cost of the system, and CO_2 emission saving of 70Kg/KWh/year in comparison to the baseline system. A potential daily untapped energy of 0.48KWh is found from the backup generator. The household's solar PV system generates 27% excess energy in a year.

The retail shop hybrid system consists of 64% solar energy share. This reduced fuel costs by 53%, levelized cost of backup electricity by 31%, and annualized cost of the system by 3.8%, and CO_2 emission by 82Kg/KWh/year in comparison to the retail shop baseline system. Potential daily untapped energy from the backup generator is found to be 0.8KWh. Excess energy from the solar PV system is found to be 28% of the total potential solar PV production in a year.

It is, therefore, concluded integrating existing backup infrastructure in a hybrid swarm-grid would complement the integration of renewable storage facilities and energy sources. Integrating solar PV system results in lower fuel costs, reduced carbon dioxide emission, and increased share of renewable energy mix for the end users. The hybrid swarm electrification, a bottom-up approach would allow the households and enterprises to become prosumers (both a producer and consumer), able to share or trade energy with neighbors, providing electricity to those without individually owned backup systems. The prosumers without comprising the multi-tier frame work would have a more affordable system due to reduced annualized system costs.

5.2 Recommendations for Future Research

The designed hybrid systems had high initial investment cost compared to the baseline system. It is therefore, recommended to further research on an adaptable and inclusive financial mechanisms to overcome the high investment cost of the hybrid systems.

The systems in this study are designed without changing the existing electrical appliances of with more efficient ones. As such this study could be repeated with the use DC and more efficient loads in the design. Also, to be assessed is the use of excess energy from solar PV system as a direct power source during the day for an end user.

There is need to carry out a research to understand the use cases of small fossil-fuel based generators during power outage. The overall aim would be to develop electricity use pattern during the power outage period and the user behaviors.

This study found out a high potential of excess energy that could be shared in a swarm-grid from the individual hybrid system. However, the study did not further analyse how much this energy can be shared, how much is recievd by a neighbor. There is therefore a need to carry out a detailed modelling and simulation of a such a swarm-grid with a case study in Nigeria.

The simulation could focus but not limited to some of the following research questions;

1. How much energy can be supplied to/taken from the swarm-grid by the participating household (node)?
2. What's the total share of energy from solar or generator supplied to the swarm-grid from the nodes?
3. What's the battery state of charge for a node in a swarm-grid within a given time step?

Other areas of further research include;

- Finding the socioeconomic dynamics of energy sharing in a hybrid swarm-grid
- Determining the potential approaches of integrating swarm-grid and their modes of operation with the national centralized grid, and the mini-grids?

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APPENDICES

Appendix 1. Parameters considered for economic and other analysis

Parameters	Value	Units
Nominal interest rate [64]	14	%
Inflation rate [64]	16.1	%
System lifetime	20	years
PV Panel lifetime	20	years
Battery lifespan	8	years
Generator lifespan	10	years
Cost of PV Panel (140W) [65]	$166.67	USD
Cost of Inverter (850VA)[66]	$196.08	USD
Cost of Battery (200Ah) [65]	$336.11	USD
Cost of Generator (1KVA) [65]	$137.25	USD
Cost of Fuel [67]	$0.46	USD /L
Carbon dioxide emission factor [63]	0.27	Kg/KWh
Reliability of PV panels	0.95	
Reliability of Inverter	0.95	
Reliability of Battery storage	0.95	
Reliability of generator	0.60	

Appendix 2. Household backup generator details [65]

- AC Output: 220V 1.3KVAa max. / 1.0KVA rated
- DC Output: 12V/8.3A
- Phase No.: Single Phase
- Power Factor: 1.0
- Engine GX90, Max 2.8HP,4-stroke single cylinder, OHV, air cooled
- Alternator brushless electric machine, synchronous,2-pole,100% Copper Enameled Wire
- Starting System Recoil
- Fuel Tank Capacity: 6.0L
- Fuel: Petrol
- Run Time per Tankful 7Hrs@75%Load
- Dimensions (L x W x H) 460*380*330
- Noise Level@ 7 Meters 66dB
- Weight: 26.5Kg

Appendix 3. Retail shop enterprise backup generator details [65]

- AC Output-220V 1.1KVA max. / 1.0KVA rated
- DC Output-12V/8.3A
- Phase No-. Single Phase
- Power Factor: 1.0
- Engine-154F Max3.0HP, 4-stroke single cylinder, OHV, air cooled
- Alternator-Brushless, self-exciting, synchronous,2-pole100% Copper Enameled Wire
- Starting System-Recoil
- Fuel Tank Capacity-5.5L
- Fuel-Petrol
- Run Time per Tankful-8Hrs@50%Load
- Dimensions- (L x W x H)455*365*355
- Noise Level@ 7 Meters-66dB
- Weight-25Kg

Appendix 4. Luminous solar hybrid inverter [66]

- Luminous 850 VA/12V Solar hybrid inverter charger
- Has both AC & DC output
- Pure sine wave output
- Protection against high temperature, short circuit, and overloading
- Up to 1000W solar PV module compatibility
- Intelligent fuzzy logic for maximum utilization of solar energy

Appendix 5. Solar panel manufacturing technical data [68]

ELECTRICAL DATA		AE135P6-36	AE140P6-36	AE145P6-36	AE150P6-36	AE155P6-36	AE160P6-36
Nominal power	Pm (Wp)	135	140	145	150	155	160
Open circuit voltage	Voc (V)	21.99	22.23	22.43	22.72	22.97	23.15
Short-circuit current	Isc (A)	8.21	8.36	8.53	8.68	8.79	8.89
Voltage at max power	Vmp (V)	18.11	18.43	18.65	18.97	19.30	19.51
Current at max power	Imp (A)	7.45	7.60	7.77	7.91	8.03	8.20
Module efficiency	(%)	13.61	14.12	14.62	15.13	15.63	16.14
Cells efficiency	(%)	15.57	16.14	16.72	17.29	17.87	18.45
System Voltage	(V)	1000					
Temp. coefficient Voc	(% / °C)	-0.36					
Temp. coefficient Isc	(% / °C)	0.06					
Temp. coefficient Pm	(% / °C)	-0.36					
Operating temp.	(°C)	-40 bis +85					
NOCT	(°C)	45±2					

The electrical data apply to standard test conditions (STC): Irradiance of 1000 W/m² with spectrum AM 1.5 and a cell temperature of 25°C.

Appendix 6. Household energy consumption profile in System-II

Loads/ Time	Indoor Lights	Outdoor Lights	Fan	Fridge	TV	DVD player	Laptop	Radio	Total	
1		0.018							0.018	
2		0.018							0.018	
3		0.018							0.018	
4		0.018							0.018	
5	0.018	0.018							0.036	
6	0.018	0.018							0.036	
7								0.02	0.02	
8								0.02	0.02	0.184
9										
10										
11				0.2					0.2	
12			0.1	0.2					0.3	
13			0.1	0.2	0.1	0.05			0.45	
14			0.1		0.1	0.05			0.25	
15			0.1		0.1	0.05			0.25	
16								0.02	0.02	
17								0.02	0.02	
18								0.02	0.02	0.04
19	0.018	0.018	0.1	0.2	0.1	0.05	0.07		0.556	
20	0.018	0.018	0.1	0.2	0.1	0.05	0.07		0.556	1.112
21	0.018	0.018		0.2	0.1	0.05	0.07		0.456	
22	0.018	0.018			0.1	0.05	0.07		0.256	
23		0.018							0.018	
24		0.018							0.018	0.748
	0.108	**0.216**	**0.6**	**1.2**	**0.7**	**0.35**	**0.28**	**0.1**	**3.554**	**2.084**

(yellow)	Solar System	0.972KWh
(orange)	Generator	1.112KWh
(white)	Assumed National Grid.	1.47KWh

Appendix 7. Retail shop energy consumption in System-II

Loads/ Time	Indoor Lights	Outdoor Lights	Fan	TV	Satellite Receiver	Phone Charger	Fridge	Radio	Total	
1		0.018							0.018	
2		0.018							0.018	
3		0.018							0.018	
4		0.018							0.018	
5		0.018							0.018	
6		0.018							0.018	
7	0.033								0.033	
8	0.033							0.015	0.048	
9								0.015	0.015	0.204
10							0.2	0.015	0.215	
11							0.2	0.015	0.215	
12				0.08	0.03	0.015			0.125	
13				0.08	0.03	0.015			0.125	
14			0.04	0.08	0.03	0.015			0.165	
15			0.04	0.08	0.03		0.2		0.35	
16			0.04	0.08	0.03		0.2		0.35	0.35
17			0.04	0.08	0.03		0.2		0.35	
18	0.033		0.04	0.08	0.03		0.2		0.383	0.733
19	0.033	0.018		0.08	0.03				0.161	
20	0.033	0.018		0.08	0.03				0.161	
21	0.033	0.018		0.08	0.03				0.161	
22		0.018							0.018	
23		0.018							0.018	
24		0.018							0.018	0.537
	0.198	**0.216**	**0.2**	**0.8**	**0.3**	**0.045**	**1.2**	**0.06**	**3.019**	**1.824**

(yellow)	Solar System	1.091KWh
(orange)	Generator	0.733KWh
(white)	Assumed National Grid	1.195KWh

Appendix 8. Daily solar irradiation and daily average temperature data for Elele, Nigeria [54]

Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)	Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)	Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)
1	6738.69	27.6	123	4628.51	26.7	245	3953.75	24.8
2	6459.01	27.6	124	5341.65	26.9	246	4118.97	24.8
3	6874.47	28.0	125	4216.99	26.8	247	3057.96	24.8
4	6908.25	28.2	126	4869.59	27.0	248	3435.85	24.6
5	6560.69	27.8	127	5402.44	26.6	249	4327.88	24.9
6	6879.77	27.7	128	4389.49	26.8	250	4441.39	24.9
7	6704.25	27.9	129	4590.85	26.9	251	3501.25	24.8
8	6325.66	27.8	130	4981.47	27.0	252	3820.64	24.6
9	6933.55	27.5	131	5215.16	26.6	253	4101.78	24.8
10	6759.55	27.6	132	5069.96	26.8	254	4129.26	24.9
11	7081.93	27.8	133	3838.62	26.4	255	4776.98	25.0
12	6933.47	27.9	134	4277.73	26.4	256	3454.73	24.8
13	6741.51	28.0	135	4293.05	26.6	257	3810.95	24.8
14	6710.17	27.8	136	5129.59	26.5	258	3953.66	24.8
15	6935.92	27.8	137	4785.12	26.8	259	3881.12	24.8
16	6814.12	28.3	138	4619.50	26.5	260	4413.33	25.0
17	6720.75	28.0	139	4610.90	26.4	261	4051.58	25.1
18	6493.83	27.6	140	4695.64	26.6	262	4403.66	25.0
19	6463.72	27.5	141	4279.90	26.7	263	3910.44	25.0
20	6567.31	27.6	142	4622.67	26.4	264	4022.99	25.0
21	6412.98	27.8	143	4414.89	26.0	265	4516.43	25.0
22	6076.76	27.8	144	4661.53	26.2	266	4594.73	25.1
23	6403.05	28.3	145	5006.64	26.5	267	4533.26	25.1
24	5916.94	28.3	146	4322.72	26.4	268	4533.40	25.3
25	5976.02	28.1	147	4377.41	26.1	269	4990.49	25.3
26	6348.65	28.0	148	4661.93	26.1	270	4125.67	24.9
27	5905.05	27.8	149	4634.31	25.8	271	4741.58	25.1
28	5748.40	27.9	150	4131.90	26.0	272	4219.95	25.1
29	6241.88	28.0	151	4333.66	26.1	273	4583.80	25.2
30	5675.98	27.7	152	4368.04	25.9	274	4895.01	25.2
31	5875.79	27.9	153	3901.39	25.7	275	4431.26	25.1
32	6265.79	27.9	154	3538.59	25.7	276	4528.13	25.1
33	6369.79	27.9	155	3781.17	25.6	277	4201.75	25.2
34	6533.07	28.5	156	4424.38	25.8	278	4679.77	25.2
35	6344.57	28.6	157	4156.72	25.5	279	4041.01	25.2
36	6179.55	28.5	158	4222.44	25.4	280	3542.40	25.1
37	6601.48	28.6	159	4413.95	25.7	281	4856.28	25.2
38	6131.10	28.1	160	4467.68	25.5	282	5130.45	25.3
39	5727.52	28.2	161	4352.91	25.6	283	4276.34	25.3
40	5495.72	28.1	162	3798.05	25.5	284	4113.11	25.1

Days	Irradiation (Wh/m²)	Ave. Temp. (°C)	Days	Irradiation (Wh/m²)	Ave. Temp. (°C)	Days	Irradiation (Wh/m²)	Ave. Temp. (°C)
41	6040.55	27.9	163	2901.31	25.4	285	4688.12	25.4
42	5840.20	27.9	164	4264.40	25.6	286	4574.04	25.3
43	5899.19	27.9	165	3924.26	25.5	287	4426.20	25.2
44	5736.87	28.1	166	3727.38	25.3	288	4542.87	25.4
45	5926.30	28.3	167	3402.93	25.2	289	5468.11	25.5
46	5517.75	28.1	168	3552.39	25.3	290	4898.26	25.5
47	6418.73	28.1	169	3579.55	25.2	291	4350.91	25.4
48	6304.24	28.3	170	3284.41	25.2	292	4650.16	25.4
49	5335.92	28.1	171	3651.66	25.1	293	4575.73	25.3
50	6088.94	27.9	172	3709.85	25.1	294	5016.45	25.5
51	5433.07	28.0	173	3987.93	25.4	295	4073.16	25.3
52	5716.51	28.1	174	3744.85	25.2	296	5099.95	25.8
53	4893.98	28.0	175	4116.17	24.9	297	4311.02	25.5
54	5667.16	28.3	176	3940.97	24.9	298	3711.95	25.5
55	5772.52	28.4	177	3665.75	25.0	299	4996.29	25.5
56	5280.59	28.2	178	3469.02	24.7	300	3959.81	25.4
57	5343.91	27.9	179	3575.95	24.8	301	4654.89	25.5
58	5769.69	27.9	180	4006.84	25.2	302	4483.90	25.4
59	5918.71	27.8	181	3837.45	25.0	303	4276.13	25.6
60	5821.05	27.5	182	3606.10	24.9	304	5001.87	25.6
61	5835.80	27.9	183	3807.27	25.1	305	4759.11	25.9
62	5909.28	28.2	184	3640.83	25.1	306	4487.26	25.6
63	5444.34	27.8	185	3621.29	25.1	307	5000.65	25.7
64	5754.53	28.1	186	3628.03	25.0	308	5035.67	25.6
65	5265.54	28.2	187	3664.77	25.0	309	4514.22	25.8
66	5632.01	28.0	188	3689.32	24.9	310	5671.78	25.9
67	5224.85	27.8	189	4120.58	24.8	311	5152.65	25.7
68	4848.21	27.2	190	3694.20	24.9	312	5451.71	25.9
69	5133.42	27.3	191	3753.87	25.0	313	5023.42	25.9
70	4408.66	27.1	192	3484.49	24.7	314	5131.45	25.8
71	6258.67	27.5	193	4101.25	24.9	315	5208.30	25.7
72	5355.27	27.5	194	3662.38	25.0	316	4345.37	25.9
73	5853.39	27.5	195	3174.43	24.9	317	5804.67	26.1
74	5476.34	27.8	196	3406.36	24.9	318	4990.28	26.0
75	5414.57	27.2	197	4090.64	24.9	319	5146.06	26.1
76	4938.97	27.5	198	3691.11	24.8	320	5005.66	26.4
77	5439.87	27.7	199	4303.43	24.9	321	5115.34	26.6
78	4858.32	27.5	200	3849.19	25.0	322	5041.58	26.2
79	5551.93	27.6	201	3693.54	24.8	323	5128.75	26.4
80	5507.85	27.9	202	3908.69	24.6	324	5242.00	26.2
81	5695.12	28.0	203	3955.98	24.8	325	5374.23	26.2

Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)	Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)	Days	Irradiation (Wh/m^2)	Ave. Temp. (°C)
82	5428.32	27.6	204	3309.65	24.6	326	5797.66	26.6
83	4141.73	27.7	205	3875.98	24.7	327	5596.51	26.5
84	5146.76	27.7	206	3445.95	24.6	328	5814.40	26.6
85	5996.81	27.8	207	3502.93	24.4	329	5719.01	26.8
86	4065.68	27.8	208	3516.74	24.6	330	5839.12	26.5
87	5833.02	27.9	209	3934.73	24.7	331	5550.75	26.6
88	5255.90	27.7	210	4347.47	24.8	332	5915.90	26.8
89	4689.30	27.5	211	4010.75	24.8	333	6430.95	26.9
90	5573.44	27.8	212	3951.28	24.7	334	5964.78	27.0
91	5210.60	26.9	213	3942.44	24.7	335	6288.75	27.8
92	4483.52	27.0	214	4228.51	24.8	336	6157.97	27.7
93	5626.63	27.4	215	3662.26	25.0	337	5745.53	27.4
94	4749.13	27.2	216	3820.76	24.8	338	6102.48	27.3
95	5568.38	27.1	217	3790.19	24.7	339	5739.50	27.4
96	5672.99	27.2	218	3925.02	24.7	340	5944.13	27.6
97	5332.46	27.0	219	3705.19	24.6	341	6192.29	27.5
98	5766.97	27.6	220	4111.02	24.8	342	5872.63	27.3
99	4476.44	27.0	221	4350.97	24.9	343	6237.70	27.6
100	5192.31	27.3	222	4622.63	25.0	344	6197.11	27.5
101	6004.52	27.5	223	4322.23	25.0	345	5969.67	27.4
102	5407.10	27.1	224	3877.84	24.8	346	6255.05	27.1
103	5536.22	27.2	225	4057.59	24.8	347	6247.55	27.3
104	4995.63	27.1	226	3675.29	24.7	348	6544.58	28.1
105	4999.44	27.2	227	4286.80	24.9	349	6658.26	27.9
106	4984.12	27.4	228	4199.73	25.1	350	6450.26	27.8
107	4972.43	27.0	229	3572.19	24.7	351	6551.68	28.1
108	5185.07	27.1	230	4329.03	24.8	352	6413.85	28.1
109	4683.31	27.4	231	4147.11	24.8	353	6545.15	28.0
110	5475.62	27.4	232	3796.93	24.7	354	6545.77	28.1
111	5202.99	27.2	233	3825.00	24.7	355	6896.01	28.1
112	5373.49	27.4	234	3461.23	24.7	356	6830.43	28.2
113	5022.10	27.3	235	3819.05	24.8	357	6936.16	28.2
114	5228.32	26.8	236	3546.20	25.1	358	6926.91	28.0
115	4166.55	27.0	237	4325.66	24.9	359	6793.24	28.3
116	4166.83	26.8	238	4439.53	24.9	360	6624.82	28.2
117	5532.74	26.9	239	4644.80	24.9	361	6602.17	28.4
118	5176.66	26.9	240	3689.73	24.8	362	6922.53	28.3
119	5631.71	27.3	241	3828.35	24.8	363	6622.56	28.2
120	4854.51	27.1	242	3774.48	24.8	364	6780.88	28.1
121	5030.44	27.0	243	3728.46	24.7	365	6263.20	27.9
122	5017.91	27.1	244	3709.63	24.6			