UNIVERSIDADE DE LISBOA

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Solar Electrification To Improve Power Access In Urban Areas In Developing Countries At No Additional Cost: Case Study Of Nigeria

“ Documento Definitivo”

Doutoramento em Sistemas Sustentáveis de Energia

Abisoye Babajide

Tese orientada por:

Professor Doutor Miguel Centeno Brito

Documento especialmente elaborado para a obtenção do grau de doutor

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Júri:

Presidente:

- Doutor João Manuel de Almeida Serra, Professor Catedrático da Faculdade de Ciências da Universidade de Lisboa

Vogais:

- Doutora Rita Hogan Teves de Almeida, Professor Ayuande da Escuela Técnica Superior de Ingenería y Sistemas de Telecomunicación da Universidad Politécnica de Madrid (Espanha)
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- Doutor Jorge Augusto Mendes de Maia Alves, Professor Catedrático da Faculdade de Ciências da Universidade de Lisboa
- Doutor Miguel Centeno da Costa Ferreira Brito, Professor Auxiliar com Agregação da Faculdade de Ciências da Universidade de Lisboa (Orientador)

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2020

Dedication

To my family –

To my sons, Duncan and Lucas, you are my heartbeats. While you are too young to understand what mom is working on, I hope that I can even in a small way make this world a better place for you.

To my husband, Craig - THANK YOU for your love and support over the several years it took to complete this work. I appreciate all the extra effort you put into watching two rambunctious kids under four years old. Thank you for helping to make my dream a reality.

To my parents, Solomon and Patricia, thank you for all you exemplify. I appreciate the wonderful family unit and support system you've created for all six of your children, for instilling a work ethic that rivals none, and most importantly, for blessing us with the gift of the knowledge of God. Your encouragement and guidance on the importance of faith, family, and charity are values I cherish. I am forever grateful for you both.

Finally, this thesis is dedicated to the remarkable, strong, and persevering people of Nigeria. You have overcome so much and will overcome much more. You are truly a blessed nation with many natural resources, gifted minds, and rich cultural diversity. Let us never forget that we have the power to impact positive change in Nigeria and the world. While a single stream of water may not have much impact, a rushing flood can break down walls. Such is the obligation of Nigerians everywhere, to strive for positive change that feeds that flowing stream. So, let us press on for our generation and the ones coming behind. It is our duty and one we must carry with pride and purpose.

Acknowledgments

Thank you to my thesis advisor, Miguel Centeno Brito, for his guidance and support. But most of all, I'm grateful to him for believing in me, challenging me, working with me on this over several years, across two continents, three countries, and multiple time zones, including through the intermittent breaks following the births of my two sons. Your encouragement and persistence were instrumental in my completing this work – thank you!

Thank you to the helpful faculty and staff of the Sustainable Energy Systems program at the University of Lisbon, particularly to Carla Silva and Tiago Domingos. They provided valuable steer in the early stages of my thesis work.

Abstract

Access to electricity has been linked to improved livelihood, education, health, economic growth, and overall poverty reduction. The vast majority of people living without electricity or unreliable electricity access are concentrated in sub-Saharan Africa and South Asia. Despite being the largest economy in Africa, Nigeria suffers from severe power outages, forcing many residents to seek self-generation options. By far, the most adopted option has been diesel generators that have a relatively low initial investment cost but carry health and environmental risks. A viable alternative is solar photovoltaic systems; however, the initial investment is much higher compared to diesel generators, creating a barrier for many Nigerians. Part one of this thesis addresses making cleaner electricity generation through solar PV systems more attainable, increasing access to more reliable electricity, and reducing or eliminating the use of diesel generators. It proposes a pathway for securing residential solar PV systems with the cost covered through fuel savings and enabled by an effective policy that improves access to financing options. Leveraging real data from a monitoring campaign in Lagos, the commercial hub of Nigeria, results show an opportunity to reduce or eliminate the use of diesel generators by applying fuel cost savings to finance solar PV systems. The second part of this thesis addresses Nigeria's commercial sector, which has been significantly hampered due to the poor availability of reliable electricity. Nearly half of the firms doing business in Nigeria have identified electricity as a major constraint, with over a quarter of them listing electricity as their biggest obstacle. The business losses due to electrical outages are significant, with losses averaging about 16% of annual sales. The lack of access to reliable electricity is one of the biggest challenges to economic growth in Nigeria. A means of powering the commercial sector in Nigeria using urban swarm electrification is proposed. This thesis outlines a conceptual framework for using a distributed network made up of grid-connected home solar PV systems as a viable option for providing the commercial sector with more reliable access to electricity. It further addresses the policy implications for the commercial sector with the enablement of more electrification options, implications that include strong economic impact, and the expansion and creation of new industries.

Keywords: renewable energy (RE); developing countries; solar home system (SHS); electricity generation; distributed network

Resumo

O acesso à eletricidade está associado à melhoria dos meios de subsistência, educação, saúde, crescimento económico e redução geral da pobreza. A grande maioria das pessoas que vivem sem, ou com acesso não fiável, a energia elétrica encontra-se na África subsaariana e sudeste asiático. Apesar de ser a maior economia de África, a Nigéria sofre de problemas graves de cortes frequentes de energia, obrigando muitos residentes a procurar opções de auto-geração, sobretudo geradores a diesel, com custos de investimento inicial relativamente baixo, mas que trazem riscos à saúde e ao meio ambiente. Uma alternativa viável são os sistemas fotovoltaicos; no entanto, o investimento inicial é muito maior em comparação com os geradores a diesel, criando uma barreira para muitos nigerianos. A primeira parte desta tese explora a opção de geração de eletricidade solar em ambiente urbano, mais limpa e mais acessível, aumentando o acesso fiável a eletricidade e reduzindo, ou eliminando, o uso de geradores a diesel. Propõe-se um caminho para a implementação em larga escala de sistemas fotovoltaicos domésticos em ambiente urbano, com o custo coberto pela poupança de combustível, possibilitado por uma política eficaz que melhora o acesso a opções de financiamento. Aproveitando dados reais de uma campanha de monitorização de consumo de eletricidade em Lagos, o centro comercial da Nigéria, os resultados mostram uma oportunidade para reduzir ou eliminar o uso de geradores a diesel aplicando a poupança de custos de combustível para financiar sistemas fotovoltaicos. A segunda parte desta tese trata do setor comercial, que tem sido significativamente prejudicado pela pouca disponibilidade de eletricidade confiável. Quase metade das empresas na Nigéria identificou a eletricidade como um grande obstáculo, com mais de um quarto delas apresentando a eletricidade como maior obstáculo. As perdas comerciais devido a interrupções elétricas são significativas, com perdas médias estimadas de cerca de 16% das vendas anuais. A falta de acesso a eletricidade confiável é um dos maiores desafios para o crescimento económico na Nigéria. É proposto um meio de fornecer energia ao setor comercial através de eletrificação solar por enxame (swarm). É descrita uma estrutura conceitual para o uso de uma rede distribuída composta de sistemas fotovoltaicos domésticos ligados à rede como uma opção viável para fornecer ao setor comercial um acesso mais confiável à eletricidade. Finalmente, são abordadas as implicações de política para o setor comercial com mais opções de eletrificação, implicações que incluem um forte impacto económico e a expansão e criação de novas indústrias.

Palavras-chave: energia renovável (ER); países em desenvolvimento; sistema solar doméstico (SHS); geração da eletricidade; rede distribuída; micro-redes

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Acronyms

DisCo	Distribution Company
EPSRA	Electric Power Sector Reform Act
ESMAP	Energy Sector Management Assistance Program
FDS	Fraction of Demand Served
FIT	Feed-in Tariff
GDP	Gross Domestic Product
GenCo	Generating Company
GHG	Greenhouse Gas
GIZ	Gesellschaft für Internationale Zusammenarbeit
HSS	Home Solar PV System
LCOE	Levelized Cost of Electricity
MYTO	Multi-Year Tariff Order
NBET	Nigerian Bulk Electricity Trading Plc
NEPA	National Electric Power Authority
NERC	Nigerian Electricity Regulatory Commission
NPC	Net Present Cost
PHCN	Power Holding Company of Nigeria
PV	Photovoltaic
RE	Renewable Energy
RECP	Africa-EU Renewable Energy Cooperation Programme
REE	Renewable Energy Engineering
SHS	Solar PV Home System
SME	Small and Medium-sized Enterprises
SPSS	Statistical Package for the Social Sciences
SSA	Sub-Saharan Africa
TCN	Transmission Company of Nigeria

Nomenclature:

In order of appearance

E_g	energy used from the grid in Watts-hour per day
P_d	power drawn in Watts
H	hours used per day
P_p	part of power access from the grid
E_a	energy from an alternate source, in Watts-hour per day
P	active electric power in output of the diesel generator in kW
S	apparent electric power in output of the diesel engine in kVA
$Cos(\Phi)$	i.e: Cos(phi) - power factor
E	active electric energy in output of the diesel engine in kWh
C	consumption of fuel in liter
h	number of hours per day the genset runs
d	the number of days the power generator runs
$Ckwh$	consumption of fuel per kWh

Chapter 1: Motivation and Research Questions

1.1. Research Motivation

Nigeria has overcome many challenges, from gaining independence in 1960 to becoming Africa's largest economy in terms of Gross Domestic Product (GDP) (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). However, one issue that persists till today is the high level of power outages across the country. The unreliable access to power has long been a target of jokes by many locals, with the former state-owned power authority, National Electric Power Authority (NEPA), often jokingly called Never Expect Power Always. Power outages are the norm in Nigeria, resulting in the use of diesel generators for backup power by those who can afford it. However, in Nigeria and sub-Saharan countries, solar radiation is abundant, a free natural resource. So, it begs the question of why this free resource is not fully tapped for its power generation potential. One reason for this is that Nigeria is also rich in mineral resources, including oil and gas, which have been the primary source of power generation. However, leveraging the free renewable energy resources in the country presents the nation an opportunity to minimize its fossil fuel consumption, reduce its negative environmental impact, and bolster its economy. Therein lies the motivation for this thesis: to demonstrate a practical and affordable pathway to access cleaner, more reliable power, aiding in improving the living conditions for Nigerians, and further stimulating economic growth. This thesis addresses the current barriers to reliable power access, what opportunities there are to improve on this, and practical approaches to achieve the desired result of more reliable access to power.

In 2011, customers connected to the grid experienced, on average, 28 blackouts per day (Energypedia, n.d.). An electrical consumption measurement campaign undertaken by Enertech for various households from March 2012 to March 2013 indicated power outages occurred on average 11 hours per day, i.e. 45% of the time (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.). Lack of reliable electricity in much of Nigeria and sub-Saharan Africa has driven the need for self-generation and electricity consumption. The predominant means for self-generation has been diesel generators, which present both a health and environmental risk. Given the abundance of the natural resource of solar radiation in this part of the world, Solar Photovoltaic (PV) systems offer a cleaner viable solution for individuals and businesses alike, where they can be used for primary and backup power generation instead of fuel-powered generators. There is ample literature on solar off-grid applications, mainly in rural areas (Azimoh, Klintenberg, Mbohwa, & Wallin, 2017) (Njoh, et al., 2019), and various literature on urban solar communities in the developed world (Orsini, Kessler, Wei, & Field, 2019) or hybrid system designs that consist of solar-PV and diesel generators (Odou, Bhandari, & Adamou, 2020). However, this thesis addresses a different challenge in the urban application in developing countries like Nigeria, where there is a grid, but it is unreliable. Furthermore, it addresses the persistent challenge of a credible pathway to making solar PV systems financially accessible to most Nigerians, given the system's initial high capital cost. This thesis proposes a viable means of enabling the use of solar PV systems for electricity generation in urban communities through fuel savings and adequate financing. The resultant effect is eliminating or significantly reducing the use of diesel generators at no additional cost to the user. This thesis specifically addresses solar PV access for middle-class Nigerians, mainly in urban areas, as they are the demographic with the greatest demand for electricity but with income levels challenged for procuring residential solar PV systems. It is suggested that this targeted demographic can be incentivized to pursue solar PV systems as it directly connects to the power outage problem they face regularly and tackles how this can be improved. For Nigeria, solar PV systems have the potential for the additional production of electricity that frees up the limited utility resources, which can assist in stabilizing the grid. It also improves energy diversity and security with little burden on the government.

According to a 2015 report by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on the Nigerian energy sector, the main barrier to stable and reliable energy supply in Nigeria is the deterioration of the power infrastructure with a resultant widening gap between power stations nameplate capacity and the actual generation capacity (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). The gap is due to the lack of investment in the power sector, which was significantly reduced in the early 1990s and further compounded by reduced maintenance budgets and no new capacity added. The lack of investment in the power sector has resulted in severe structural issues in all critical areas of the country’s power sector, generation, transmission, and distribution (Nigeria Power Baseline Report, 2015). Overall, there are considerable challenges in all phases of the power value chain. A PWC report on the power sector in Nigeria indicated that, as of 2015, the country’s power supply was only a third of its minimum demand (Nigeria Power Baseline Report, 2015) (PriceWaterhouseCoopers, PWC July 2016 issue). That power supply is mainly from thermal power (oil and gas) which provides approximately 82% of the power generated. This is followed by hydropower which makes up nearly 18% of the power generated, and the remainder approximately 0.2% is made up of non-hydropower renewable sources.

Given the national grid's unreliability for electricity supply, many consumers have turned to the use of generators, also known as gensets, for electricity generation. The total gensets market in Nigeria is estimated to be the largest in Africa in terms of revenue. Nigeria is already one of the largest importers of diesel generators in the world and is estimated to spend $250 million annually to import gensets and their spare parts (Frost & Sullivan, 2011). However, diesel generators carry health and environmental risks because they emit fine particulate matter (PM), including black carbon, which is derived from the incomplete combustion of diesel (The World Bank, 2014). According to a World Bank report that inventoried diesel power generation in Nigeria and its emission of various types of pollutants, particulate matter can lead to respiratory and cardiopulmonary disease, which in turn can result in more hospital visits and a higher risk of premature death (The World Bank, 2014). The report further notes that Nigeria's residential and commercial sectors are significant users of diesel generators for electricity generation.

The World Bank report on diesel generators estimates that nearly 12 percent of households in Nigeria (approximately 4.5 million) own generators. The results from the analysis indicate that in 2010, diesel gensets in the residential sector emitted about 0.16 million tons of carbon dioxide (CO_2), 154 tons of sulfur dioxide (SO_2), 4,069 tons of nitric oxides (NO_X), 114 tons of Black Carbon (BC), and 129 tons of Organic Carbon (OC). CO_2 is the largest contributor to climate change.

The health and environmental risks caused by diesel generators are significant. In addition, diesel generators create noise pollution. A much more preferred option is reducing or eliminating the use of diesel generators for a cleaner, renewable alternative. However, many Nigerian households find this challenging because diesel generators have a much lower initial investment cost and can be switched on when needed. In comparison, solar PV systems have a much higher capital investment cost and require expensive batteries for continuous power. In this thesis, we propose a pathway for ownership of solar PV systems through fuel savings, thereby eliminating or reducing diesel generators' use.

The issues faced by the lack of reliable power access have also been detrimental to Nigeria's commercial sector. While being Africa’s biggest economy in nominal GDP, the frequent power outages are among the most significant economic development challenges. The World Bank reports that private sector firms experienced as much as 33 electrical outages in a typical month, with the duration of a typical electrical outage being about 12 h [44]. The same report further states that the proportion of electricity from diesel generators was 59%. Almost half of the firms doing business in Nigeria (48%) identified electricity as a significant constraint, with 27% of firms listing electricity as their biggest obstacle. Losses due to electrical outages averaged 16% of annual sales. More reliable access to electricity will have a knock-on effect in spurring economic growth.

A widescale implementation of solar PV systems in Nigeria has the potential for additional electricity production that frees up the limited utility resources, thereby helping to stabilize the grid. Doing so not only improves energy diversity and security but does so with little burden on the government.

Solar PV systems work by capturing solar energy using photovoltaic (PV) cells, which convert the sunlight into electricity. As solar PV systems can only operate when the sun is shining, it must be coupled with expensive storage or other power generation mechanisms to ensure a continuous supply of electricity. Therein lies one of the drawbacks of solar PV systems, but also the opportunity to combine its use with an existing but strained grid system for more continuous power generation. The problems and opportunities that are the motivation for this thesis lead to the research questions asked and subsequently answered.

1.2. Research Questions

This thesis aims to address the following questions:

1) Is it feasible to build and establish a solar PV home network in urban communities in Nigeria in an economically sustainable way for more reliable continuous power access?
2) Can a home solar PV system based microgrid support increasing electricity reliability to power the commercial sector, improve productivity, and promote economic growth?

3) What policies may be most effective in enabling diffusion and adoption of solar PV home systems for residential use and supporting powering the commercial sector?

In addressing the first question on how to sustainably establish a solar PV home network in urban communities, this thesis will first tackle why there is a need to provide more reliable access to power. It will do so by giving the history and current state of Nigeria's power sector and the barriers to reliable power access from the national grid. It will then look at the main backup option used by residents and the pros and drawbacks to it. Next, this thesis will provide an overview of Nigeria's renewable energy options and why solar PV has been chosen as the preferred option. Following that, a literature review will be done on some of the solar projects undertaken to date in Nigeria, assessing their successes and failures. In so doing, this thesis will address why the proposed option will enable not just building or putting in place solar PV systems, but how this can be done sustainably going forward. Key sub-questions that must be answered to address the first question effectively are: (1) Is there an issue with reliable power access in Nigeria? (2) What are the options to improve power access? (3) What is the power demand in the residential sector? (4) Does solar PV offer a means to provide more reliable power access, and can this be done in a way that is attainable and sustainable for Nigerians in urban communities?

The second question is a follow-up to the first, supposing that residential home solar PV systems can be established sustainably. In that case, the opportunity is assessed for how this can be used to power the commercial sector and stimulate economic growth in Nigeria. This thesis will first establish the case for why action must be taken to improve power access in the commercial sector and the economic damage being done by the power outages. Next, it will assess how home solar PV systems can help power the commercial sector by assessing the demand in the residential and commercial sectors and the potential available excess electricity that can be supplied from the residential to the commercial sectors. Key sub-questions that must be answered to address the second question effectively include (1) What is the economic damage from the commercial sector's lack of reliable and affordable power access? (2) What is the power demand in the commercial sector, and can this be wholly or partially met by excess power from the residential sector? (3) Is an urban community-based microgrid a feasible means for powering the commercial sector in Nigeria?

Finally, this thesis addresses the third question of what effective and enabling policies would be to get the recommended improvements in the residential and commercial sectors. This will be discussed from two lens – (1) what has been tried and successful in other developing countries, and (2) for the specific Nigeria environment, what additional policies should be looked at to enable the adoption of the proposed option further. Policy implications and enablers will be addressed separately for the residential and commercial sectors but will be complementary in terms of achieving the shared goal of more reliable access to power.

1.3. Original Contributions

This thesis explores the novelty of residential microgrids in urban communities in developing countries like Nigeria to generate power for both themselves as well as industry. While all microgrid systems are somewhat similar, in this thesis, the context is quite different from others, as well as the motivation and concept described. There is a different challenge in an urban application in Nigeria. While there is a grid, it is not reliable and thus introduces more challenges than other urban applications in the developed world. This thesis sets out a framework for gaining more reliable electrification of the residential and commercial sectors in urban communities in Nigeria.

The following are publications to date on this work:

Babajide, A, Brito, M.C, " Solar PV Systems to Eliminate or Reduce the Use of Diesel Generators at No Additional Cost: A Case Study of Lagos, Nigeria. Renewable Energy Journal, July 2021. DOI: 10.1016/j.renene.2021.02.088.

Babajide, A, Brito, M.C, "Powering the Commercial Sector in Nigeria Using Urban Swarm Solar Electrification," Sustainability Journal, May 2020. DOI: 10.3390/su12104053.

1.4. Thesis Outline

This thesis is divided into seven main chapters.

As already covered, chapter 1 provides the motivation for this work as well as the research questions to be answered and the thesis outline.

Chapter 2 provides further context for this work, covering Nigeria’s electricity landscape and power outage problem, and electricity supply and demand.

Chapter 3 of this thesis discusses the various renewable energy sources in Nigeria, why solar PV should be an option of choice, as well as the successes and failures of previous solar projects in Nigeria.

Chapter 4 uses a case study of residential households in Nigeria to present the case for enabling the use of solar PV systems for electricity generation in urban communities through fuel savings. This part of the thesis also covers the knock-on effect this has on reducing the use of diesel generators, and in so doing, eliminate or greatly reduce the use of diesel generators at no additional cost to the user.

Chapter 5 directly addresses the hypothesis that the use of home solar PV systems used collectively for distributed generation can significantly reduce or eliminate power outages in the commercial sector in Nigeria, accelerating economic growth as well as the dissemination of solar PV systems.

Chapter 6 discusses and recommends policies for enabling the adoption of solar PV systems in Nigeria's urban communities. In this chapter, policy proposals are made that specifically address the electrification concepts proposed in this thesis. This chapter covers policies that enable securing residential solar PV systems, incentivizing its use, and promoting collective generation to help power the commercial sector and further bolster the economy.

Chapter 7 is the final chapter and presents conclusions and recommendations for further work.

Due to constraints in setting up a test group community in Nigeria to trial implementation, this work takes a qualitative approach. In so doing, the aim is to challenge the status quo and encourage novel lines of thinking and investigation that enable further research opportunities to emerge.

Chapter 2: Context

Chapter 2 of this thesis provides further context for this work. The chapter sets the scene by covering Nigeria's electricity landscape and power outage problem. It compares Nigeria's energy source and consumption in relation to peer countries and its electricity supply and demand.

2.1. Nigeria's electricity landscape and power outage problem

This section details the power outage problem in Nigeria, first by exploring the history of electricity generation in the country and gaining insights on the causes, effects, and potential solutions to the problem.

2.1.1. History

Electricity generation started in Nigeria in 1896, but the first electric utility company, known as the Nigerian Electricity Supply Company, was established in 1929. Most substations and electrical networks in Nigeria were established in the 1950s and 60s. These networks with some upgrading are still in operation today, though with poor performance.

By the year 2000, the state-owned National Electric Power Authority (NEPA) oversaw the generation, transmission, and distribution of electric power in Nigeria. NEPA operated as a vertically integrated utility company controlling both generation, transmission, and distribution of electricity. It had a total generation capacity of about 6,200 MW from two hydro and four thermal power plants fueled by gas. NEPAs operations were overwhelmed with unstable and unreliable electric power supply in the country with customers experiencing frequent power cuts and long periods of power outages and an industry characterized by lack of maintenance of power infrastructure, outdated power plants, low revenues, high losses, power theft and non-cost reflective tariffs (Nigerian Electricity Regulatory Commission).

In the year 2001, the electricity sector reform began with the creation of the National Electric Power Policy, which had as its goal the establishment of an efficient electricity market in Nigeria. It had the overall objective of transferring the ownership and management of the electricity industry's infrastructure and assets to the private sector to create all the necessary structures required to form and sustain an electricity market in Nigeria.

In 2005 the Electric Power Sector Reform Act (EPSRA) was passed, and the Nigerian Electricity Regulatory Commission (NERC) was established as an independent regulatory body for the electricity industry in Nigeria. Also, the Power Holding Company of Nigeria (PHCN) was formed as a transitional corporation that comprises of the 18 successor companies (six generation companies, eleven distribution companies, and one transmission company) created from NEPA. From 2007 until September 2013, PHCN acted as the state-owned agency responsible for generating, transmitting, and distributing electricity for the entire country while the federal government sought to privatize the electricity services industry.

In 2010, the Nigerian Bulk Electricity Trading Plc (NBET) was established to engage in the purchase and resale of electric power and supplementary services from independent power producers and the generation companies. By November 2013, the privatization of all the generation and ten distribution companies was completed with the Federal Government retaining the Transmission Company of Nigeria, TCN. The privatization of the 11^{th} distribution company was completed in November 2014. In 2015, the unbundling of the TCN into an Independent System Operator (public) and a Transmission Service Provider (private) began.

Figure 1 summarizes the timeline of the evolution of the electricity market.

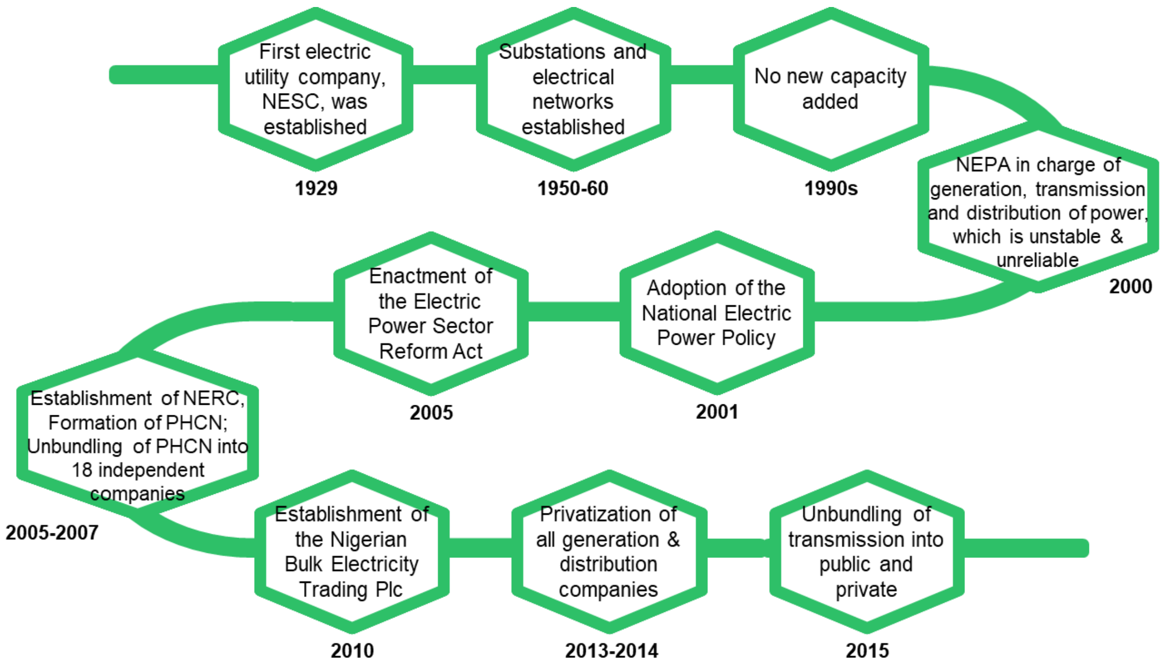

Figure 1: Timeline of the evolution of the electricity market in Nigeria.

2.1.2. Overview of the Power Generation and Distribution System

While the Nigerian government has fully divested its interest in the 6 generation companies (GenCos) and 60% of its shares in the 11 distribution companies (DisCos), it has retained full ownership of the transmission company. The Operator of the Nigerian Electricity Market (ONEM) was established within TCN to act as a wholesale market and settlement operator. ONEM manages the metering system among generation, transmission, and distribution companies.

2.1.2.1. Generation

The Power Holding Company of Nigeria (PHCN) was formed as a transitional corporation owned by the state and responsible for generating, transmitting, and distributing electricity while the federal government sought to privatize the sector. Following the privatization of Nigeria's distribution and generation companies, PHCN ceased to exist. Table 1 reflects the generation companies created following the dissolving of PHCN.

Table 1: Nigerian power generation companies and installed capacity (MW). Source (Nigerian Electricity Regulatory Commission).

GenCo	Installed Capacity (MW)	Type	Privatization Status
Afam Power Plc	776	Gas	100% Sold
Sapele Power Plc	414	Gas	51% Sold
Egbin Power Plc	1,020	Gas	100% Sold
Ughelli Power Plc	900	Gas	100% Sold
Kainji Power Plant	760	Hydro	Long Term Concession
Jebba Power Plant	578	Hydro	Long Term Concession
Shiroro Power Plc	600	Hydro	Long Term Concession

There are four basic generation options within the Nigerian electrical power system (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). These power generation options include (1) transmission-based on-grid generation, (2) embedded generation, (3) off-grid generation, and (4) captive generation.

The transmission-based on-grid power generation option requires on-grid generation licenses for all power plants which output their power on the national transmission grid.

Embedded generation is where electricity is output through a distribution system of an external distribution company; hence embedded generators are usually connected to the distribution grid. This type of power generation requires a license.

Off-grid generation, where the electricity generated requires external off-takers, typically households within a remote village, public facilities (e.g. schools, health stations), and/or businesses, require a power generation license. A distribution license may also be required for this kind of power generation.

Captive generation is where the electricity generated is entirely consumed by the generator itself, for instance, households or companies running their own diesel generators. Also considered as off-grid, the power generated is not output to the national grid or a distribution grid. No license is required for this type of power generation, though it does require a permit from the NERC.

2.1.2.2. Distribution System Operators (DisCos)

The coverage areas of the 11 Electricity Distribution Companies (DisCos) are indicated in the map in Figure 2. Geographically, DisCos in the northern part of the country have a larger coverage area compared to DisCos in the southern part of the country.

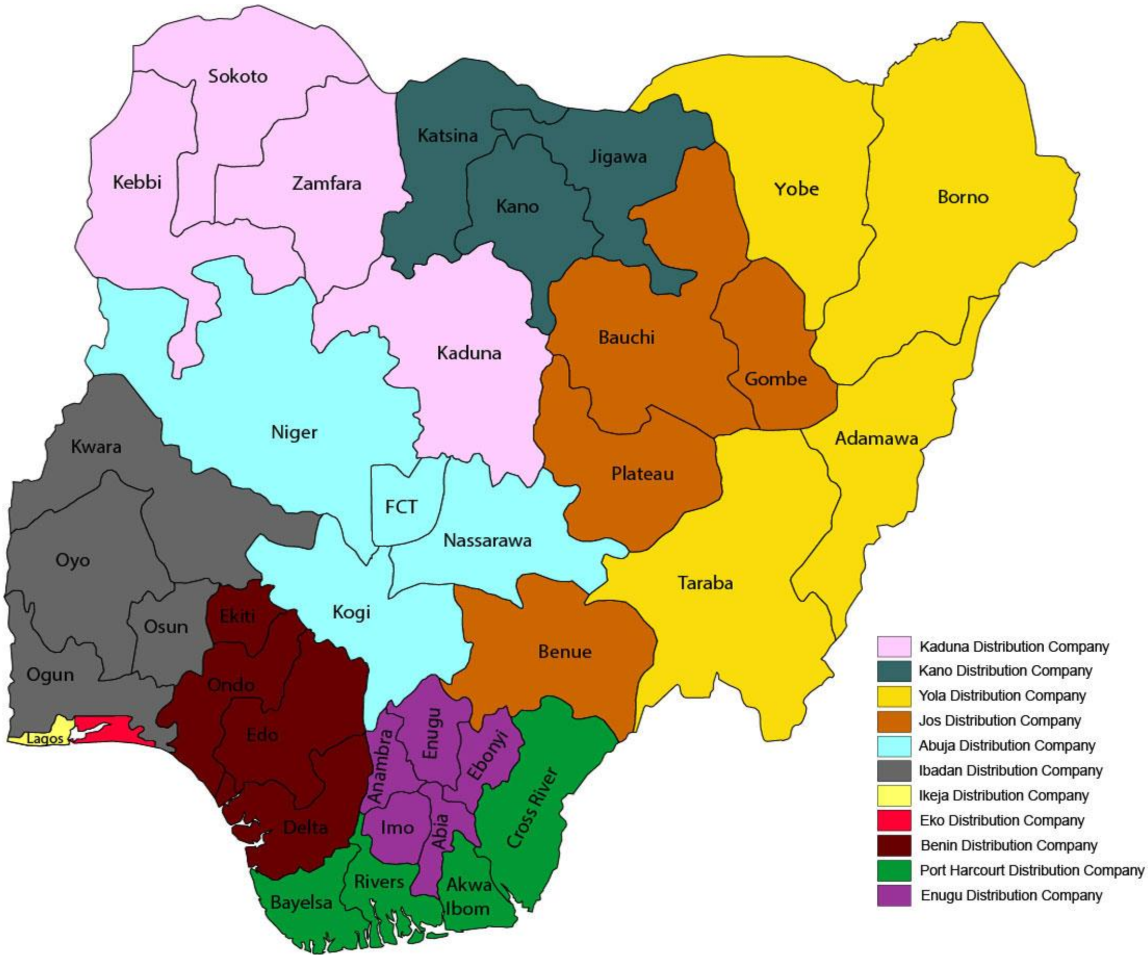

Figure 2: Nigeria's Electricity Distribution Companies (DisCos). Source (Nigerian Electricity Regulatory Commission)

2.1.2.3. Transmission

Transmission Company of Nigeria (TCN) manages the electricity transmission network in the country. It is presently wholly owned and operated by the government. TCN's licensed activities include electricity transmission, system operation, and electricity trading. It is responsible for transmitting electric power generated by the electricity generating companies (GenCos) and wheeling it to distribution companies (DisCos). It provides a critical transmission infrastructure between the GenCos and the DisCos' Feeder Sub-stations.

According to the Nigerian Electricity Regulatory Commission’s (NERC) report (Nigerian Electricity Regulatory Commission), Nigeria’s transmission network consists of high voltage substations and over 15,000 km of transmission lines. The transmission wheeling capacity of 5.3 GW is higher than the average operational generation capacity of 3.9 GW but is far below the total installed generation capacity of 12.5 GW. Furthermore, the entire infrastructure is without redundancies, thus creating inherent reliability issues. “At an average of approx. 7.4%, the transmission losses across the network are high compared to emerging countries’ benchmarks of 2-6%” (Nigerian Electricity Regulatory Commission). The layout of Nigeria’s transmission network can be seen on the map in Figure 3.

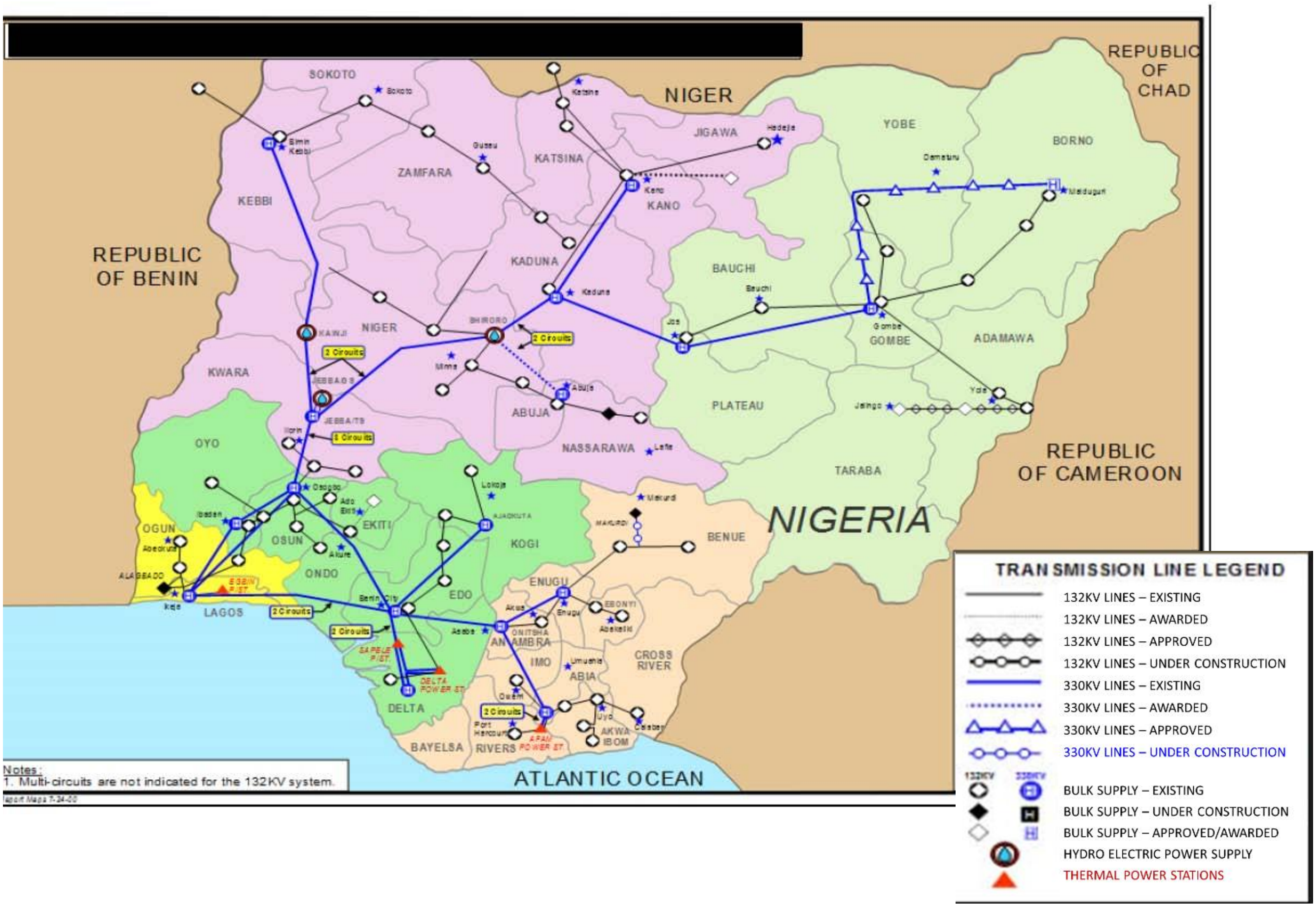

Figure 3: Nigeria's Transmission Network. Source (Nigerian Electricity Regulatory Commission).

The following information on the TCN is gathered from the Nigerian Electricity Regulatory Commission’s (NERC) report (Nigerian Electricity Regulatory Commission):

TCN consists of three operational departments:

1. Transmission Service Provider (TSP): This department oversees the development and maintenance of the transmission infrastructure. It is responsible for the national inter-connected transmission system of substations and power lines and providing open access transmission services. Its role is to maintain the physical infrastructure that makes up the transmission grid and expand it to new areas.
2. System Operations (SO): The SO manages electricity flow throughout the power system from generation to distribution companies. It operates the Grid Code for the Nigerian Electricity Supply Industry (NESI). The SO has the responsibility to ensure that the transmission grid lines are reliable and maintain the grid's technical stability through planning, dispatch, and control of the electricity on the grid.
3. Market Operations (MO): The MO administers the market rules of the NESI. It is responsible for the administration of the Electricity Market and promoting efficiency in the market.

2.2. Power Supply and Barriers to Adequate Power Provision

According to a 2015 report by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on the Nigerian energy sector, the main barrier to stable and reliable energy supply in Nigeria is the widening gap between power stations nameplate capacity and the actual generation capacity (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). This gap is due to the lack of investment in the power sector, which severely diminished in the early 1990s, compounded by reduced maintenance budgets and no new capacity added.

The 2015 Nigeria Power Baseline Report states that the country’s power sector has structural issues in all key areas: generation, gas supply, transmission, and distribution. “Chronic vandalism has crippled oil and gas pipelines, creating gas shortages at power plants” (Nigeria Power Baseline Report, 2015). Lack of adequate investment in maintenance and infrastructure significantly constrained the transmission grid, which, coupled with the high collection and commercial losses, has severely weakened the privatized distribution companies' financial viability.

The July 2016 PWC report on the power sector in Nigeria states that, in 2015, Nigeria’s power supply averaged 3.1 GW, which is estimated to be only a third of the country’s minimum demand (Nigeria Power Baseline Report, 2015) (PriceWaterhouseCoopers, PWC

July 2016 issue). That power supply was from thermal power, mainly oil and gas, providing 82.0% of the power generated, hydropower making up 17.8%, and non-hydropower renewable sources making up the remainder.

The structural inefficiencies in power generation cause the underutilization of Nigeria's generation capacity. There are three stages in delivering power to customers: generation at the power plant, transmission to the distribution companies, and distribution to the end-user. Only about 25% of Nigeria's 12.5 GW of installed capacity reaches the end-user. The widespread inefficiency means that only 3.9 GW of this capacity is operational, with about 3.6 GW transmitted and approximately 3.1 GW distributed (Nigeria Power Baseline Report, 2015).

Figure 4 shows Nigeria's power sector energy flow in Gigawatts (GW). Of the 8.6 GW capacity not utilized, 5.38 GW is unavailable due to obsolete equipment and poor maintenance or ongoing maintenance and repair activities at existing power plants. Approximately 3.3GW is non-operational primarily due to gas, water, high frequency, and line constraints. According to the Nigeria Power Baseline report, the sector's financial health is below par as the distribution companies are unable to collect sufficient revenue to pay their full market costs. Consequently, all of the upstream sectors (TCN, generation companies, and gas producers) do not receive total compensation for their costs (Nigeria Power Baseline Report, 2015).

There are considerable challenges in all phases of the power value chain. Findings from the 2015 Nigeria Power Baseline Report (Nigeria Power Baseline Report, 2015) indicate the following issues across generation, distribution, and transmission.

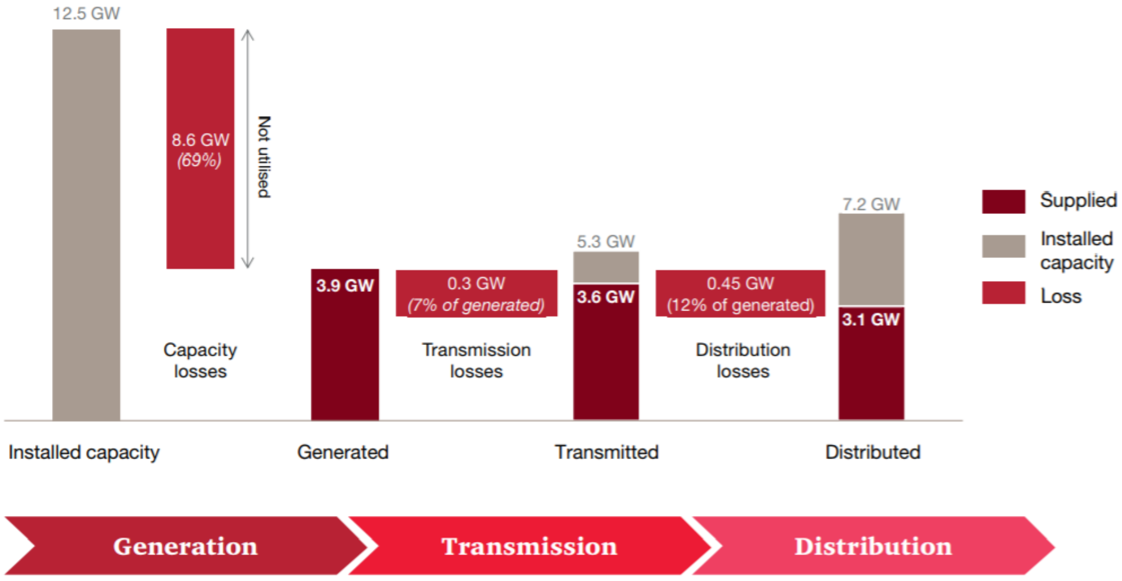

Figure 4: Nigeria's power sector energy flow (GW). Source (PriceWaterhouseCoopers, PWC July 2016 issue)

2.2.1. Generation Issues

The main power generation sources in Nigeria are plagued with issues. With gas being a primary energy source with just over 80% of power generation from gas thermal plants, gas constraints heavily impact Nigeria's power generation. Pipeline vandalism has been partly to blame for restrictions in gas supply.

The key constraints to operational generation capacity are:

- Insufficient gas supply due to low production, inadequate infrastructure, and vandalism, which heavily impacts power generation from gas thermal plants.
- Poor water management which impacts power generation from hydro systems.
- Demand imbalances.
- Line constraints due to inadequate transmission infrastructure.

Improving Nigeria's power generation is a crucial factor in resolving the power shortage. With the current structure, tackling supply, infrastructure, and vandalism challenges are needed to provide the gas volumes needed for greater power generation. Building more generation capacity alone is not enough with the current infrastructure; it needs to be supported upstream with improved gas availability and downstream with additional transmission capacity.

This work addresses part of the generation issue by proposing that self-generation through solar PV also presents a mostly untapped opportunity to improve Nigeria's power generation.

2.2.2. Transmission Issues

Nigeria's transmission network consists of 159 substations and over 15,000 km of transmission lines. Currently, transmission capacity (~5.3 GW) is higher than the average operational generation capacity of 3.9 GW, but it is far below the total installed capacity of 12.5 GW. When operating generation capacity increases to the same level as transmission capacity, transmission will become the bottleneck to electricity supply. The transmission losses across the network average 7.4%, which is high compared to emerging country benchmarks of ~2-6% (Nigeria Power Baseline Report, 2015). Poor maintenance and system management contribute to partial or total system failures. The number of system failures has fallen over the last seven years from a peak of 42 in 2010 to 13 in 2014. However, the occurrence of forced outages has not improved at the same rate, and maintenance challenges persist with an average of 67% of planned maintenance completed per month. Nigeria's transmission system cannot transmit the installed generation capacity. Grid stability and capacity must improve to keep up with current and future installed generation capacity (Nigeria Power Baseline Report, 2015).

2.2.3. Distribution Issues

The biggest challenge the distribution sector faces is the level of distribution losses (Nigeria Power Baseline Report, 2015). This includes technical, commercial (energy not billed for), and collection losses (energy billed but not paid for). In 2014, about 46% of energy was lost through technical (12%), commercial (6%), and collection losses (28%).

This work addresses part of the distribution issue by leveraging the growing use of an electronic energy prepayment system for the electricity generated. With this concept, users can top-up their electricity consumption allowance. When combined for use with any added generation sources, it provides a more reliable payment system, thus significantly reducing commercial and collection losses.

Overall, while improving, large challenges remain in all phases of the power value chain with regard to meeting the current and growing electricity demand. Nigeria's power sector's long-term viability is tied to the health and sustainability of all stages of the value chain from generation to payment by end-users. The economic development of the country is linked to a more reliable power supply.

2.3. The power outage problem

Nigeria averages over 32 outages per month, the highest of any African country (Enterprise Surveys, The World Bank, n.d.). Figure 5 shows the average electricity outages for various African countries. Nigeria's power outage problems made the international news circuit in January 2018 when there was a nation-wide blackout (Reuters World News, n.d.). Gas supply to several power stations was cut off because of the fire on a pipeline system in the southern state of Edo. The sudden loss of generation due to interruption in gas supply from these stations caused the national transmission grid to trip off and resulted in a nation-wide black-out. While reports of widespread power outages may be new for those abroad, this has become the norm for almost everyone living in Nigeria. Furthermore, Nigeria's outages are random, making it challenging to work around due to its unpredictability. While more affluent locations in urban communities experience comparatively lower power outages than others, the power outage problem has had a widespread effect across the entire nation, negatively impacting the general population's standard of living.

The severe power outages in Nigeria have also had a detrimental effect on the economy. Nigeria's telecommunications company, MTN, has 62 million subscribers and has reported spending 70% of its operating expenditure on diesel, amounting to more than 10 million liters a month (The Guardian, n.d.). In a study, Amadi et al. estimate the economic costs of power outages among Nigerian industries, ascertaining both the direct cost of power outages to the respective industries and the costs incurred by each industry as it invests in backup facilities to mitigate power outages (Amadi, Okafor, & Izuegbunam, 2016). The study found that the direct cost of power outages incurred by Nigeria's industries amounted to 387 billion Naira (NGN) (1.3 billion USD), while the indirect cost was 2.2 trillion NGN (7.2 billion USD). The study results further showed that Nigeria's industries suffer low capacity utilization, a significant reduction in productivity, loss of revenue, and lack of competitiveness in the international markets due to persistent shortages in energy supply. Addressing the power outage issue for industries will be vital for the economic growth of Nigeria.

Understanding how best to tackle Nigeria's power outage problem requires not only understanding the available power supply but also Nigeria's power demand.

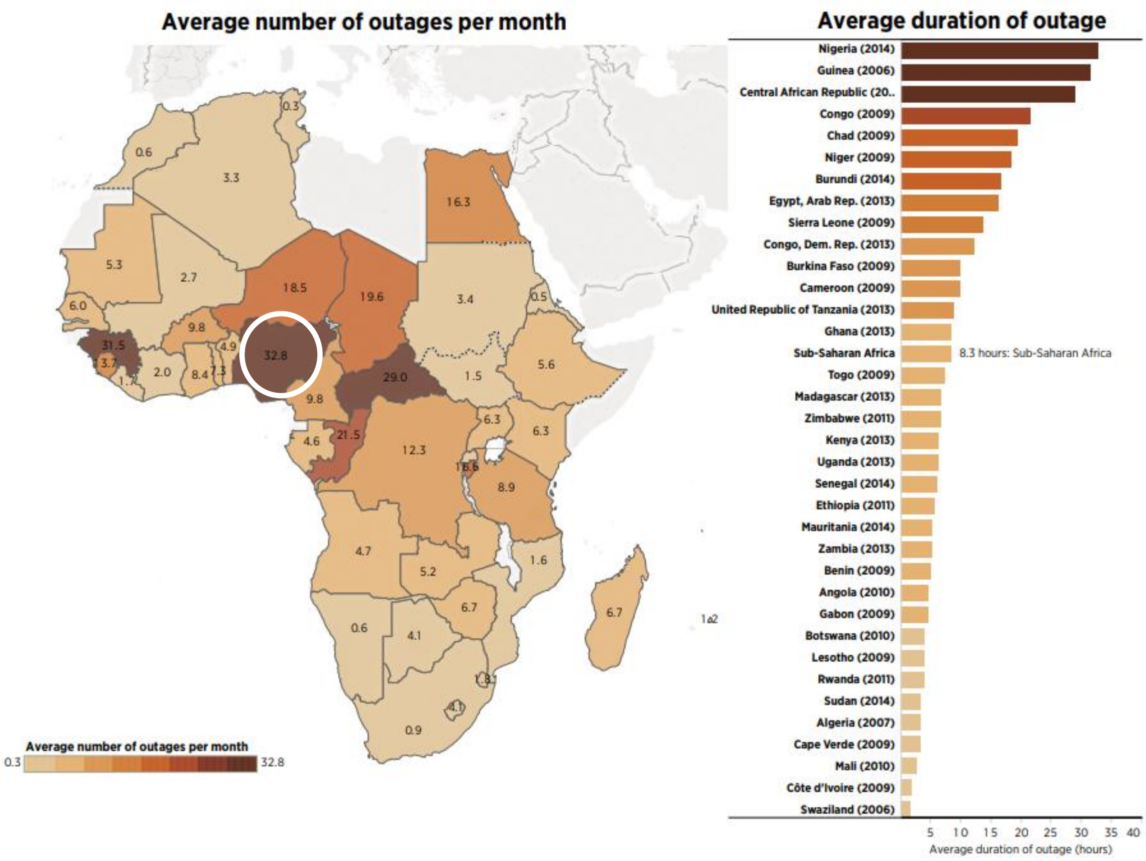

Figure 5: Average number of outages per month in Nigeria and other African countries. Source: (IRENA, 2016)

2.4. Power Demand and Energy Consumption

Given the strained national grid system and the resultant power outages, it is useful to understand how energy is consumed in Nigeria. According to the International Energy Agency (IEA) collated data for 2018 on the Nigerian energy sector (International Energy Agency (IEA), 2020), the residential sector dominates Nigeria's final energy consumption at 75% of total consumption. The transportation sector follows this at 16%, and industry at 5%.

In the 2015 GIZ report (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015), Nigeria's energy consumption is compared against four other countries that have been classified as peer groups, namely Bangladesh, Brazil, Indonesia, and South Africa. With data adapted from the IEA's latest energy statistics (International Energy Agency (IEA), 2020),

Figure 6 illustrates the total energy consumption by economic sectors and the consumption per capita for Nigeria and the four peer countries. More detailed data can be found in Appendix A.

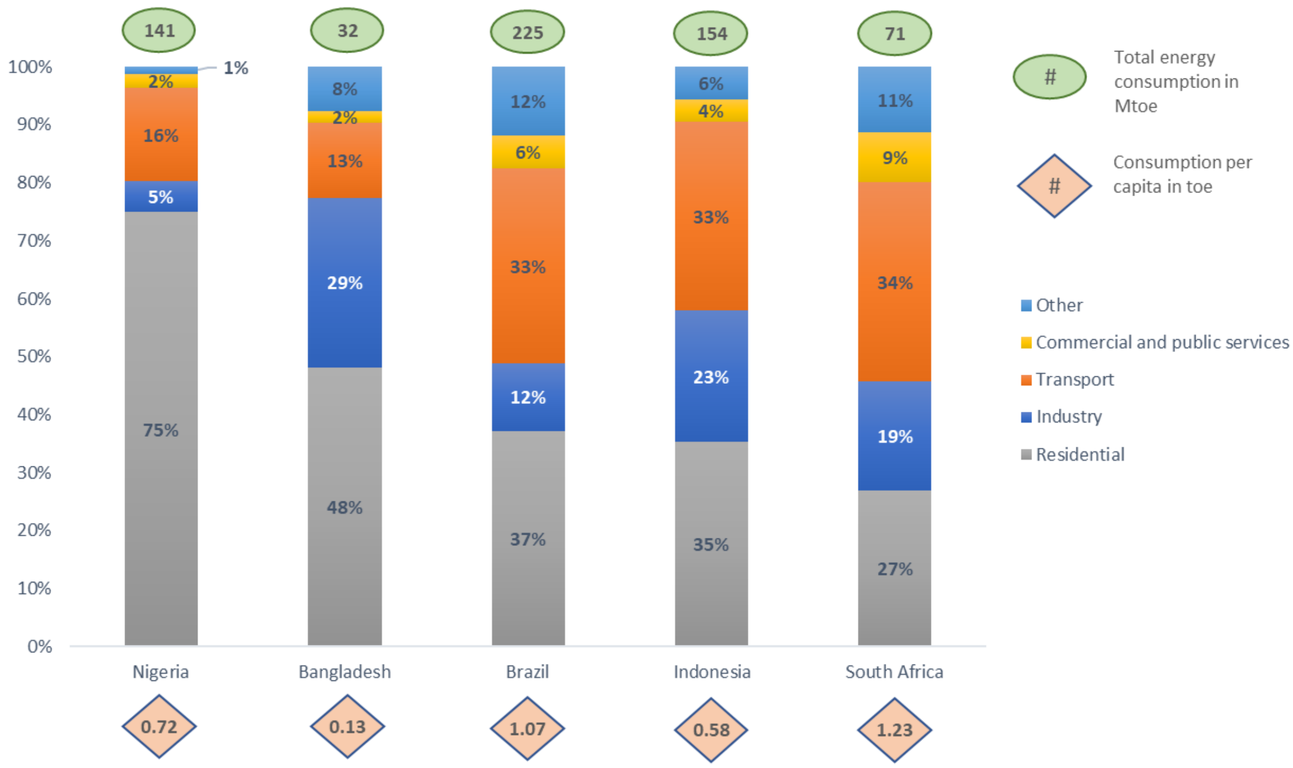

Figure 6: Total energy consumption by economic sectors and consumption per capita for Nigeria and peer countries (2018). Data collated from https://www.iea.org/countries (International Energy Agency (IEA), 2020).

Nigeria's energy consumption data indicates that most of Nigeria’s energy consumption is in the residential sector. When comparing Nigeria’s final energy consumption with the other four peer group countries, on a percentage basis, Nigeria’s energy consumption is heavily skewed towards the residential sector compared to peer countries. It is also largely lagging in energy consumption in the industry, transportation, and commercial and public services. Among peer countries, Nigeria’s residential energy consumption compared to its industrial sector is by far the highest at about fifteen times more residential consumption than industrial. For all other peer countries, the residential sector is two to three times the industrial sector's energy consumption. The wide disparity for Nigeria is especially concerning as industry drives economic growth.

While the residential sector has a high percentage of energy consumption in Nigeria, it should be noted that the consumption per capita is still relatively low. Nigeria's per capita energy consumption is 0.72 toe, which is considerably below that of South Africa (1.23 toe) and Brazil (1.07 toe), but above Indonesia (0.58 toe) and Bangladesh (0.13 toe).

Most of Nigeria's residential energy consumption is from biofuels and waste (International Hydropower Association (IHA), 2018). This is mostly comprised of firewood and mainly used for cooking. Biofuels and waste cover 98% of the residential sector's energy demand and is attributed as the single largest factor accounting for the change in the country's vegetation and the increase in deforestation. Figure 7 represents energy consumption by source for Nigeria and its peer countries. Biofuels and waste make up 79% of Nigeria's total energy consumption, more than two and a half times that of the next nearest peer country's consumption from the same source. The next biggest source of energy consumption in Nigeria is oil products at 17%, mostly for transportation, with natural gas (3%) and electricity (2%) far behind.

In contrast, three of the four peer countries have oil products as their biggest source of energy consumed, ranging from 38-48%. The second highest consumption source varies among peer countries, from natural gas in Bangladesh, to coal in South Africa, and biofuels in Brazil and Indonesia. All the peer countries show electricity consumption ranging from 14-25%; this is well ahead of Nigeria's 2% electricity consumed. The data highlights the stark contrast of Nigeria's lack of electrification compared to its peers and the need to make fast progress towards clean electricity. Electricity generation, particularly to drive industrialization, must be a key policy imperative.

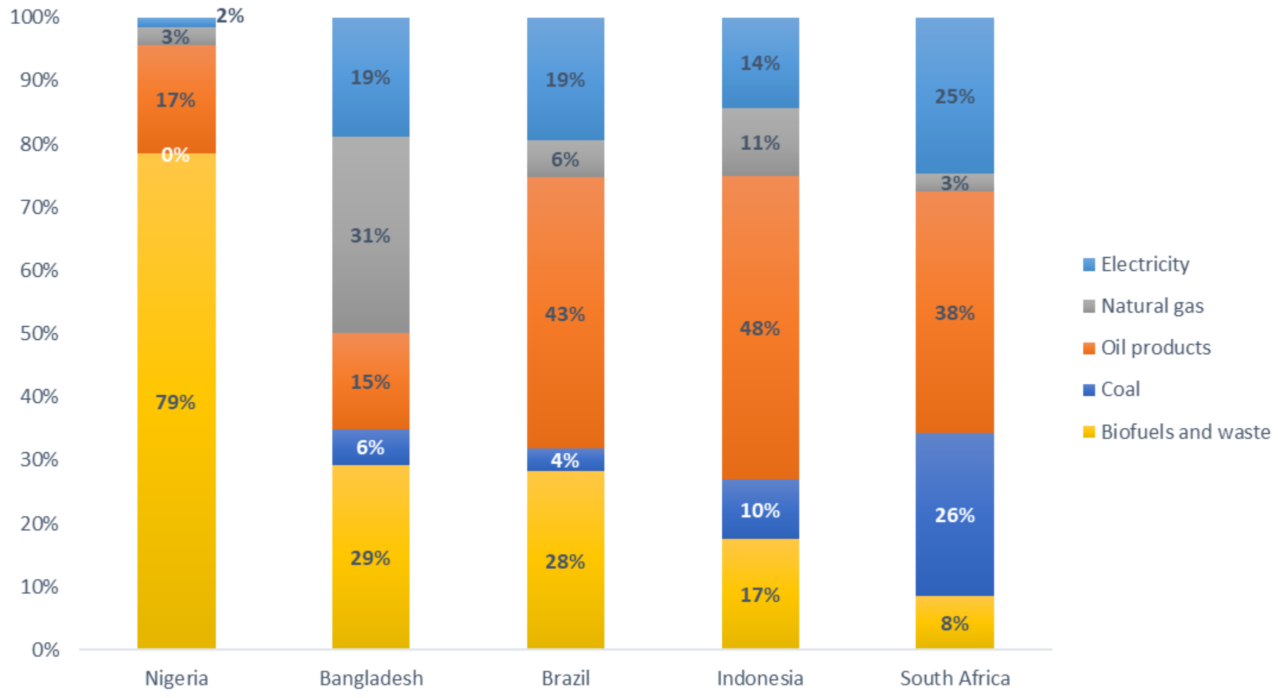

Figure 7: Total energy consumption by source, Nigeria and peer countries (2018). Data collated from https://www.iea.org/countries (International Energy Agency (IEA), 2020).

2.4.1. Electricity Consumption

Compared to its peer countries, Nigeria has by far the lowest electricity consumption, seventeen times less than Brazil, about eight times less than Indonesia and South Africa, and nearly two-and-a-half times less than Bangladesh. Three peer countries show an increase in electricity consumption over the last decade, except for South Africa and Nigeria, which show a near-flat trend for the same period. However, of the five countries, South Africa leads with the highest electricity consumption per capita, and Nigeria again the lowest. Figure 8 and Figure 9 show the electricity consumption and consumption per capita for Nigeria and its peer countries in the last 20 years.

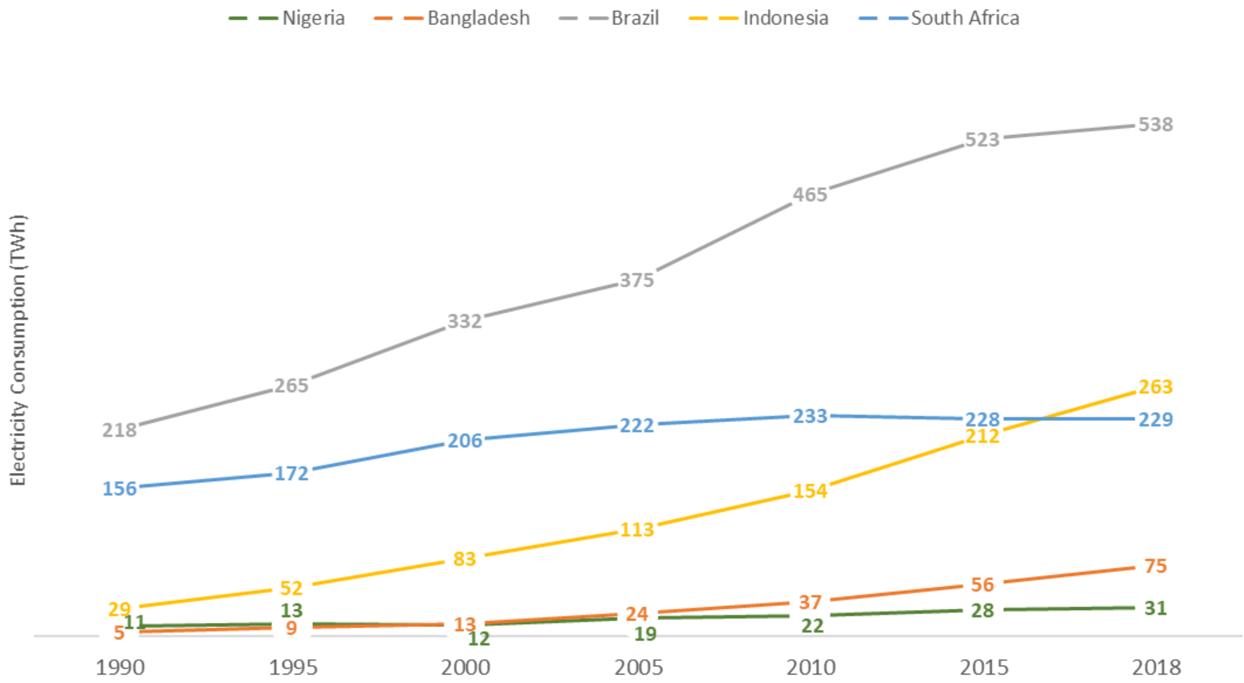

Figure 8: Electricity consumption for Nigeria and peer countries (2018). Data collated from https://www.iea.org/countries (International Energy Agency (IEA), 2020).

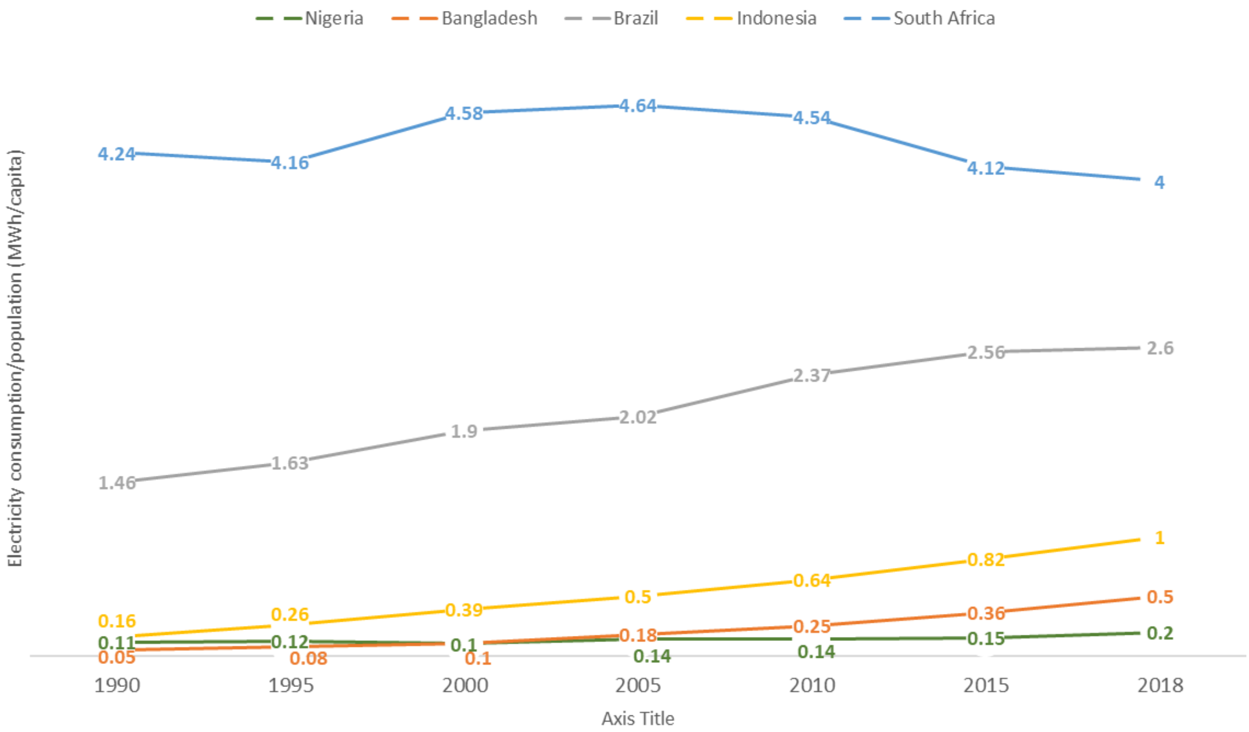

Figure 9: Electricity consumption per capita, Nigeria and peer countries (2018). Data collated from https://www.iea.org/countries (International Energy Agency (IEA), 2020).

With electricity availability and reliability as critical enablers for economic development in Nigeria, and the need for this to increase significantly, all generation sources should be explored and exploited. Figure 10 shows the electricity generation by source for Nigeria and peer countries.

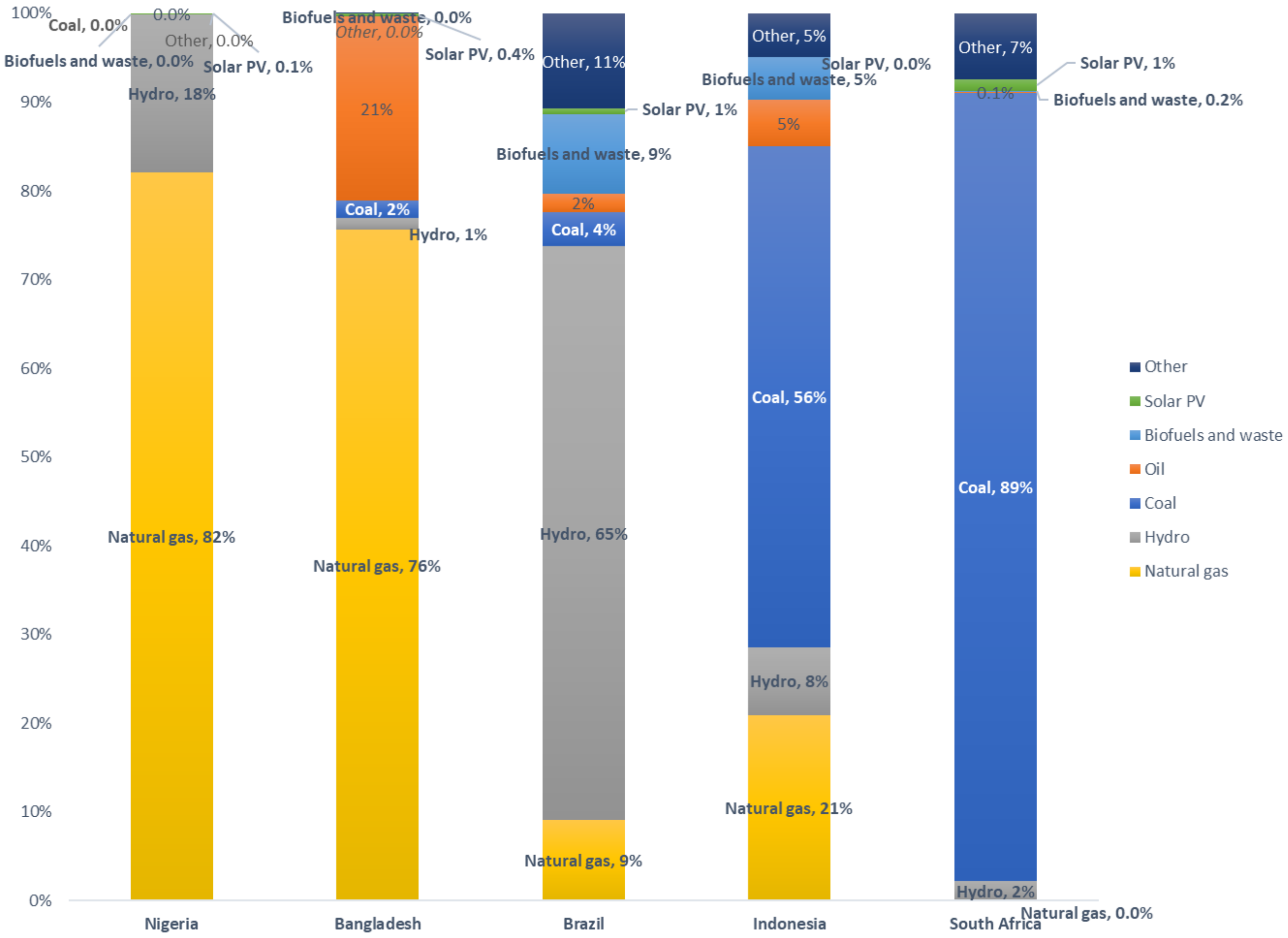

Figure 10: Electricity generation by source, Nigeria and peer countries (2018). Data collated from https://www.iea.org/countries (International Energy Agency (IEA), 2020).

Natural gas is the leading source of electricity generation in Nigeria and Bangladesh, with coal leading for South Africa and Indonesia and Hydro for Brazil. Solar PV is still a small and growing part of electricity generation for Brazil and South Africa, but this represents over 3,000 GWh for each of those countries, far leading the other peer countries with only about 91 GWh generated by Bangladesh and by Indonesia, and just 28 Gwh by Nigeria. More detailed data can be found in Appendix A. To increase clean electricity generation in Nigeria, all clean generation options should be assessed, both looking at the utilities or commercial sector and also looking at less traditional options such as generation from the residential sector, the biggest user group. After reviewing various clean electricity generation options, this thesis makes a case that electricity generation from the residential sector using solar PV can effectively and quickly materialize, whereas it can be used not only for self-consumption but for added generation capacity to the grid as well as the local neighborhood.

2.4.2. Household Electricity Demand

To adequately assess the electricity generation requirements for a household solar PV system, or HSS for short, it is essential to understand typical urban households' electricity needs in Nigeria. The basic energy requirements in Nigerian homes are for lighting, cooking, and running household appliances. In a first of its kind undertaking, a project by Enertech represents the first measurement campaign ever made in Nigeria to monitor a large number of households for their electrical consumption of lighting, cold appliances, and air conditioning (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.). The project was also able to assess the frequency, duration, and time of day of the monitored households' power outages. Enertech's project was developed in partnership with the United Nations Development Programme (UNDP) with support from the Global Environment Facility (GEF) and collaboration with the Energy Commission of Nigeria, the Nigeria Federal Ministry of Environment (FME), and the National Centre for Energy Efficiency and Conservation (NCEEC). The monitoring campaign was carried out from March 2012 to March 2013 and was split between six areas with 35 households per area. In total, 210 households were monitored for one month, and 20 households were monitored for one year. For most of the monitored areas, the temperature variation throughout the year is very little and as such seasonality impact is discounted in this study but may be a point for further refinement in future work.

Figure 11 shows the six monitored areas in the Enertech study, covering different geographical and geopolitical zones in the country: Abuja (North Central), Lagos (South West), Benin (South), Enugu (South East), Bauchi (North East), and Sokoto (North West). All six geographical areas are assessed in this thesis.

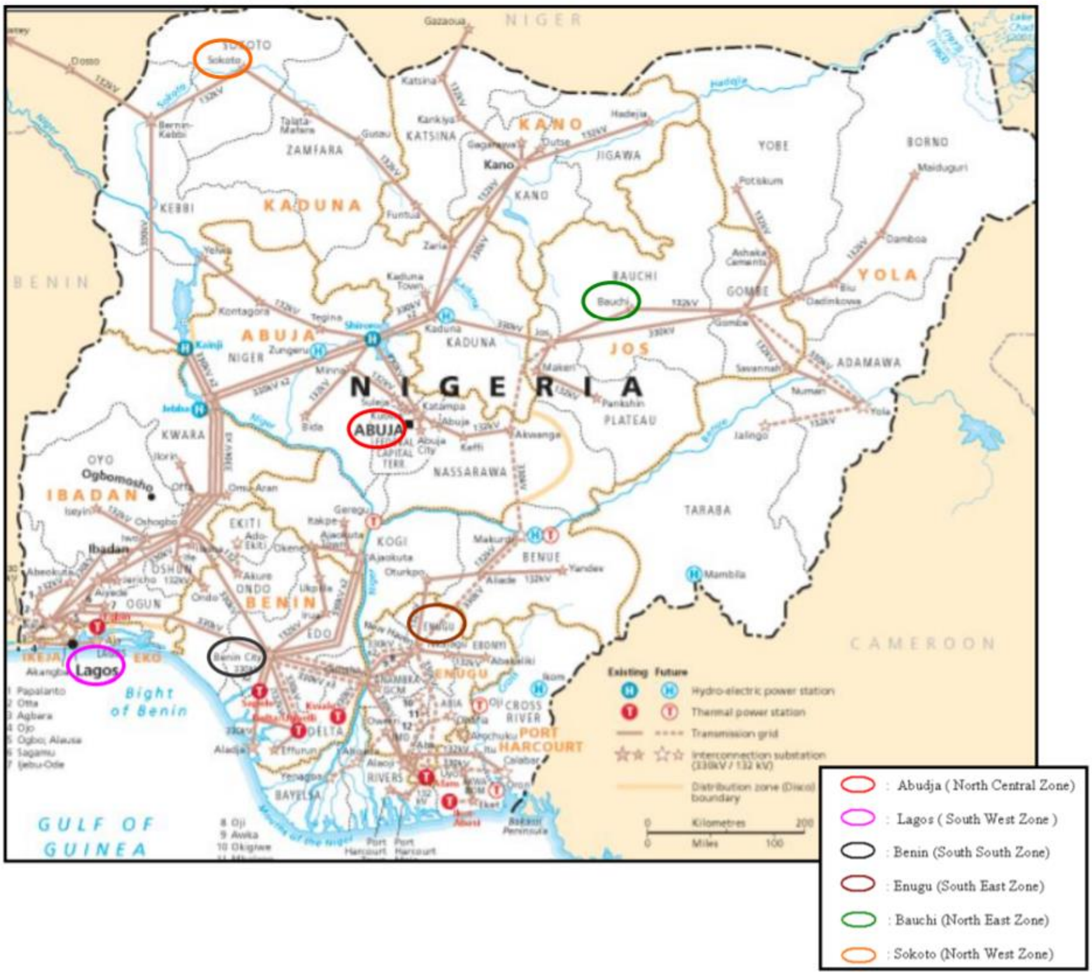

Figure 11: The different areas for the monitoring campaign. Source: (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.)

Using data from households in the monitored areas, the measured data indicated power outages occurred 45% of the time. As can be expected, the power outage periods have a big influence on the calculation of average annual consumption. For example, an appliance that is off for half of the time due to power outages will consume less than an appliance that remains on the whole time.

Figure 12 represents the part of power access/ power outage per monitored area. The farther away a location is from the power plants, the more power outages were observed, varying from 34% for the Lagos area to 61% for Bauchi and Sokoto areas.

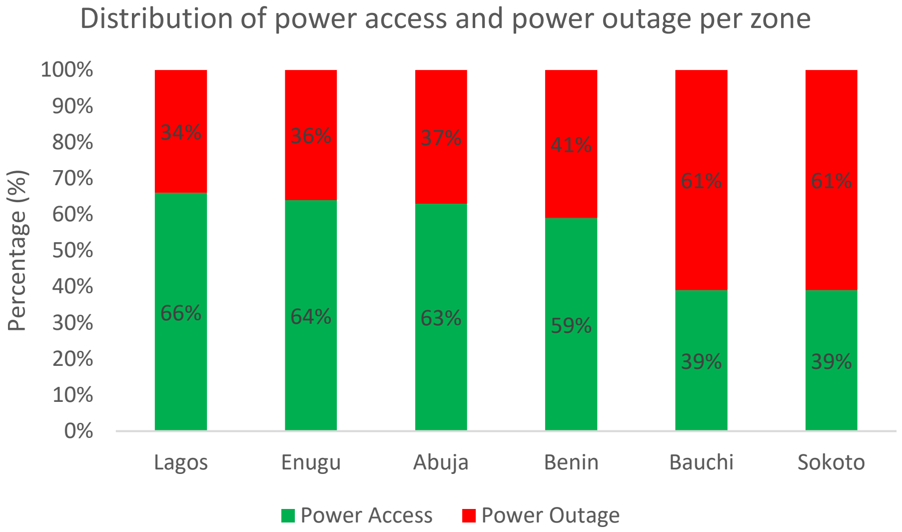

Figure 12: Distribution of power access and power outage per zone. Adapted from (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.)

Figure 13 represents the average part of power access during a typical day for the different households monitored in the various geographical areas. Notable is that power outages are most likely to occur in the middle of the day when the industries are also in need of energy. While each zone has a slight variation in the pattern of the curve, for all zones, power outages occur most often during the day.

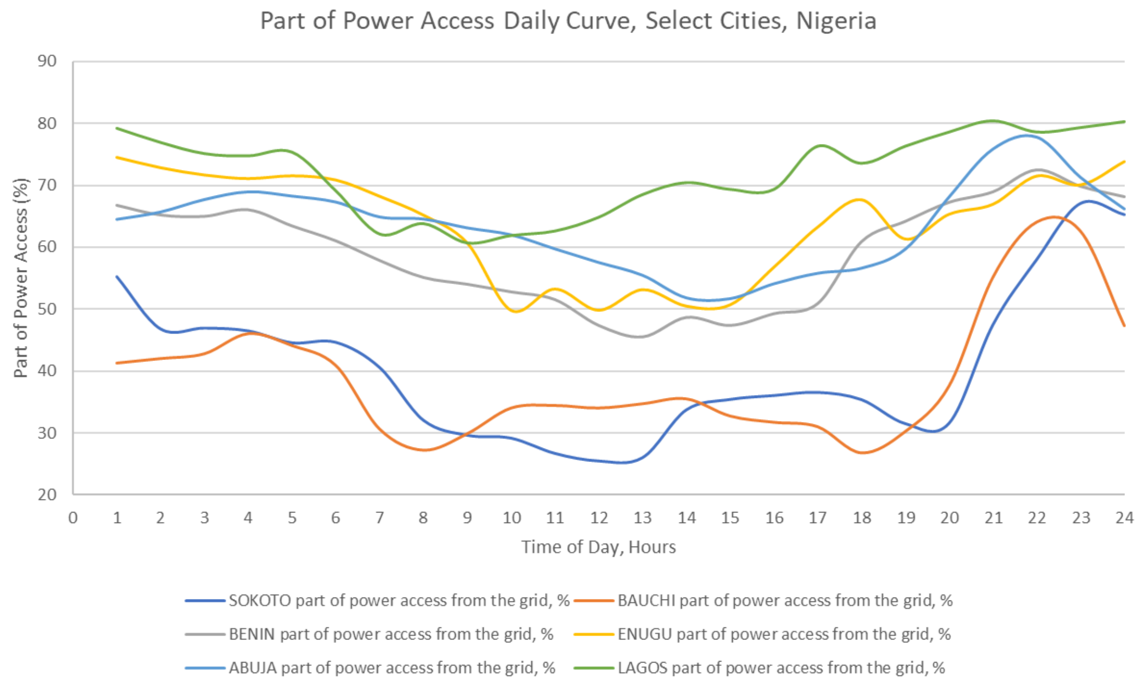

Figure 13: Part of power access daily curve of each geopolitical zone. Adapted from (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.)

The Enertech study showed that the daily household electricity access for the various zones varied from 2 to 24 hours with an average value at 13 hours and 11 hours of power outages. Of the 11 hours without electricity access, it was observed that the average duration per power outage cycle was 4 hours, with the difference across the households varying from 1 hour to 15 hours.

Based on the monitoring campaign data, the average annualized household electricity consumption was calculated to be 3710 kWh/year, or 10.2 kWh/day, with the highest consumption in Lagos and the lowest in Bauchi. The calculated average consumption includes the power outage periods, and therefore consumption expectedly would be higher without this limitation.

Figure 14 shows the average load curve for the six geographical areas when there is power access. The load profile is different for each area, but nearly all show an increase in demand during the morning hours of 6-7 a.m. and during evening hours from approximately 6 p.m. to 10 p.m. The daily average load during power access is 790 W, with an average peak of 900 W across the households. However, it can be observed that three of the six geographical areas reach a peak load of 1 kW or more. Peak load also needs to be taken into consideration for the design basis of the solar home system.

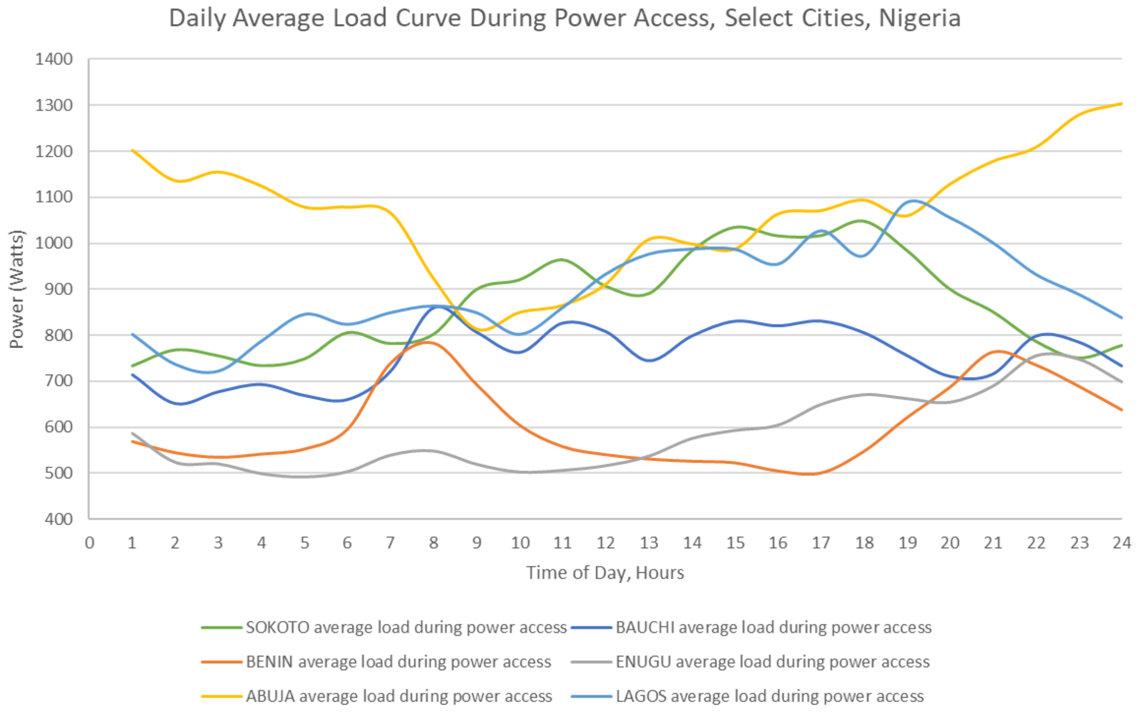

Figure 14: Average Daily Load Curve During Power Access. Adapted from (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.)

The Enertech study results clearly show a significant power access gap across all six geographical areas in the study. The inadequate national grid infrastructure is mostly to blame for the lack of power access, and alternate sources of power generation must be investigated. Renewables offer an opportunity to tap into the country's natural resources to increase generation capacity in a cleaner, environmentally friendly way. Also, the Enertech study showed that power outages are most likely to occur in the daytime, presenting an opportunity and a compelling case for electrification through solar to bridge the power access gap. The next chapter will discuss viable options for generating renewable electricity in Nigeria.

Chapter 3: Renewable electricity in Nigeria

Renewable energy as a source of electrification is not new in Nigeria. Large hydropower plants have been used in Nigeria since the 1960s and are currently the second largest energy resource for electricity generation in Nigeria (Nigeria Power Baseline Report, 2015) (Energy Commission of Nigeria, 2003). To meet the current and growing demand, the government must continue to explore the various avenues for more and cleaner electricity generation sources. This includes the continued assessment of small and large hydropower plant opportunities. It also must include assessing opportunities with solar power which is arguably the biggest untapped opportunity for electricity generation in Nigeria. Chapter 3 discusses the various renewable energy sources in Nigeria, why solar PV should be an option of choice, and the successes and failures of previous solar projects in Nigeria.

3.1. Renewable Energy Sources in Nigeria

Nigeria is a country rich with many natural resources. Aside from the agricultural and mineral resources abundant in the country, the country also enjoys a geography that provides an abundance of sunlight and is well endowed with large water resources, such as the river Niger, the third-longest river in Africa.

An overview of renewable energy system options for Nigeria include:

Hydropower: Hydropower is generated from the energy from water falling from a height, with the mechanical conversion of the energy into electricity through a turbine. The power generated can be large or small depending on the volume of water discharged and the height of the fall (or head). This form of power generation is already being aggressively pursued at the national level. Presently hydro is the second largest energy resource for electricity generation in Nigeria, contributing about 32% of the total installed grid-connected electricity generating capacity. Nigeria is currently exploring the use of hydropower plants for the provision of electricity for rural areas and remote settlements (Energy Commission of Nigeria, 2003) (International Hydropower Association (IHA), 2018).

Biomass: Opportunities exist in biomass generated energy, especially in combination with solar or other renewable energy systems. However, the impact on deforestation must be considered, especially as Nigeria is heavily dependent on its agricultural produce to meet its population needs. A natural by-product that would otherwise be waste and possibly used as a landfill can present a biomass energy potential. However, it is important to note that biomass generated energy is not always a green option or carbon neutral. Biomass production with some agricultural practices can exacerbate other environmental problems if not carefully addressed. Plus, pesticides and fertilizers negatively impact soil, water, and natural ecosystems, add costs, and decrease energy efficiency. The effects of biomass-generated energy should be carefully assessed, as well as its impact on carbon emissions.

Wind: The potential for wind energy in Nigeria is very modest, with annual average speeds of about 2.0 m/s in the coastal region and 4.0 m/s in the far north of the country at heights of 10 meters (Energy Commission of Nigeria, 2003). According to the Africa-EU Renewable Energy Cooperation Program (RECP), two large-scale wind projects are currently under development in Kano State (30 MW) and Katsina State (The Africa-EU Renewable Energy Cooperation Program (RECP)). They can provide first-hand experience on operating conditions and perspectives for grid-level wind power in Nigeria and be significant for other policy decisions.

Solar: Arguably, solar presents the most significant untapped opportunity for electricity generation in Nigeria. The opportunities presented by solar energy are aptly put in the Nigerian National Energy Policy document issued in April 2003 (Energy Commission of Nigeria, 2003). It states:

> *"Nigeria lies within a high sunshine belt and, within the country, solar radiation is fairly well distributed. . . . Solar energy is renewable and its utilization is environmentally friendly. Consequently, when the availability and environmental costs of the utilization of other forms of energy are considered, the competitiveness of solar energy in comparison with these other forms becomes very evident, particularly for low to medium power applications."*

3.2. Solar Resource

The solar energy potential in Nigeria is significant. The Africa-EU Renewable Energy Cooperation Program (RECP) estimates that the potential for concentrated solar power and photovoltaic generation is around 427,000 MW. If only 5% of the suitable land in central and northern Nigeria was designated for solar thermal use, the theoretical generated capacity would be 42,700 MW (The Africa-EU Renewable Energy Cooperation Program (RECP)).

Figure 15 shows a map of Nigeria with a solar resource estimate provided by PVGIS © European Communities (European Commission EU Science Hub, 2019). PVGIS provides solar radiation data consisting of one value for every hour over a multi-year period.

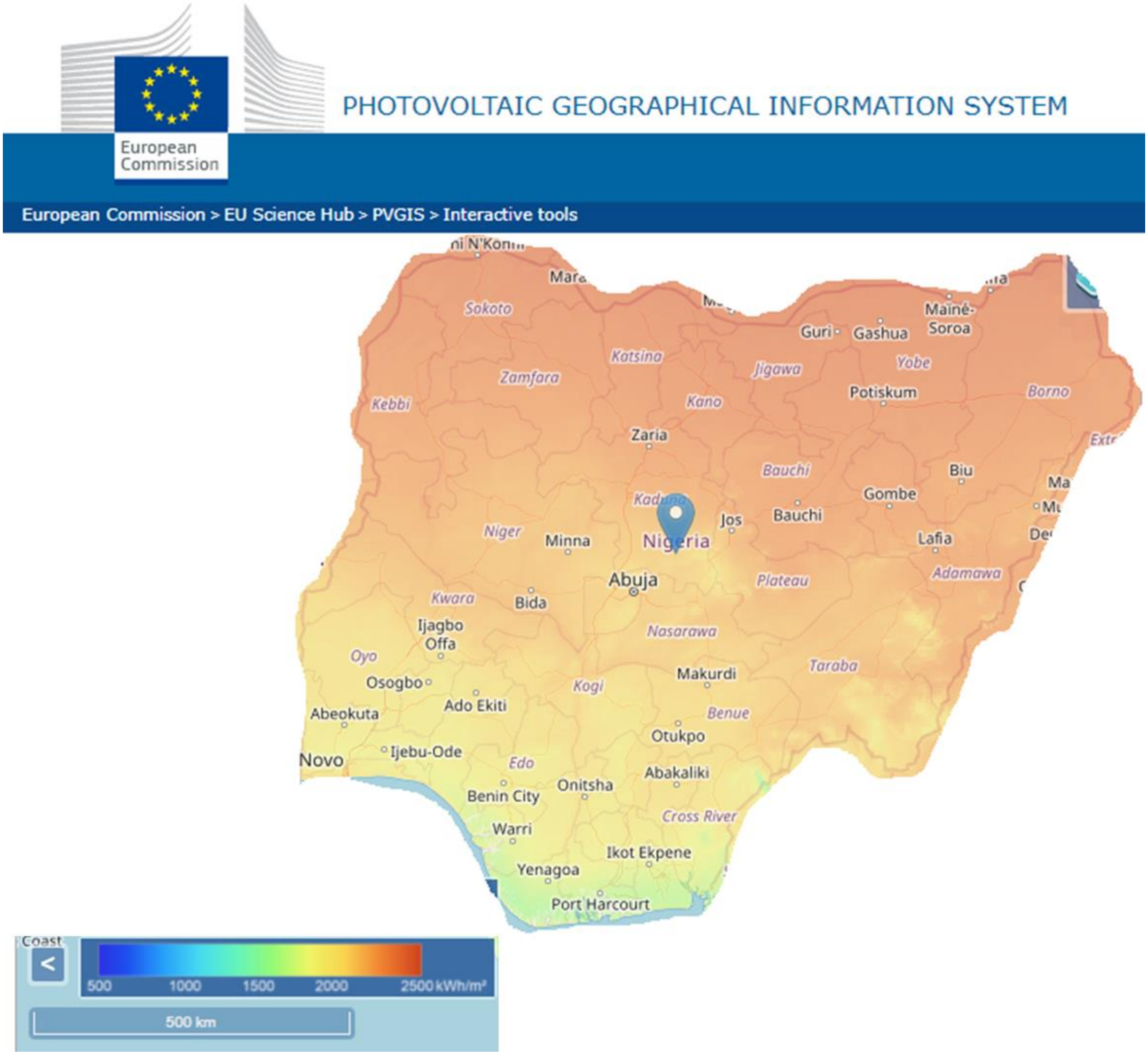

Figure 15: Nigeria Solar Resource Estimate - Yearly Average, period 2007-2016. Source: (European Commission EU Science Hub, 2019)

3.3. Type of Solar Technology

Solar radiation can be used to generate heat or electricity. Solar heat has many applications, including crop drying, heating of process water for industries, hospitals, etc., air-conditioning, preservation of foods and drugs, etc.

Technologies for converting solar radiation into electricity are generally classified as either photovoltaic (PV) or concentrated solar-thermal (CSP) type. Solar PV works by using semiconductor technology to convert sunlight into electricity directly. In contrast, solar CSP works by using mirrors to concentrate sunlight as a source of heat used to run a heat engine, turning a generator to make electricity. This also means that solar CSP tends to have a higher maintenance cost than solar PV (Habib, Idris, Ladan, & Mohammad, 2012).

While both solar thermal and solar photovoltaic should be actively explored for additional generation options for Nigeria as a whole, arguably, for the proliferation of solar energy in Nigeria, solar PV may prove to be the most viable option given that it is cheaper and modular, and as such better suited for urban electrification.

There are advantages and disadvantages to using both types of solar technology. The advantage of solar photovoltaic systems is that the Levelized Cost of Electricity (LCOE) is lower than diesel or alternative renewable energy technologies. Solar PV has a long lifespan and can provide clean energy for about 30 years. The system is modular and is convenient for low to medium power applications. Given the average energy demand in Nigeria, solar PV can cover all the daytime energy needs of a typical household, with the potential for excess capacity generated for other uses. Coupling solar PV with a battery will enable meeting a typical household’s energy needs throughout a 24-hour period. Where there is a structure in place that allows feeding to the grid, solar PV provides an opportunity for selling excess energy to the grid, thereby increasing its value. Another advantage is the speed at which solar projects can be implemented with solar PV. The well-established supply chain for solar PV means it can be rapidly deployed compared to many other power generation options. This is a key advantage for deployment in Nigeria given the pressing need to address the low rates of access to electricity and poor electricity supply for those with access to the grid.

Solar PV does have some disadvantages. The initial investment is high, and based on Nigeria's average salary, it would take over 50% of an annual average wage to pay for its installation. Also, solar PV systems can only operate when the sun is shining and must be coupled with expensive storage or other power generation mechanisms to ensure a constant electricity supply.

The main advantage of concentrated solar thermal systems is that since solar thermal only directly produces heat, it can store thermal energy in various mediums, allowing for electricity generation when the sun is not shining. Solar thermal can also be used to combine electricity and heat generation, which may be convenient for some applications.

Concentrated solar thermal also has drawbacks. One main disadvantage currently is that CSP is more expensive than solar PV. The improvements in solar PV technology, economies of scale and well-established and competitive supply chain has resulted in an 82% drop in solar PV costs between 2010 and 2019, dropping from USD 0.378/kWh to USD 0.068/kWh for utility-scale systems (IRENA, 2020). While residential roof-top solar generally has higher costs than utility-scale systems due to their small-scale, the total installed cost also decreased by between 47-80% between 2010 and 2019. Costs for solar CSP has also reduced, but not as quickly as solar PV. Utility-scale CSP system cost dropped by 47% for the same period 2010-2019, from USD 0.346/kWh to USD 0.182/kWh. However, CSP is still the least developed solar technology with new capacity added very low compared to solar PV (IRENA, 2020). Aside from the cost disadvantage compared to solar PV, depending on its application, CSP may use a large amount of water which may only be competitive for large scale power plants.

Of the two solar technologies, solar PV is more advantageous for the Nigerian environment given its cost advantage and suitability for both urban and rural application. Solar PV can be used for power supply to remote villages not connected to the national grid, and it is also possible to generate PV power for feeding into the grid. Its modularity and versatility makes it convenient for urban application as it can supply electricity to a single home, expanded over time with increasing demand, and can also be incorporated into microgrids than can scale from several kilowatts to megawatts. Plus, solar PV provides the opportunity for rapid deployment. For these reasons, solar PV is considered the solar technology of choice for electrification in Nigeria.

3.4. Solar Photovoltaic Systems

Solar electricity systems using photovoltaic (PV) arrays convert sunlight into electricity. It can only operate when the sun is shining. Because there will be mismatches between solar radiation and load, the solar PV system must be coupled with expensive storage or other power generation mechanisms to ensure a continuous supply of electricity.

The main component of a solar PV system is the solar array, consisting of one or more PV modules, where PV cells convert the sunlight into electricity. Although the PV array produces power when exposed to sunlight, other components are required to properly conduct, control, convert, distribute, and store the energy produced by the array. The additional components required may vary depending on the functional and operational requirements of the system and may include major components such as a DC-AC power inverter, battery bank, system and battery controller, as well as connection to a supplementary energy source(s). In addition, there are various balance of system (BOS) hardware such as wiring, overcurrent, surge protection and disconnect devices, and other power processing equipment.

Batteries are an optional component of solar PV systems. Batteries are often used in PV systems for storing energy produced by the PV array during the day for later use to supply electrical loads as needed, e.g., during the night and periods of cloudy weather. Batteries are typically the highest cost component of a solar PV system.

There are various types and scales of solar photovoltaic systems. The solar PV market is characterized into five main market segments, as shown in Table 2.

Table 2: Characteristics of five different solar PV market segments. Adapted from (Hansen, Pedersen, & Nygaard, 2015) and (IRENA, 2016).

	Market Segment		**Market Characteristics**	**Installed Capacity/Size**
1	Small pico-systems such as solar lanterns, LED lamps, solar chargers		Private (over the counter) consumer devices, used for lighting and charging of batteries and mobile phones in mainly nonelectrified areas.	1 - 10 W
2	Solar home systems (SHS)		Residential SHS (private households). Off-grid electricity demand in private homes typically in dispersed settlements, in smaller non-electrified villages and on the outskirts of electrified towns and villages far from existing distribution lines.	10 – 5000+ W
3	Stand-alone 'institutional PV systems		Government/municipality procurement for public institutions such as schools, hospitals, and health clinics. Typically, institutions located in villages without grid or mini-grid, or on the outskirts of grid-electrified villages.	100 – 5000+ W
4	Telecommunications and tourism		Procurement by commercial companies in the telecom and tourism sector. Powering telecom base receiver stations (BTS), link sites, and remote telecentres, and basic electricity supply (mainly lighting) typically used for rural lodges and hotels.	0.2 - 15 kW
5	Utilities	Mini-grids	Mini-grids for utilities, cooperatives (community-based), etc. Typically, in villages and towns located far from the existing grid.	5 kW - 1 MW
		Large scale grid-connected PV systems	Large scale grid-connected PV systems for utilities, Independent Power Producers (IPPs). Typically used for the expansion of production capacity in an existing grid.	1 – 50+ MW

As shown in Table 2, pico-systems are small solar PV systems such as solar lanterns or chargers. With an installed capacity range of 1-10 W, these systems would not be appropriate for backup power given the electricity consumption needs of the typical Nigerian urban household (c.f. Chapter 2).

Solar Home Systems (SHS), which are typically privately owned and placed on the roof of residential homes, have an installed capacity that ranges from 10 – 5000+ W. As the name implies, these systems would be most appropriate for installation in urban households in Nigeria. While these systems have a high initial investment cost, there is low maintenance, and the modularity of the system means the system size may be increased as demand and/or financing become available. If grid-connected, SHS allows for households to be self-generators and consumers of electricity. They provide an opportunity to take advantage of feed-in tariffs or other means of selling excess power generated, which can provide a means to recoup some of the system's cost. The commonly defined SHS comprises a PV and a battery for an individual home and is not connected to the grid or its neighbors. To avoid confusion with the commonly used SHS term, and to distinguish with the proposal of this thesis, another acronym is used – HSS. HSS refers to household solar PV systems that may not include a battery and can be connected to the grid or a neighbor.

When discussing mini-grids and microgrids, there is often confusion on the definition and/or the terms are used interchangeably. This is because there is no consensus in the industry on the definition of both terms. The Federal US Department of Energy (DOE) defines a microgrid as follows: "A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode" (Ton & Smith, 2012). However, in fast emerging microgrid markets like Africa and India, what North America calls a 'microgrid' would likely be considered a 'mini-grid. The Indian Ministry of New and Renewable Energy (MNRE), defines a mini-grid as a renewable-based distribution, usually solar, with a capacity of 10 kW and above (typically 10-200 kW) (Ministry of New and Renewable Energy SPV Division, 2012). A mini-grid can connect to the central grid to exchange power or operate independently. For the purpose of this thesis, microgrid and mini-grid refer to the same type of system. Microgrids are typically owned by the utility company or cooperatives, which are community-based and have an installed capacity ranging from 5kW to 1 MW.

Large scale PV systems are typically connected to the grid and owned by utility companies and independent power providers, including foreign investors. The installed capacity of these systems typically ranges from 1-50+ MW. Large scale solar PV systems usually take up several acres of land to place solar panels, essentially creating solar farms. This means they tend to be situated in remote locations (Ong, Campbell, Denholm, Margolis, & Heath, 2013).

This thesis explores the combination of two concepts – using residential solar PV systems to form a microgrid for the distributed generation of power.

3.5. Solar Projects in Nigeria

There have been several solar projects in Nigeria to date. This section reviews some of these projects, assessing their successes, failures, and opportunities for improvement for furthering the use case of solar PV in Nigeria.

3.5.1. Solar PV Projects Successes and Failures in Nigeria

There have been several solar PV projects to date in Nigeria, bringing some light to success and failure cases on PV implementation in Nigeria.

One project success case is the Jigawa project, which was implemented in Jigawa State (Omisore, 2011). The project was implemented and maintained by the Solar Electric Light Fund (SELF), a nongovernmental organization based in Washington, D.C., with over two decades of experience in leading solar projects in the developing world. The project's scope was to provide power for a water-pumping system that pushed clean water into the village, allowing easy access to fresh water in the town center. The project also included installing a microenterprise center, street and home lighting, and access to a portable pump that could be moved between fields to water crops. The Jigawa project is widely viewed as a success. The implemented system provides power for health centers, including lighting, vaccine refrigeration, and emergency care for residents at night. Schools and religious centers have also benefited from the system, with examples of primary schools doubling as adult education centers at night. The steady access to power in Jigawa enabled residents to open a computer technology trade school, becoming the first state in northern Nigeria to create a satellite-based broadband Internet and communications system to link all local government districts. The success of the Jigawa project is attributed to careful planning, adequate funding, and proper execution.

In contrast to the Jigawa project, a project in the Onisowo village of Bishop Kodji is largely viewed as a failure. A telling view on the project’s failures starts from its financing information, which has been difficult to obtain (Omisore, 2011). The Bishop Kodji project was the first of its kind in the State of Lagos. The project was built to power water pumps, fish driers, and streetlamps. While the project had initial success, it was short-lived. When technical issues arose over time, resources were not deployed to fix them. However, the failure of the Bishop Kodji project is largely believed to be non-technical in nature.

Residents have blamed “jealousy” and “sabotage” from neighboring communities as the cause of many of the failures. Residents site examples where state workers replaced cut wires, only to be called out again when the panels failed a second time due to an undetermined mechanical failure. Residents further stated that state workers have not returned for routine servicing since then (Omisore, 2011). Five years after the execution of the Bishop Kodji project, the solar panels still do not work.

Over a dozen states in Nigeria have experienced failures of state-run solar projects. They include Lagos State, the capital Abuja, Sokoto, Borno, Nasarawa, Bayelsa, and the Delta States. In Sokoto, the state government abandoned other solar projects and the accompanying federal funding to instead focus on connecting to the national grid. Connection to the national grid is expected to cost over $22 million and take decades to complete (Omisore, 2011).

Ikejemba and Schuur (Ikejemba & Schuur, 2018) attribute the failure of RE development projects in sub-Saharan Africa to theft and vandalism. Their study aimed to analyze the impact of theft and vandalism on the sustainability of renewable energy development projects. The authors highlight skepticism on the sustainability of publicly implemented projects given the “vast numbers of these projects are deserted after their commissioning.” They site various factors to blame, including “the utilization of inexperienced personnel during and after the implementation, the unsustainable management of the project after implementation, inappropriate location selection, absence of protection of the infrastructure from theft and vandalism, unsuitable technological utilization, etc.” The authors use a model formulation that names three factors as “the most influential instigators that lead to the vandalism and theft of renewable energy related infrastructures.” They are: (1) government inequality, (2) crime and (3) sabotage. While these three factors are viewed by the authors as the leading causes of theft and vandalism, they also include “non-inclusion” as a notable contributing factor to the problem. Non-inclusion here refers to RE projects being implemented without the involvement of the local communities.

Ikejemba et al. (Ikejemba, Mpuan, Schuur, & Hillegersberg, 2017) have also explored renewable energy project failures in sub-Saharan Africa, reviewing 29 publicly funded projects from 10 countries, including Nigeria. The Nigeria projects included street lighting, public hospital, public office, and public school. The study attributes the failure of RE projects to the absence of a sustainable management method. The study focuses on publicly funded projects because the authors believe private organizations will execute suitable management methods to maximize their profits. They believe the failure of publicly funded RE projects is because of "the absence of a sustainable management method and more specifically, the inability to appropriately trace the designation of responsibilities."

According to Ikejemba et al., most public RE projects fail because it is often not clear whether the projects belong to the government or to the people, which leads to issues around ownership, especially when problems, maintenance, or other issues arise. Many West African countries have had many small and medium-sized photovoltaic (PV) projects implemented, covering a broad spectrum from street lighting to powering hospitals' emergency departments. However, most of these projects have deteriorated with a lack of maintenance, cleaning, or repairs, a problem that the authors attribute to a lack of a sustainable management method. With some of these projects discontinued during the planning stage and sometimes during implementation, it puts further strain on the limited public funding available. This also creates a negative public impression, diminishes belief in the technology, and makes it more challenging to build the public's confidence in adopting solar PV systems.

The authors also believe that publicly funded RE projects have a higher rate of failure because, unlike privately funded projects, public sector funded projects put social and environmental benefits above economic reasons. The authors assert that "The energy problems experienced in sub-Saharan Africa today can only be solved by the decentralization of energy generation to the smallest subset possible" (Ikejemba, Mpuan, Schuur, & Hillegersberg, 2017).

In a follow-up work by Ikejemba et al., they deliver recommendations for the sustainable management of renewable projects in sub-Saharan Africa. Given the project failures in public RE projects, the authors' recommendations center around: (1) transparency, (2) ownership, (3) shared responsibility, and (4) community involvement (Ikejemba E. C., Schuur, Hillegersberg, & Mpuan, 2017). Their recommendations present an area for further study that is covered in this thesis, i.e., a potential solution to PV project failures by incentivizing private citizen-owned and generated solar PV power instead of publicly owned systems.

Based on the learnings from several state-funded solar projects' failures, an opportunity to improve is having individuals personally invested in solar projects. When privately owned and financed, the sense of ownership is much higher, with strong vesting in the solar PV system's long-term success. It is for this reason that this thesis specifically espouses household-based solar PV systems for electrification.

3.5.2. Mini-Grid Projects in Africa

A report by the Rocky Institute on the growing mini-grid market in sub-Saharan Africa focuses on four African countries with significant mini-grid markets and mini-grid-friendly regulatory environments – Senegal, Kenya, Tanzania, and Uganda (Agenbroad, Carlin, Doig, Henly, & Wanless, 2017). Noteworthy is that all four-leading mini-grid markets referred to have between 6 and 10 outages per month, with an average outage duration of 8.3 hours. However, this still reflects higher uptime when compared to the average outage duration in Nigeria.

In gathering insights for Africa, the Rocky institute report refers to the India mini-grid market. It found that in India, mini-grids often function in parallel with the electric grid. This allows customers to connect to both systems and switch back and forth as is most beneficial to them. In a case like this, the customer often chooses the cheaper subsidized grid power when available and more reliable power from the mini-grids when grid power is not available.

The Rocky Institute report points to an issue in the four focus African countries, where nearly 35-45% of the population cannot pay for mini-grid energy access. With the market penetration of mini-grids below 1%, the report's authors see funding issues as the key barriers to mini-grid commercial viability in sub-Saharan Africa. The report notes that "Venture capital investments excluding impact investments are still rare because investors see the mini-grid market as too risky. Market rate debt is prohibitively expensive, and access to project financing is limited." The report further suggests that accelerating the growth of the mini-grid industry requires: (1) proving the business model, (2) attracting investment, and (3) ensuring an enabling environment.

A recommendation from the Rocky Institute report is that governments in Africa help provide enabling environments for mini-grids to achieve their energy access targets. It suggests governments can "reduce regulatory risk for companies and their investors with clear, comprehensive off-grid energy plans; streamlined import procedures; dependable incentives for renewables and energy-efficient appliances; and education/awareness campaigns that communicate to their citizens how off-grid products, and mini-grids in particular, work and their benefits."

Notable is that in the Rocky Institute report, the suggested ways of growing the mini-grid market are all commercial in nature. This report misses an opportunity that this thesis discusses, i.e., increasing mini-grids through individual/private citizen-owned home networks that can form a distributed generation network.

3.5.3. Renewable Energy Training

A critical success factor for sustainable renewable energy use is proper installation, operation, and maintenance, supported by having the requisite skill set in the market. Therefore, in addition to growing the adoption of solar PV systems, it is also essential to develop the necessary skill sets to ensure its sustainability.

A consortium of GOPA consultants issued a 2014 report covering the training needs assessment for renewable energy, rural electrification, and energy efficiency in Nigeria (Consortium of GOPA Consultants and intec, 2018). The German agency GOPA is short for Gesellschaft für Organisation Planung und Ausbildung mbH. The assessment done had two main objectives – (1) to identify skills gaps and training needs in RE evolving market demand and existing educational courses, and (2) to define viable training courses capable of addressing the mid-term market demand that could be successfully introduced by the Nigerian Energy Support Programme (NESP).

The GOPA report found that the high failure rate of off-grid projects brings with it a "considerable risk that the continued absence of skilled personnel may exacerbate reputational damages already incurred, stifling prospects of further deployment." The report found various educational programs or courses related to RE within Nigeria, either ad-hoc in nature or in the curricula of undergraduate courses at universities. Most courses were found to be academic and not skills-based, which was identified as a critical gap. While there is a need for an engineer to design, plan and implement RE projects, solar PV systems, in particular, require skills in installing, troubleshooting, and maintaining PV systems, paired with a basic understanding of designs.

Chapter 4: Solar PV Through Fuel Savings[1]

Using a case study of residential households in Nigeria, chapter 4 presents the case for enabling the use of solar PV systems for electricity generation in urban communities through fuel savings. In so doing, the usage of diesel generators can be eliminated or greatly reduced at no additional cost to the user. The case study specifically addresses solar PV access for middle-class Nigerians, mainly in urban areas, as they are the demographic with the most demand for electricity yet with income levels challenged for procuring residential solar PV systems. This chapter starts with the Lagos case study to illustrate the methodology and then shows the results for other geographical locations.

4.1. Solar PV Design for a Typical Urban Household

To adequately design the solar PV system, the load and energy use is first assessed. For the first case study, solar PV design cases are assessed for households in Lagos, which show the highest electricity consumption of the geographical areas in the Enertech study. To assess the load profile for different periods throughout the day, in Figure 16, the Enertech data of the power access and outage periods is overlaid against the average load profile for households when there is power access throughout the same period. The energy used can be calculated for the period where power is drawn from the grid as well as when power is drawn from another source when there is no power access from the grid.

[1] Part of this text is adapted from Babajide, A, Brito, M.C, " Solar PV Systems to Eliminate or Reduce the Use of Diesel Generators at No Additional Cost: A Case Study of Lagos, Nigeria. Renewable Energy Journal, July 2021. DOI: 10.1016/j.renene.2021.02.088.

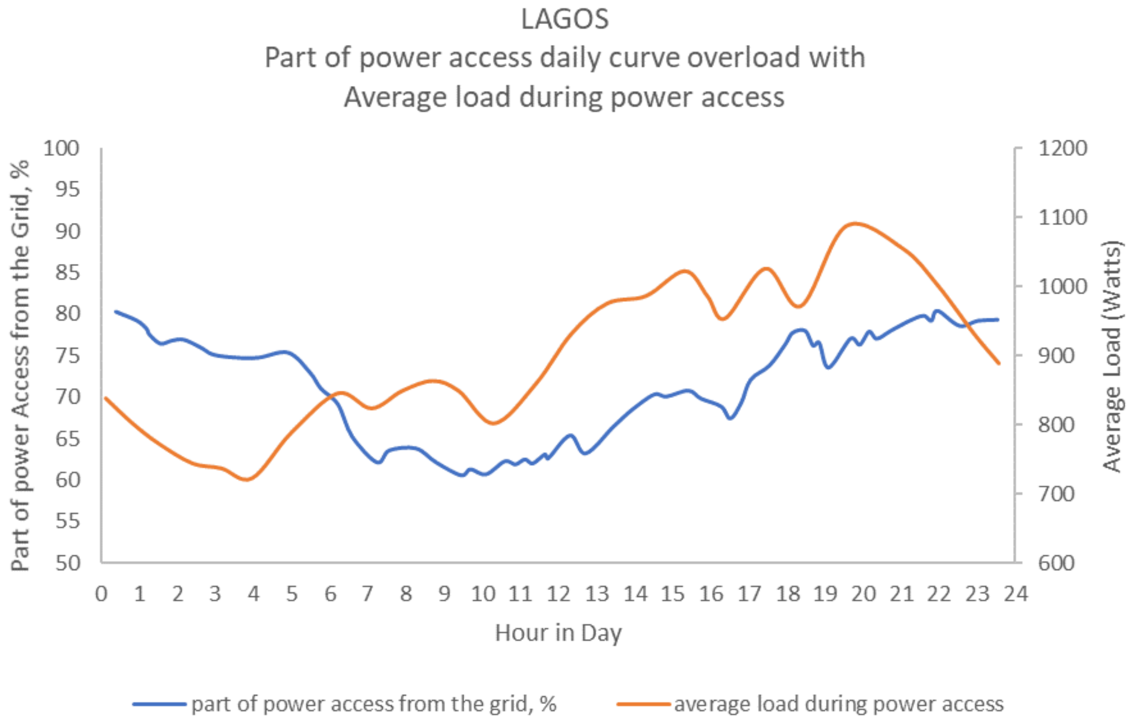

Figure 16: Lagos - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

The energy used during periods of power access from the grid can be calculated as follows:

$$\overline{E_g} = \overline{P_d} * H * P_p \quad \text{[Eq 1]}$$

where $\overline{E_g}$ is the average energy used from the grid in Watt-hour per day; $\overline{P_d}$ is the average power drawn when there is no outage, in Watt; H is the hours used per day, and P_p is the part of power access from the grid. Conversely, the energy used from an alternate power source, such as a diesel generator or solar system, during periods of no power access from the grid can be calculated as follows:

$$\overline{E_a} = \overline{P_d} * H * (1 - P_p) \quad \text{[Eq 2]}$$

where $\overline{E_a}$ is the average energy from an alternate source, in Watt-hour per day.

A summary of the results of various load cases and the energy used is shown in Table 3.

Table 3: Average Energy Used for Various Load Cases and Power Access Periods for Lagos Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (kW)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	21.6	1.088
Average grid power access throughout day	72%	17.3	15.6	1.088
CASE 1: Average No-grid power access throughout day	28%	6.7	6.0	1.088
Sun-up period only, 6:30 a.m. - 6:30 p.m.				
Assuming 100% access from the grid during sun-up period of day	100%	12.0	11.1	1.027
Average grid power access during sun-up period of day	67%	8.0	7.4	1.027
CASE 2A: Average No-grid access during sun-up period of day	33%	4.0	3.6	1.027
Sun-down period only, 6:30 p.m. - 6:30 a.m.				
Assuming 100% access from the grid during sun-down period of day	100%	12.0	10.5	1.088
Average grid power access during sun-down period of day	77%	9.2	8.0	1.088
CASE 2B: Average No-grid access during sun-down period of day	23%	2.8	2.4	1.088

Lagos households had an average annualized consumption of about 5600 kWh/year, including the periods of a power outage.

A solar PV system is designed for the 2 cases of no-grid power access that include daylight hours, i.e., Case 1 and Case 2A as shown in Table 3. System design and cost are performed using Lee and Callaway's model (Lee & Callaway, 2018) to calculate the cost of reliability. Lee et al. have developed a tool for estimating the cost of stand-alone solar-plus-storage systems in sub-Saharan Africa, with a specific emphasis on reliability that distinguishes it from other solar system calculators. The tool design uses the fraction of demand served (FDS) as the reliability metric of interest, which measures the ratio of energy supplied to energy demanded over a period. The model solves the cost-minimization numerically by simulating different system configurations over 11 years of daily solar irradiance. It does this by finding the configuration of solar and storage capacity that minimizes the levelized cost of electricity (LCOE) for a given target reliability and technical and economic parameters.

Some important notes regarding the calculated cost of electricity and reliability tool for decentralized solar power systems in sub-Saharan Africa (Lee & Callaway, 2018):

- Solar production modeling was done using 11 years of daily average insolation incident on a horizontal surface at each location with a 1° latitudinal and longitudinal resolution. The data was obtained from the NASA Langley Research Center

Atmospheric Science Data Center Surface meteorological and Solar Energy web portal for the period spanning 1 January 1995 to 31 December 2005.

- Reliability is quantified using FDS, which is, over the analysis period, the sum of all the energy delivered divided by the sum of all the energy demanded. An FDS of 1 indicates perfect reliability.
- The model uses the World Bank's Energy Sector Management Assistance Program (ESMAP) Tiers of Access, analyzed for Tier 5 which is considered the highest level of access (Bhatia, M. and Angelou, N. (The World Bank), 2015). These parameters were used to calculate the LCOE using a multistep optimization to compute the least-cost system with the fraction of demand served as a design constraint, considering the daily variation in solar resources and costs of solar and storage.
- Electricity tariff data was obtained from the World Bank report, accessed online at http://databank.worldbank.org/data/download/avpfa/avpfatariff.xlsx. The grid tariff data is averaged across the country. The differences in LCOE within the country come from the difference in solar radiation.
- Reliability data was computed from the World Bank Enterprise Infrastructure Surveys, accessed online at http://www.enterprisesurveys.org/data/exploretopics/infrastructure#sub-saharan-africa.
- When using the estimator tool to design a solar PV system without batteries, setting the battery price to zero indicates that storage is free so the optimization would choose to use a lot of storage. To reflect no battery use, select the day heavy load shape ensuring that a high enough battery cost is input so that the optimal solution has zero battery storage in it. In addition to setting a high battery cost, achieving a result with zero battery storage may also require a combination of setting a higher than needed daily load and lowering the reliability to achieve the target daily load (e.g.: 60% reliability at 6.6 kWh/d daily load to achieve 4 kWh/d energy delivered, vs near 100% reliability at 4 kWh/d).
- Designing a decentralized system with battery that is less than ~90% FDS tends to be more expensive because it indicates providing less energy but still incurring the same fixed cost for installation and the power supply. In Lee et al.'s paper, they calculate the LCOE for decentralized systems at FDS of 48% in Nigeria to see the difference in cost between the decentralized system and the grid at the same FDS but point out that

the decentralized system would actually be cheaper (by LCOE) if it was designed to have better FDS than 48%.

- It should be noted that most solar inverters that connect to the grid by design will not function when the grid goes down. A good technical solution would be needed. A battery with an inverter is usually necessary to combine with solar to supply AC power without the grid. Without a form of storage, the system is not available for power supply during nighttime and may go down on cloudy days with no power supply to the household in the event the grid is also down at the same time. Some form of energy storage is typically needed to keep a stable voltage for all the appliances when the grid is down. Where affordable, the preferred option would be to use some energy storage to increase reliability.

For application in this study, Lee et al.'s modeling tool is used to design a solar PV system based on the input load cases. The solar PV system design inputs are shown in Table 4.

Table 4: Inputs Solar PV System Design

Technical input:	**Economic input:**
Target reliability (Fraction of Demand Served), FDS = 95%	Currency: USD
Daily Load (kWh/day): varied	Battery Cost (USD/kWh): 400***
Peak Capacity (kW): varied*	Solar Cost (USD/kW, including racking): 1000
Solar Derating (%): 85	Charge Controller Cost (USD/kW): 200
Battery Lifetime (yrs): 10	Capacity Cost (USD/kW) - Includes inverter/DC power supply, balance-of-system, etc.; i.e. variable costs per peak capacity: 1300
Daily load profile: Constant**	Additional Fixed Cost (USD): 0
	Operations and Maintenance Factor (% of total capital cost): 5
	Project Term (yrs): 20
	Discount Rate (%): 10

**Peak capacity is not the same as the peak of the load profile. This is because the load profile is the average daily profile. The peak capacity shows that apart from the average, there are times when more power is needed.*
***A choice of four different load profile shapes is available: constant, day heavy, night heavy, or representative (which represents an empirical sample from a microgrid in Uganda). The option chosen will factor into how much battery storage capacity is designed for. According to the load profile observed in the Enertech monitoring campaign* (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.), *the highest demand is observed during evening*

hours from approximately 6 pm to 10 pm. However, that peak demand is balanced out by low consumption late at night, so the constant case is used as a good approximation on battery capacity needs. When modeling a scenario for solar panel only with no battery used, the day heavy load profile is used.
**** Note that the cost of a battery may or may not be included based on the given scenario.*
For detailed model notes, refer to Lee et al.'s work (Lee & Callaway, 2018).

In the estimator tool, the "peak capacity" is not the same as the peak of the load profile. This is because that load profile is the average daily profile. The peak capacity shows that apart from the average, there are certain times when more power is needed, and that is used to determine the size of the inverter or power supply. The peak capacity parameter is used along with the capacity cost parameter to determine the cost of the power supply. Technically it should be determined from the peak load on the system, and the cost should reflect the cost of the DC / AC inverter if it is an AC system or any DC / DC converter if it is a DC system, plus any costs associated with circuit breakers and wiring (a reasonable assumption is that these costs scale with the capacity of the system). The solar capacity is the nominal power of the panels. So, for example, one could have a small solar capacity and accumulate the energy in a battery and then discharge the battery quickly.

Aside from the technical inputs, there are economic inputs for the solar PV system design. These include operations and maintenance cost, estimated to be 5% of the total capital cost. A project term of 20 years is conservatively used although solar panels have an industry standard life span of 20-30 years. The discount rate often varies in various studies and can be subjective. For this thesis, the discount rate applied by the Brazilian National Bank for Economic and Social Development (Sorgato, Schneider, & Rüther, 2018) and Espinosa and Rojo (Espinoza & Rojo, 2015) is used, which is 10%. This is also a reasonable estimate given that Brazil is considered a peer country for Nigeria.

The solar PV system costs for the 2 cases of no-grid power access that include daylight hours, i.e., Case 1 and 2A in Table 3, are shown in Table 5. Case 1 design is for a full day with battery included. Case 2A design is for daylight hours only, with no battery included.

Table 5: Solar PV System Costs (in USD) - Lagos

	CASE 1 (full day): FDS = 95%, Daily load = 6.5 kWh/d, Peak = 1.5 kW	**CASE 2A (6:30 a.m. - 6:30 p.m.):** FDS = 60% of 6.6 kWh/d, Daily load = 4 kWh/d, Peak = 1.5 kW
LCOE	0.49	0.37
Up-front Cost	6043	3158
Replacement Cost (present cost)	488	0
Total Capital Cost	6531	3158
O&M Cost	327	158
Solar Capacity (kW)	2	0.88
Storage Capacity (kWh)	3.5	0

A household solar power system without a battery is a workable option for Nigerian urban households, given the profile of the power access and outage periods as observed from the Enertech monitoring study. Furthermore, not including a battery can reduce total capital cost by as much as 40-50%. In the Enertech study, most of the outages occur in the middle of the day, and most of the demand for residential households are in the early morning hours and evening hours. An appropriately sized and installed solar power system can feed the grid the excess electricity generated during the daytime and draw from the grid during sundown hours. When there are outages during the high demand periods, households can compensate with diesel generators for those who already have access to these. Nigeria is already one of the largest importers of diesel generators globally and spends approximately $250 million annually on the importation of generators and their spare parts (Frost & Sullivan, 2011). However, these generators carry health and environmental risks, including noise pollution, which makes reducing or eliminating their use imperative. The use of solar PV systems to affordably reduce or eliminate the use of diesel generators is covered next.

4.2. Use of Solar PV Systems to Reduce or Eliminate the Use of Diesel Generators

Given that many Nigerian households already have diesel generators, it is unrealistic to expect that these gensets will be quickly discarded. However, operating a diesel generator in Nigeria carries a high financial cost. The pump price of diesel was approximately $1 per liter in 2014, which meant running a diesel genset cost almost twice as much compared to getting subsidized power from the grid (The World Bank, 2014). Given the high cost of a battery for solar PV systems and the widespread availability and use of diesel generators, a solar-hybrid system consisting of a household solar PV system and diesel generator may present the most economical configuration for continuous power access. Furthermore, this solar-hybrid configuration helps reduce the adverse health and environmental impact on society compared to using diesel generators alone during periods of a power outage.

Solar PV systems can be made more affordable by using the associated fuel savings to purchase the system. One approach to assessing this is from Ferrero et al. who propose that customers could potentially use fuel savings towards a payment plan for purchasing solar PV home systems (Ferrero, 2018). However, in the paper by Ferrero et al., there is no actual household data to support the scenario described, and the financial analysis done does not consider the time value of money. Using the Enertech study data, cost information for the solar systems designed, and financial analysis taking into account the time value of money, this thesis shows how solar PV systems can be funded through fuel savings, enabling households in urban communities to reduce or eliminate the use of diesel generators. Below are further details for the Lagos case:

Case Assumptions for Lagos:

- Lagos households in the Enertech study are used for this case. According to a world bank report that inventoried diesel power generation in Nigeria, Lagos has the highest number of diesel gensets in the residential sector as well as the highest reported spend on diesel (The World Bank, 2014).
- It is assumed households already have a diesel generator, so only the associated fuel cost of running them is included in the economic analysis. Fuel cost is calculated for a 2 kW diesel generator based on the load case for Lagos households in the Enertech study, as well as the widespread use of this size diesel generator in Nigeria.
- The diesel generator is assumed only to be used when there is no power supply from the grid. Part of power access from the grid and power demand data from the Enertech study are used. Scenarios tested will include:
    - Case 1 (full day): The diesel generator is run during all instances of a power outage, day and night.
    - Case 2A (6:30 a.m. – 6:30 p.m.): The diesel generator is run when outages occur during sun-up hours to compare the cost of its use during this period versus a solar PV system without a battery.

- Case 2B (6:30 p.m. – 6:30 a.m.): The diesel generator is run when outages occur during sun-down hours to compare the cost of its use during this period versus a solar PV system with a battery.

- The O&M cost for a diesel generator is meager and deemed negligible for this estimation.
- The loan interest rate used is estimated based on information on the Trading Economics Nigeria interest rate site, which includes historical rates from 2007 to date (Trading Economics, n.d.).
- The discount factor used in the financial analysis accounts for the time value of money, but not inflation. Inflation is not considered as the real discount rate is used instead of the nominal discount rate. All costs are in year-zero dollars, so the fuel and O&M costs remain the same for each year of the project lifetime.

The following equations are used to calculate the energy, fuel consumption, and total cost per year for a diesel generator:

First, to calculate the output power of the diesel engine, the following equation is used:

$$\text{Active power } P = S \cos(phi)$$

$$\text{Apparent power } S = P / \cos(phi) \qquad \text{[Eq 3]}$$

where P is the active electric power in the output of the diesel generator in kW; S is the apparent electric power in the output of the diesel engine in kVA, and *Cos*(*phi*) is the power factor (usually between 0.8 and 1)

The following equation is used to calculate the output energy and consumption of the diesel engine:

$$\text{Energy in output: } E = \bar{P} * h * d$$

$$\text{Consumption of fuel: } C = E * Ckwh \qquad \text{[Eq 4]}$$

where E is the active electric energy is the output of the diesel engine in kWh; $\bar{P}$ is the average active electric power output of the diesel engine in kW; h is the number of hours per day the genset runs; d is the number of days the power generator runs; *Ckwh* is the Consumption of fuel per kWh, and C is the Consumption of fuel in liter.

The output energy and fuel consumption for a diesel engine is a fairly straight-forward calculation. Alternatively, Power Calculation online provides a simple excel based file to calculate power and electricity production for a diesel generator based on input data on load, fuel consumption, and fuel cost per liter (Power Calculation, n.d.).

The inputs for this calculation are as shown in Table 6:

Table 6: Input data for diesel generator energy and fuel cost calculation

Apparent Power, S (kVA)	2.5
Cos(phi)	0.80
Active Power, P (kW)	2
Load, %	50%
Ratio consumption L/h*	1.1
Number of hours running, h/d (CASE 1/2A/B)	6.7 / 4 / 2.8
Cost of fuel per liter, USD/L**	0.97
Caloric value of diesel (PCI), kWh /L	0.98

**The fuel consumption for a 2kW/2.5kVA diesel generator was obtained from a diesel generator manufacturer* (Greaves Power, n.d.)
***Average pump price for diesel in 2012-2013* (The World Bank, n.d.)*, for the same period the Enertech study was done.*

The total cost for diesel fuel for the three use cases is shown in Table 7.

Table 7: Cost of diesel fuel for use cases - Lagos

Diesel Generator Use Cases		**CASE 1: outages throughout day**	**CASE 2A: outages when sun-up**	**CASE 2B: outages when sun-down**
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		6.7	4.0	2.8
Electric production in kWh		6.7	4.0	2.8
Consumption fuel in liter/day		7.4	4.4	3.1
Total cost per day	USD/d	7.1	4.3	3.0
Total cost per year	USD/yr	2609	1558	1090

The results of the 3 cases comparing use of diesel fuel versus purchase and use of a solar PV system, either as the sole backup system (100% fuel replacement), sun-up period backup (partial fuel replacement) and sun-down period backup (partial fuel replacement) are shown in Table 8 and Table 9.

For the financial assessment of the various cases, Net Present Cost (NPC) is used. The NPC represents the lifecycle cost when all the costs for the life of the project are adjusted to the present-day cost. The present-day cost can be calculated as follows:

$$NPC = -C_0 + [-C_1/(1+r)^1] + [-C_2/(1+r)^2] + [-C_3/(1+r)^3] + \ldots + [-C_T/(1+r)^T] \quad \text{[Eq 5]}$$

where C_0 is the initial investment, C is the cash flow; r is the discount rate, and T is the Time.

In case 1, the cost of running a diesel generator as the sole backup option during power outages from the grid results in a high Net Present Cost (NPC) value of over $20,000 over a 20-year period. In contrast, when a solar PV system is used with a battery as backup, the cost savings over the life of the project is almost 60%. Furthermore, if the amount that would have been spent on diesel fuel was spent on financing the solar PV system with batteries, the system can be paid off in 4 years. The cost of the battery replacement is included now in the total capital cost as it is more cost effective for the owner to pay the supplier now for the battery replacement versus when it is needed in 10 years.

Cases 2A and 2B incorporate both the sun-up diesel expense based on the power outages in the daytime, as well as the sun-down diesel expense based on the power outages after sunset. Part of the daytime fuel expense is replaced by using the solar PV system for outages that occur in the daytime. Not utilizing a battery reduces the cost of the solar PV system significantly. Further savings on the solar PV system also come from sizing it for a lower daily load case as it will only be used during the period of the day when there is sunlight and no access from the grid. Note that when using Lee et al.'s estimator tool to optimize for no battery use, a higher daily load was input (6.6 kWh/d) at an FDS of 60% to obtain the 4 kWh/d target daily load. Furthermore, an artificially high battery cost was set causing the tool to optimize for a solar PV design without using a battery. The hybrid system combining both a solar PV system without battery with a diesel generator to meet energy needs during outages results in a cost savings of 80% over the life of the project compared to if only a diesel generator was used as the sole backup system. Like the first case, if the cost savings on diesel fuel was applied towards financing a solar PV system without a battery, the system could be paid off in 3 years. However, to achieve the most stable system, a solar PV system with batteries would be most preferred. Both these cases show it would be incredibly beneficial to have accessible financing options to enable the adoption of solar PV systems.

Table 8: Diesel genset vs. solar PV system (100% fuel replacement) - Lagos

DIESEL GENERATOR FOR FULL BACKUP vs SOLAR PV SYSTEM WITH BATTERY (100% FUEL REPLACEMENT) - LAGOS

FUEL SPEND USAGE CASE	USD/PER YEAR	USD/PER MONTH	
Diesel genset used for full backup	2,609	217	Discount rate = 10%

Diesel Generator							
Year	1	2	3	4	5 …	10	20
Cost of fuel	$ (2,609)	$ (2,609)	$ (2,609)	$ (2,609)	$ (2,609) …	$ (2,609)	$ (2,609)
Discounted Costs	$ (2,372)	$ (2,156)	$ (1,960)	$ (1,782)	$ (1,620) …	$ (1,006)	$ (388)
						Net Present Cost (NPC)->	**$ (22,212)**

Solar PV system WITH battery, NOT FINANCED								
Year	0	1	2	3	4	5 …	10*	20
Cost of solar PV system, NOT financed	$ (6,531)	$ -	$ -	$ -	$ -	$ - …	$ -	$ -
Cost of operation and maintenance	$ -	$ (327)	$ (327)	$ (327)	$ (327)	$ (327) …	$ (327)	$ (327)
Total Cost	$ (6,531)	$ (327)	$ (327)	$ (327)	$ (327)	$ (327) …	$ (327)	$ (327)
Discounted Costs	$ (6,531)	$ (297)	$ (270)	$ (245)	$ (223)	$ (203) …	$ (126)	$ (49)
							Net Present Cost (NPC)->	**$ (9,311)**
	*new battery in year 10						**Cost saved over project life ->**	**58%**

SOLAR SYSTEM DETAILS

Target reliability FDS	95%
Daily Load (kWh/day)	6.5
Peak Capacity (kW)	1.5
Project life, yrs	20

FINANCING OPTION DETAILS

Amount borrowed	$ 6,531
Loan interest rate	15%
Loan term	48 months (4 years)
Payment due	monthly
Discount Factor	35.93
Monthly loan Payment	181.76
Monthly fuel cost (100% fuel replacement)	*0*
Averge Monthly PV O&M cost	*27.21*
Total customer monthly payment	*208.98*

Solar PV system WITH battery, FINANCED (assumes financing the total capital cost, including for the battery replacement in 10 years)

Year	1	2	3	4	5 …	10	20
Cost of solar PV system, financed	$ (2,181)	$ (2,181)	$ (2,181)	$ (2,181)	$ - …	$ -	$ -
Cost of operation and maintenance	$ (327)	$ (327)	$ (327)	$ (327)	$ (327) …	$ (327)	$ (327)
Total Cost	$ (2,508)	$ (2,508)	$ (2,508)	$ (2,508)	$ (327) …	$ (327)	$ (327)
Discounted Costs	$ (2,280)	$ (2,072)	$ (1,884)	$ (1,713)	$ (203) …	$ (126)	$ (49)
						Net Present Cost (NPC)->	**$ (9,694)**
	*new battery in year 10					**Cost saved over project life ->**	**56%**

Table 9: Diesel genset + solar PV system (partial fuel replacement) - Lagos

DIESEL GENERATOR FOR BACKUP + SOLAR PV SYSTEM WITHOUT BATTERY (PARTIAL FUEL REPLACEMENT) - LAGOS

FUEL SPEND USAGE CASE	USD/PER YEAR	USD/PER MONTH
Diesel genset for full backup	2,609	217
Diesel genset during sun-up period	1,558	130
Diesel genset during sun-down period	1,090	91

Discount rate = 10%

Diesel Generator								
Year	1	2	3	4	5	…	10	20
Cost of fuel during daytime outages	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558)	…	$ (1,558)	$ (1,558)
Cost of fuel during nighttime outages	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090)		$ (1,090)	$ (1,090)
Discounted Costs	$ (2,407)	$ (2,188)	$ (1,989)	$ (1,809)	$ (1,644)	…	$ (1,021)	$ (394)
							Net Present Cost (NPC)->	**$ (22,544)**

Solar PV system WITHOUT battery									
Year	0	1	2	3	4	5	…	10	20
Cost of solar PV system, NOT financed	$ (3,158)	$ -	$ -	$ -	$ -	$ -	…	$ -	$ -
Cost of operation and maintenance	$ -	$ (158)	$ (158)	$ (158)	$ (158)	$ (158)	…	$ (158)	$ (158)
Total Cost	$ (3,158)	$ (158)	$ (158)	$ (158)	$ (158)	$ (158)	…	$ (158)	$ (158)
Discounted Costs	$ (3,158)	$ (144)	$ (130)	$ (119)	$ (108)	$ (98)	…	$ (61)	$ (23)
								Net Present Cost (NPC)->	**$ (4,502)**
								Cost saved over project life ->	**80%**

SOLAR SYSTEM DETAILS

Daily Load (kWh/day)	4
Peak Capacity (kW)	1.5
Project life, yrs	20

FINANCING OPTION

Amount borrowed	$ 3,158
Loan interest rate	15%
Loan term	36 months (3 years)
Payment due	monthly
Discount Factor	28.85
Monthly loan Payment	109.47
Monthly fuel cost (use of fuel during sundown period)	*90.83*
Averge Monthly PV O&M cost	*13.16*
Total customer monthly payment	*213.46*

Solar PV system WITHOUT battery								
Year	1	2	3	4	5	…	10	20
Cost of solar PV system, financed	$ (1,314)	$ (1,314)	$ (1,314)	$ -	$ -	…	$ -	$ -
Cost of operation and maintenance	$ (158)	$ (158)	$ (158)	$ (158)	$ (158)	…	$ (158)	$ (158)
Total Cost	$ (1,472)	$ (1,472)	$ (1,472)	$ (158)	$ (158)	…	$ (158)	$ (158)
Discounted Costs	$ (1,338)	$ (1,216)	$ (1,106)	$ (108)	$ (98)	…	$ (61)	$ (23)
							Net Present Cost (NPC)->	**$ (4,611)**
							Cost saved over project life ->	**80%**

While a strong case can be made for Lagos replacing diesel generators with solar PV systems, it is worth testing the hypothesis in another urban community. A similar assessment is performed for the Federal Capital Territory (FCT) – Abuja, which is the capital of Nigeria.

Case Assumptions for Abuja:

- The case assumptions for Abuja are similar to that of Lagos except that the Abuja specific households in the Enertech study were used for this case.
- As shown in Figure 14, Abuja households have a higher average load during the periods of power access and more outages than Lagos – see Figure 13.
- Similar to the Lagos case, the load analysis for Abuja indicates a 2kW diesel generator is sufficient. The diesel generator is assumed only to be used when there is no power supply from the grid.

The part of power access and average load for Abuja households in the study is shown in Figure 17. Various case scenarios, similar to those used for Lagos, are shown in Table 10. The fuel and the solar PV system cost for the use cases is shown in Table 11 and Table 12. The results of the financial assessment are shown in Table 13 and Table 14. The detailed data for the Abuja case can be found in Appendix C.

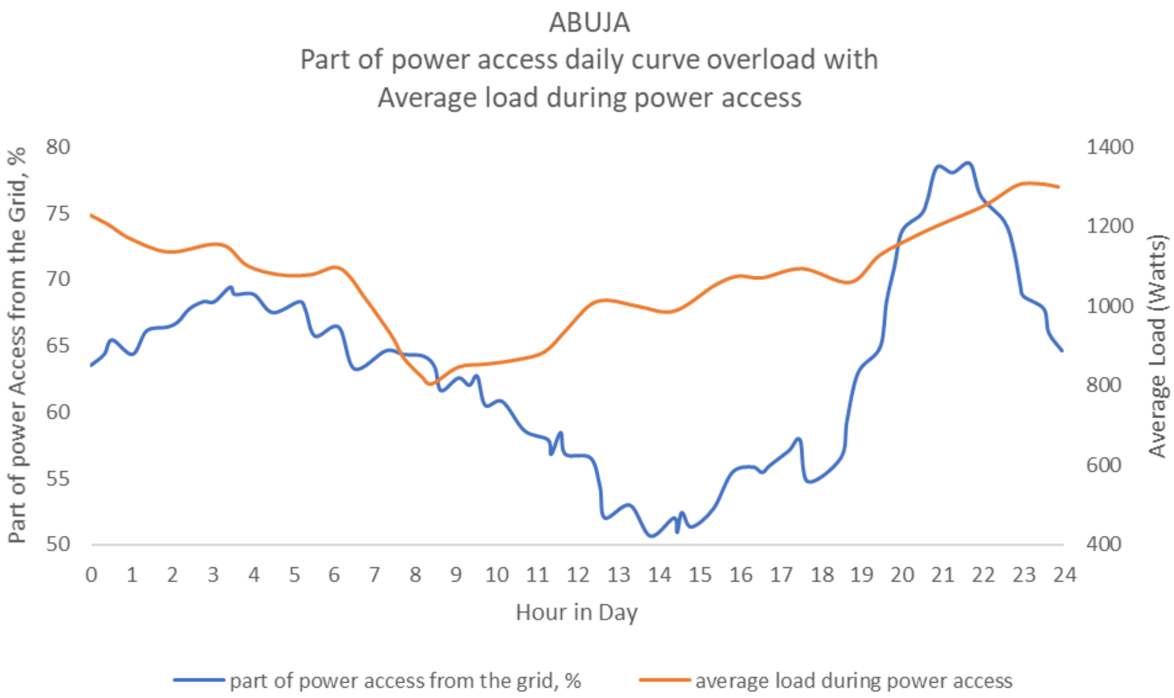

Figure 17: Abuja - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

Table 10: Average Energy Used for Various Load Cases and Power Access Periods for Abuja Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (kW)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	25.6	1.305
Average grid power access throughout day	63%	15.2	16.3	1.305
CASE 1: Average No-grid power access throughout day	37%	8.8	9.3	1.305
Sun-up period only, 6:30 a.m. - 6:30 p.m.				
Assuming 100% access from the grid during sun-up period of day	100%	12.0	11.7	1.095
Average grid power access during sun-up period of day	58%	7.0	6.8	1.095
CASE 2A: Average No-grid access during sun-up period of day	42%	5.0	4.9	1.095
Sun-down period only, 6:30 p.m. - 6:30 a.m.				
Assuming 100% access from the grid during sun-down period of day	100%	12.0	13.9	1.305
Average grid power access during sun-down period of day	68%	8.2	9.6	1.305
CASE 2B: Average No-grid access during sun-down period of day	32%	3.8	4.4	1.305

Table 11: Cost of diesel fuel for use cases - Abuja

Diesel Generator Use Cases		**CASE 1: outages throughout day**	**CASE 2A: outages when sun-up**	**CASE 2B: outages when sun-down**
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		8.8	5.0	3.8
Electric production in kWh		8.8	5.0	3.8
Consumption fuel in liter/day		9.7	5.5	4.2
Total cost per day	USD/d	9.4	5.3	4.1
Total cost per year	USD/yr	3427	1947	1480

The solar PV system is designed using the estimator tool from Lee et al (Lee & Callaway, 2018).

Table 12: Solar PV System Costs (in USD) - Abuja

	CASE 1 (full day): FDS = 95%, Daily load = 9.5 kWh/d, Peak = 1.5 kW	**CASE 2A (6:30 a.m. - 6:30 p.m.):** FDS = 60% of 8.3 kWh/d, Daily load = 5 kWh/d, Peak = 1.5 kW
LCOE	0.38	0.30
Up-front Cost	6850	3260
Replacement Cost (present cost)	720	0
Total Capital Cost	7570	3260
O&M Cost	379	163
Solar Capacity (kW)	2.06	0.95
Storage Capacity (kWh)	5.2	0

In the Abuja case, over 20 years, the cost of running a diesel generator as the sole backup option during power outages from the grid results in a high Net Present Cost (NPC) value of nearly $30,000. Table 13 shows the results of this assessment. When a solar PV system is used with a battery as backup, the cost savings over the project's life is just over 60%. Through financing based on fuel spend, the solar PV system with batteries can be paid off in 4 years, and at a slightly lower monthly cost to the user than if they were spending on diesel fuel.

The Abuja case is also assessed for a solar PV system without batteries, shown in Table 14. In this case, diesel expense is only incurred during periods of outages after sunset as power is drawn from the solar PV system during outages in the daytime. As such, there is only a partial replacement of the fuel expense. Not utilizing a battery reduces the solar PV system's cost significantly, to less than half the system's cost with batteries. Further savings on the solar PV system also come from sizing it for a lower daily load case as it will only be used during the period of the day when there is sunlight and no grid access. The hybrid system combining both a solar PV system without battery with a diesel generator to meet energy needs during outages results in a cost savings of 84% over the project's life compared to if only a diesel generator were used as the sole backup system. The payoff period for a solar PV system with no battery is a year less than for a system with a battery when the same fuel savings principle is applied with no additional cost to the user each month. Notable is that the expense on the partial use of a diesel generator is still quite significant, even when it is only used for periods of outages after sunset in Abuja. The user ends up paying more each month in fuel cost than they are towards financing the solar PV system. It would be more beneficial to finance a solar PV system with batteries and eliminate spending on diesel fuel.

Table 13: Diesel genset vs. solar PV system (100% fuel replacement) - Abuja

DIESEL GENERATOR FOR FULL BACKUP vs SOLAR PV SYSTEM WITH BATTERY (100% FUEL REPLACEMENT) - ABUJA

FUEL SPEND USAGE CASE	USD/PER YEAR	USD/PER MONTH	
Diesel genset used for full backup	3,427	286	Discount rate = 10%

Diesel Generator								
Year	1	2	3	4	5	...	10	20
Cost of fuel	$ (3,427)	$ (3,427)	$ (3,427)	$ (3,427)	$ (3,427)	...	$ (3,427)	$ (3,427)
Discounted Costs	$ (3,115)	$ (2,832)	$ (2,575)	$ (2,341)	$ (2,128)	...	$ (1,321)	$ (509)
							Net Present Cost (NPC)->	**$ (29,176)**

Solar PV system WITH battery, NOT FINANCED									
Year	0	1	2	3	4	5	...	10*	20
Cost of solar PV system, NOT financed	$ (7,570)	$ -	$ -	$ -	$ -	$ -	...	$ -	$ -
Cost of operation and maintenance	$ -	$ (379)	$ (379)	$ (379)	$ (379)	$ (379)	...	$ (379)	$ (379)
Total Cost	$ (7,570)	$ (379)	$ (379)	$ (379)	$ (379)	$ (379)	...	$ (379)	$ (379)
Discounted Costs	$ (7,570)	$ (344)	$ (313)	$ (284)	$ (259)	$ (235)	...	$ (146)	$ (56)
	*new battery in year 10							Net Present Cost (NPC)->	**$ (10,792)**
								Cost saved over project life ->	**63%**

SOLAR SYSTEM DETAILS	
Target reliability FDS	95%
Daily Load (kWh/day)	9.5
Peak Capacity (kW)	1.5
Project life, yrs	20

FINANCING OPTION DETAILS	
Amount borrowed	7570
Loan interest rate	15%
Loan term	48 months (4 years)
Payment due	monthly
Discount Factor	35.93
Monthly loan Payment	*210.68*
Monthly fuel cost (100% fuel replacement)	*0*
Averge Monthly PV O&M cost	*31.54*
Total customer monthly payment	242.22

Solar PV system WITH battery, FINANCED ((assumes financing the total capital cost, including for the battery replacement in 10 years)

Year	1	2	3	4	5	...	10	20
Cost of solar PV system, financed	$ (2,528)	$ (2,528)	$ (2,528)	$ (2,528)	$ -	...	$ -	$ -
Cost of operation and maintenance	$ (379)	$ (379)	$ (379)	$ (379)	$ (379)	...	$ (379)	$ (379)
Total Cost	$ (2,907)	$ (2,907)	$ (2,907)	$ (2,907)	$ (379)	...	$ (379)	$ (379)
Discounted Costs	$ (2,642)	$ (2,402)	$ (2,184)	$ (1,985)	$ (235)	...	$ (146)	$ (56)
	*new battery in year 10						Net Present Cost (NPC)->	**$ (11,236)**
							Cost saved over project life ->	**61%**

Table 14: Diesel genset + solar PV system (partial fuel replacement) - Abuja

DIESEL GENERATOR FOR BACKUP + SOLAR PV SYSTEM WITHOUT BATTERY (PARTIAL FUEL REPLACEMENT) - ABUJA

FUEL SPEND USAGE CASE	USD/YEAR	USD/MONTH	
Diesel genset for full backup	3,427	286	Discount rate = 10%
Diesel genset during sun-up period	1,947	162	
Diesel genset during sun-down period	1,480	123	

Diesel Generator								
Year	1	2	3	4	5	...	10	20
Cost of fuel during daytime outages	$ (1,947)	$ (1,947)	$ (1,947)	$ (1,947)	$ (1,947)	...	$ (1,947)	$ (1,947)
Cost of fuel during nighttime outages	$ (1,480)	$ (1,480)	$ (1,480)	$ (1,480)	$ (1,480)	...	$ (1,480)	$ (1,480)
Discounted Costs	$ (3,115)	$ (2,832)	$ (2,575)	$ (2,341)	$ (2,128)	...	$ (1,321)	$ (509)
							Net Present Cost (NPC)->	**$ (29,176)**

Solar PV system WITHOUT battery									
Year	0	1	2	3	4	5	...	10	20
Cost of solar PV system, NOT financed	$ (3,260)	$ -	$ -	$ -	$ -	$ -	...	$ -	$ -
Cost of operation and maintenance	$ -	$ (163)	$ (163)	$ (163)	$ (163)	$ (163)	...	$ (163)	$ (163)
Total Cost	$ (3,260)	$ (163)	$ (163)	$ (163)	$ (163)	$ (163)	...	$ (163)	$ (163)
Discounted Costs	$ (3,260)	$ (148)	$ (135)	$ (122)	$ (111)	$ (101)	...	$ (63)	$ (24)
								Net Present Cost (NPC)->	**$ (4,648)**
								Cost saved over project life ->	**84%**

SOLAR SYSTEM DETAILS	
Daily Load (kWh/day)	5
Peak Capacity (kW)	1.5
Project life, yrs	20

FINANCING OPTION		
Amount borrowed	$ 3,260	
Loan interest rate	15%	
Loan term	36	months (3 years)
Payment due	monthly	
Discount Factor	28.85	
Monthly loan Payment	113.01	
Monthly fuel cost (use of fuel during sundown period)	*123.33*	
Average Monthly PV O&M cost	*13.58*	
Total customer monthly payment	*249.93*	

Solar PV system WITHOUT battery								
Year	1	2	3	4	5	...	10	20
Cost of solar PV system, financed	$ (1,356)	$ (1,356)	$ (1,356)		$ -	...	$ -	$ -
Cost of operation and maintenance	$ (163)	$ (163)	$ (163)	$ (163)	$ (163)	...	$ (163)	$ (163)
Total Cost	$ (1,519)	$ (1,519)	$ (1,519)	$ (163)	$ (163)	...	$ (163)	$ (163)
Discounted Costs	$ (1,381)	$ (1,255)	$ (1,141)	$ (111)	$ (101)	...	$ (63)	$ (24)
							Net Present Cost (NPC)->	**$ (4,760)**
							Cost saved over project life ->	**84%**

The remaining four geographical areas in the Enertech study were assessed with detailed results shared in Appendix D. For all six geographical areas the results show it is beneficial to replace the use of diesel generators with solar PV. In Bauchi and Sokoto, given the higher number of power outages compared to the other areas, the cost of fuel as 100% backup during an outage becomes very expensive, nearing $500 per month. This will most likely result in residents at those locations forgoing running diesel generators often and staying without power for longer durations given the high fuel expense. In the analysis for the other geographical locations, the same basic principle is followed in comparing the cost of fuel to solar PV installation. Bauchi and Sokoto would have a faster payoff time if the fuel expense for 100% backup coverage during outages was spent on a solar PV system. However, more realistic is that half that amount, or less, is spent on fuel and residents stay without power for longer. For the analysis, this will in effect lower the monthly payment cap and increase the duration for loan repayment. However, the benefits are similar in that it is far more cost-effective to install a solar PV system than to spend the same amount on fuel over the long term.

Of the six locations assessed, Enugu stands out as a location to quickly implement the transition of households to solar PV given the shorter payout time and the minimal difference in financing payback between a solar PV system with battery versus without. Enugu could be a choice location for a pilot that can then be extended to other locations following proven success. Abuja and Lagos would be logical choices to implement transitioning households to solar PV as well. Both locations are commercial hubs in Nigeria and have a relatively high fuel expense and high demand for more power access. Benin also would benefit long term from transitioning to solar PV. However, the much higher cost of a PV system with battery compared to the system without, as well as payback for a system with battery versus one without, makes a compelling case for residents in Benin to invest in solar PV systems without batteries.

Chapter 5: Powering the Commercial Sector Using Urban Swarm Electrification[2]

Chapter 5 directly addresses the hypothesis that the use of home solar PV systems used collectively for distributed generation can greatly reduce or eliminate power outages in Nigeria's commercial sector, thereby accelerating economic growth and the dissemination of solar PV systems. The commercial sector definition here refers to the part of the country’s economy that includes all businesses except those involved in manufacturing and transport. A framework is proposed, whereas a beneficial and symbiotic relationship can be formed with the homeowners of solar PV systems and the businesses they support.

In earlier chapters, this thesis discussed the impact the lack of reliable electricity has on driving the self-generation of electricity for consumption. Given the abundance of the natural resource of solar radiation in this part of the world, solar photovoltaic (PV) systems were proposed as a viable solution for individuals and businesses alike. Solar PV systems can be used for primary and backup power generation instead of fuel-powered generators. More households in urban communities in Nigeria are turning to solar PV for power generation. Earlier in this thesis, making solar systems more attainable for households was discussed. While the households with home solar systems (HSS) are self-generators and benefit from self-consumption, this thesis further postulates that a framework can be established that will allow for a distributed generation network microgrid, enabling collective generation that can be used to power the country’s commercial sector.

While the concept of microgrids is not new, this thesis explores the novelty of residential microgrids in urban communities in developing countries like Nigeria to generate power for both themselves as well as industry. In much of the literature, there are mainly two types of microgrid systems described in practice. The first has to do with microgrid systems in rural communities, typically set up by a third-party to sell electricity to the rural community because they are not connected to the grid. This is the case described in literature, such as Bhagavathy et al.’s paper on PV microgrid design for rural electrification (Bhagavathy & Pillai, 2018) or Kyriakarakos et al.’s report on microgrids in rural areas (Kyriakarakos & Papadakis, 2018). In a similar vein, other authors have looked at microgrid systems in rural

[2] Part of this text is adapted from my publication in the Sustainability Journal, reference:
Babajide, A, Brito, M.C, "Powering the Commercial Sector in Nigeria Using Urban Swarm Solar Electrification," Sustainability Journal, May 2020. DOI: 10.3390/su12104053

communities with self-consumption from PV systems and surplus sold to its neighbors whenever possible, and then to the grid—a practice that has been called swarm electrification (Groh, Philipp, Lasch, & Kirchhoff, 2015) (Bhattacharya, 2016). The second main type of microgrid system described in literature has to do with microgrids in urban communities in the developed world. In these urban communities, residents are well-connected to reliable grids but may want to generate their electricity to be free from utility companies and/or make money (Orsini, Kessler, Wei, & Field, 2019) (Vandebron, 2014) (Mitson, 2016). While all microgrid systems are somewhat similar, in this thesis, the context is quite different from others, as well as the motivation and concept described. There is a different challenge in an urban application in Nigeria. While there is a grid, it is not reliable and thus introduces more challenges than other urban applications in the developed world. Challenges of the unreliable electricity supply from the grid in urban communities in Nigeria adversely affect people's standard of living, and for the commercial sector amounts to billions of dollars in losses, discussed more in detail in the subsequent section.

5.1. Impact of Power Outages on Nigeria's Commercial Sector

Amadi et al. (Amadi, Okafor, & Izuegbunam, 2016) estimate the economic costs of power outages among Nigerian industries, ascertaining both the direct cost of power outages to the respective industries and the costs incurred by each industry as it invests in backup facilities to mitigate power outages. The study applied both the direct costs and the captive costs assessment methods, and relevant data in simulations in the Statistical Package for the Social Sciences (SPSS). The simulations covered statistical data from two hundred and fifty (250) electricity-intensive industries from three major industrial cities in Nigeria. The study found that the direct cost of power outages incurred by the firms surveyed amounted to 387 billion Naira (NGN) (1.3 billion USD), while the indirect cost was 2.2 trillion NGN (7.2 billion USD). Through the simulation of the statistical data, the study found that in 2014, Nigeria's industries spent 2.6 trillion NGN (8.5 billion USD) as a result of power outages, which is equivalent to 2.26% of the nation's gross domestic product (GDP) in 2014 or 57% of the nation's budget for 2015. The study results further showed that Nigeria's industries suffer low capacity utilization, a significant reduction in productivity, loss of revenue, and lack of competitiveness in the international market due to persistent shortages in energy supply.

Olowosejeje et al. (Olowosejeje, Leahy, & Morrison, 2019) also studied the economic cost of unreliable grid power in Nigeria. Their research showed that nearly 40% of the total cost incurred by industries was associated with the operation of diesel/petrol generators for electricity supply. It further showed that a typical industrial user would save 905 million Naira (3 million USD) per annum if diesel/generators were less utilized and only available in cases of an emergency power outage. The research indicated a more favorable scenario where industries were in control of their source of power generation, with a renewable energy system coupled with a diesel generator backup providing the most profitability and sustainability.

In recent research done by Abonyi (Abonyi, 2019), the feasibility of a solar PV (hybrid) mini-grid system for small businesses in Lagos, Nigeria, was studied. Small and medium-sized enterprises (SMEs) employ about 84% of Nigeria's total labor force, contributing about 80% of the annual GDP growth rate. The author’s study indicates over 85% of businesses in Nigeria rely on standalone generators due to poor electrification access, with the high cost of operation leading to business failures and low margins for those that remain in operation. However, while investigating the feasibility of a mini-grid system to support SMEs, the challenges listed include a lack of community involvement, poor load demand data capturing that leads to under or over-sizing of mini-grid systems, and lack of financing for mini-grid developers. Notwithstanding, using a case study of a cluster market made up of about 200 shops in Lagos, Nigeria, the research indicated a solar PV and generator hybrid mini-grid system was most suitable for the shop owners.

The aforementioned studies clearly show that Nigeria’s industries continue to face acute shortages of power from the national grid, with many forced to resort to self-generation of electricity, mainly from fuel-based generators, which further increases operational costs and reduces profit margins. Addressing the power outage issue for industries will be vital for the economic growth of Nigeria.

Many analysts see the power sector in Nigeria as the key constraint on economic development. In its 2018 Doing Business report, the World Bank ranked Nigeria 172 out of 190 countries in terms of ease, or lack thereof, of getting electricity (The World Bank). This is an improvement from its 2015 ranking of 187 and 2017 ranking of 180. The number of days to obtain a permanent electricity connection also showed improvements, from 260 days in the 2015 rankings, 195 days in the 2017 rankings, and 150 days in the latest 2018 rankings.

In 2016, the World Bank Doing Business report added quality indicators to four indicator sets, including ‘getting electricity.’ The quality indicator for the getting electricity category is known as ‘reliability of supply and transparency of tariffs index,’ and has a range from zero to eight. Since the introduction of this electricity quality index in 2016, Nigeria has had a rating of zero out of eight, including in the latest 2018 report. Whereas the time to obtain a permanent electricity connection has significantly improved, the reliability of electricity supply has not. In other words, when businesses finally get connected to electricity, they experience erratic power outages. The severe power outages remain one of the biggest challenges to Nigeria’s economic development. Unreliable power supply forces both households and industry to rely on privately owned generators for much of their power. Electricity from these generators is more than twice as expensive (NGN 62–94/kWh, approx. \$0.20–\$0.31/kWh) than grid-based power (end-user tariff of NGN 26–38/kWh, approx. \$0.09–\$0.12/kWh) (The World Bank). The exchange rate used in this work is the average for 2017, as quoted by the World Bank, which is 305.79 NGN to 1 USD (The World Bank).

Table 15 provides an overview of the biggest obstacles experienced by private sector firms in Nigeria. According to the Enterprise Survey’s World Bank report, in 2014, there were as many as 33 electrical outages in the private sector in a typical month, with the duration of a typical electrical outage being 12 hours (Enterprise Surveys, The World Bank, n.d.). The report also stated that the proportion of electricity from a generator was 59%. Almost half of the firms doing business in Nigeria (48%) identify electricity as a major constraint, with 27% of firms listing electricity as their biggest obstacle. Losses due to electrical outages averaged 16% of annual sales. A key enabler for economic development in Nigeria will be access to continuous and reliable electricity.

Table 15: World Bank report on an overview of the biggest obstacles experienced by private sector firms in Nigeria. Source (Enterprise Surveys, The World Bank, n.d.).

Indicator	Nigeria	Sub-Saharan Africa	All Countries
Percent of firms experiencing electrical outages	77.6	79.1	59.4
Number of electrical outages in a typical month	32.8	8.9	6.4
If there were outages, average duration of a typical electrical outage (hours)	11.6	5.8	4.5
If there were outages, average losses due to electrical outages (% of annual sales)	15.6	8.5	4.7
Percent of firms owning or sharing a generator	70.7	53.3	34.6
If a generator is used, average proportion of electricity from a generator (%)	58.8	28.6	20.4
Days to obtain an electrical connection (upon application)	9.4	36.7	33.1
Percent of firms identifying electricity as a major constraint	48.4	40.7	31.7

5.2. Solar PV Home System Based Microgrids for Electrification

In this chapter, this thesis explores using residential solar PV systems to form a microgrid for the distributed generation of power to help power the commercial sector. The benefit of solar power is evident to the Nigerian government. The Federal Government is planning for solar power to "outstrip all sources of electricity generation other than gas and thus become the second key pillar of energy delivery in the nation" (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). The diffusion of solar PV in Nigeria stands to make a major step-change in the reliability of electricity generation for both individuals and businesses by adding more, cleaner, and renewable power generation options to the mix.

The concept of using a network of home solar PV systems for electrification has been covered in the literature as swarm electrification (Groh, Philipp, Lasch, & Kirchhoff, 2015). Swarm electrification is based on swarm intelligence, where information and electricity flow between neighbors to achieve a compounding network effect, whereby each household is linked together to form a microgrid but at the same time can operate independently. The concept is heavily geared toward rural communities not connected to a national grid, and where the neighborhood network created is used to form a microgrid to support the community. However, swarm electrification by nature is organic and unplanned. A key benefit of such a system is that it is likely to grow fast as people come up with their own cost-effective way of implementing their solar home systems. However, lack of planning, standardization, and regulation will likely mean that such a system will be challenging to connect to the grid and optimize to ensure grid stability. Furthermore, swarm electrification has been primarily geared towards rural electrification. In this thesis, a hybrid approach is proposed. Firstly, the framework proposed allows better planning and organization compared to the traditional organically grown and unorganized premise of the swarm electrification concept. Secondly, it promotes the HSS-based microgrid's utilization as a balancing network for power outages in urban communities for both self-consumption, as well as to further support the commercial sector. This section of the thesis explores an urban community-planned and government- and industry-facilitated approach to electrification from home solar PV systems as a supporting system to reduce or eliminate power outages in urban communities.

Like the swarm electrification concept, a distributed generation network of home solar PV systems firstly requires an infrastructure base of solar home systems to create a microgrid. Households with solar PV systems can act not only as consumers of electricity but also feed excess electricity into the microgrid. Parties that both produce and consume electricity at the same time are known as prosumers. Prosumers can cash in on the excess electricity supplied.

Figure 18 shows the concept of an HHS-based microgrid, a network of home solar PV systems used to form a distributed generation network for electrification.

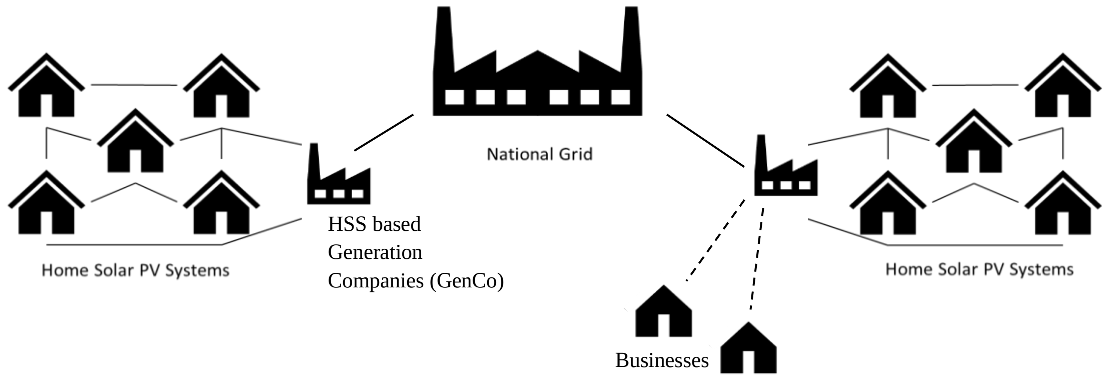

Figure 18: Distributed generation network of home solar PV systems.

The model proposed in this work is one in which individual household solar PV systems in urban communities are linked to form a microgrid that can be connected to the national grid and/or businesses to help power the commercial sector. The microgrid can be operated to buy power from the national grid when there is not enough power generated from the network of homes in the microgrid and sell power when the power generated is in excess. Government enabling policies in this area are further discussed in the section on policy implications.

While the electricity generated from household solar PV systems will likely first be used for own consumption, there is far less use of electricity by households during the daytime (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.). Electricity demand in the urban households monitored is generally lowest during the daytime when solar PV systems would get the most benefit from solar radiation. The low residential usage period ranges from about 8 a.m. until the early or late afternoon, depending on the geographical area. In contrast, Adesanya and Schelly (Adesanya & Schelly, 2019) have presented a case study of the electricity usage pattern of three companies that show peak usage in the daytime, primarily from 9 a.m. to 8 p.m. These results show a viable option for capturing the excess electricity from household solar PV systems to be available for use by the commercial sector. This is particularly desirable when having a battery, which would enable evening consumption of locally generated solar energy in the households, is too expensive.

The case study of Lagos, the country's commercial hub, may be used to illustrate the feasibility and benefit of the proposed HSS-based microgrid for powering the commercial sector. Lagos households showed the highest electricity consumption of all households (c.f. Chapter 4). To assess the load profile for different periods throughout the day, previously shown in Figure 16 was the Enertech data of the power access and outage periods overlaid against Lagos households' average load profile when there is power access throughout the same period. The energy used can be calculated for the period where power is drawn from the grid, as well as when power is drawn from another source, such as solar PV systems when there is no power access from the grid. The solar PV system can be sized for the household’s usage as well as for excess electricity to be supplied to the microgrid for access by local businesses. The benefit to businesses is twofold: (1) more access to power, (2) less spend on fuel-powered generators.

The case for powering the commercial sector leverages previous data shared on residential home solar systems. As such, some of the equations and data is similarly repeated in this section. Assessed in this section is a HSS without batteries, operating during daylight hours, with the excess electricity sold to local businesses. The average energy used for various load cases and power access periods for Lagos households was previously shown in Table 3.

Calculating the diesel engine's output power follows the earlier shared equations 3 and 4 (c.f. Chapter 4). The inputs for the power calculation are shown in Table 16:

Table 16: Input data for diesel generator energy and fuel cost calculation.

Apparent Power, S (kVA)	2.5
Cos(*phi*)	0.80
Active Power, P (kW)	2
Load, %, residential/commercial	50%/75%
Ratio consumption L/h *	1.1
Number of hours running, h/d (CASE 1/2/3)	6.7/4/2.8/4.8
Cost of fuel per liter, USD/L **	0.97
Caloric value of diesel (PCI), kWh/L	0.98

* The fuel consumption for a 2kW/2.5kVA diesel generator was obtained from a diesel generator manufacturer (Greaves Power, n.d.); ** Average pump price for diesel in 2012–2013 for the same period in which the Enertech study was done (The World Bank, n.d.).

The cost of diesel fuel usage during outages in the periods specified in Table 3 in cases 1, 2A, and 2B are shown in Table 17.

Table 17: Cost of Diesel Usage During Power Outage.

	Apparent Power S (kVA)	**Cos (*phi*)**	**Active Power P (kW)**	**Load %**	**Ratio Consump-tion l/h**	**Ratio Fuel Consump-tion l/kVAh**	**Ratio Fuel Consump-tion l/kWh**	**Cost of Fuel Per Liter l**	**Calculated Cost kWh**	**Nb hour Running h/d**	**Electric Production in kWh**	**Consump-tion Fuel in Liter/day**	**Total Cost Per Day USD/d**	**Total Cost Per Year USD/yr**
Residential - DG use during outages throughout day	2.5	0.8	2	50%	1.1	0.88	1.1	0.97	1.07	6.7	6.7	7.4	7.1	2609
Residential - DG use during outages when sun-up	2.5	0.8	2	50%	1.1	0.88	1.1	0.97	1.07	4.0	4.0	4.4	4.3	1558
Residential - DG use during outages when sun-down	2.5	0.8	2	50%	1.1	0.88	1.1	0.97	1.07	2.8	2.8	3.1	3.0	1090
Commercial - DG use during outages when sun-up	2.5	0.8	2	75%	1.1	0.59	0.7	0.97	0.71	3.2	4.8	3.5	3.4	1246

The costs for a solar PV system for use during sun-up periods are shown in Table 18. In addition, two cases are added to reflect a solar PV system designed to allow for excess electricity to be sold. The detailed data that feeds the input for the PV system design can be found in Appendix B.

Table 18: Solar PV system costs - Lagos

SOLAR PV SYSTEM DESIGNS	Up-Front Cost	Battery Replacement Cost (Present Cost)	Total Capital Cost	Operations and Maintenance Cost	Solar Capacity (kW)	Storage Capacity (kWh)
Daily load = 6.5 kWh/d, Peak = 1.5 kW	6043	488	6531	327	2.0	3.50
Daily load = 4 kWh/d, Peak = 1.5 kW (enough electricity generated for own use during daylight from 6:30 a.m.–6:30 p.m.)	3158	0	3158	158	0.88	0
Daily load = 5 kWh/d, Peak = 1.5 kW (1.4kWh/d excess electricity generated)	3469	0	3469	173	1.10	0
Daily load = 6 kWh/d, Peak = 1.5 kW (2.4 kWh/d excess electricity generated)	3780	0	3780	189	1.33	0

For the financial assessment of the various cases, Net Present Cost (NPC) is used. The NPC equation was previously shared in equation 5.

In this chapter, this thesis addresses the opportunity presented to both households and small businesses through the sale of excess electricity generated. In the example presented in Table 19, during the daylight period of 9 a.m.–6 p.m., the household can generate enough electricity for its consumption (3.6 kWh/d) and sell 1.4 kWh/d of excess electricity. The higher capacity solar PV system is only 10% more costly compared to a system sized for just its own consumption. Furthermore, the same loan payback period of 3 years can be achieved if the revenue from selling the excess electricity were used to offset the additional cost. The household can take advantage of the income generated from selling the excess electricity to pay off the loan faster or apply this regular stream of income towards operations and maintenance costs for the solar system. Table 20 shows another example of an even higher capacity solar PV system that can generate 2.4 kWh/d of excess electricity to be sold. With the financials not overly burdened by the additional solar capacity, it would be optimal to design the solar PV system to generate as much excess electricity as the owner can reasonably afford given that the excess generated is also a potential source of additional income.

Table 19: Solar PV system selling 1.4 kWh/d excess

Table 19: SOLAR PV SYSTEM WITHOUT BATTERY SELLING 1.4 kWh/d EXCESS ELECTRICITY - LAGOS

FUEL SPEND USAGE CASE	USD/YEAR	USD/MONTH	
Household - Diesel genset used during sun-up	1,558	130	Discount rate = 10%
Household - Diesel genset used during sun-down	1,090	91	
Commercial - Diesel genset used during business hrs	1,246	104	(*business hours = 9 a.m.-6 p.m.)

Diesel Generator For Household - comparison of fuel spend without solar PV system

Year	1	2	3	4	5 …	10	20
Cost of fuel during daytime outages	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558) …	$ (1,558)	$ (1,558)
Cost of fuel during nighttime outages	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090) …	$ (1,090)	$ (1,090)
Discounted cost	$ (2,407)	$ (2,188)	$ (1,989)	$ (1,809)	$ (1,644) …	$ (1,021)	$ (394)
						Net Present Cost (NPC)->	**$ (22,544)**

Household Solar PV system WITHOUT battery, generating 1.4kWh/d excess electricity

Year	0	1	2	3	4	5 …	10	20
Cost of solar PV system, **NOT financed**	$ (3,469)	$ -	$ -	$ -	$ -	$ - …	$ -	$ -
Cost of operation and maintenance	$ -	$ (173)	$ (173)	$ (173)	$ (173)	$ (173) …	$ (173)	$ (173)
Revenue from selling excess electricity	*$ -*	*$ 149*	*$ 149*	*$ 149*	*$ 149*	*$ 149 …*	*$ 149*	*$ 149*
Total cost	$ (3,469)	$ (24)	$ (24)	$ (24)	$ (24)	$ (24) …	$ (24)	$ (24)
Discounted cost	$ (3,469)	$ (22)	$ (20)	$ (18)	$ (17)	$ (15) …	$ (9)	$ (4)
							Net Present Cost (NPC)->	**$ (3,676)**
							Cost saved over project life ->	**84%**

HOUSEHOLD FINANCING OPTION

Amount borrowed $ 3,469
Loan interest rate 15%
Loan term 36 months (3 years)
Payment due monthly
Discount Factor 28.85
Monthly loan payment 120.25
Monthly fuel cost (use of fuel during sundown) 90.83
Average Monthly PV O&M cost 14.45
Total customer monthly payment 225.54
Income from selling excess electricity generated -12.43 *
Reduced customer monthly payment burden 213.12

SOLAR SYSTEM DETAILS

Daily load (kWh/day) 5
Peak capacity (kW) 1.5
Project life, yrs 20

*diesel fuel spend for a small business approx. $0.71/kWh. Daily household energy own use from solar during sun-up hours = 3.6kWh/d. Estimate selling back 1.4Wh/d excess generated for 1/2 of what diesel spend would have been for the business if operating 25 working days each month)

FINANCING THROUGH FUEL SAVINGS - Household Solar PV system WITHOUT battery, generating 1.4kWh/d excess electricity

Year	1	2	3	4	5 …	10	20
Cost of solar PV system, **financed**	$ (1,443)	$ (1,443)	$ (1,443)	$ -	$ - …	$ -	$ -
Cost of operation and maintenance	$ (173)	$ (173)	$ (173)	$ (173)	$ (173) …	$ (173)	$ (173)
Revenue from selling excess electricity	*$ 149*	*$ 149*	*$ 149*	*$ 149*	*$ 149 …*	*$ 149*	*$ 149*
Total cost	$ (1,467)	$ (1,467)	$ (1,467)	$ (24)	$ (24) …	$ (24)	$ (24)
Discounted cost	$ (1,334)	$ (1,213)	$ (1,102)	$ (17)	$ (15) …	$ (9)	$ (4)
						Net Present Cost (NPC)->	**$ (3,796)**
						Cost saved over project life ->	**83%**

Table 20: Solar PV system selling 2.4 kWh/d excess

Table 20: SOLAR PV SYSTEM WITHOUT BATTERY SELLING 2.4 kWh/d EXCESS ELECTRICITY - LAGOS

FUEL SPEND USAGE CASE	USD/YEAR	USD/MONTH	
Household - Diesel genset used during sun-up	1,558	130	Discount rate = 10%
Household - Diesel genset used during sun-down	1,090	91	
Commercial - Diesel genset used during business hrs	1,246	104	(*business hours = 9 a.m.-6 p.m.)

Diesel Generator For Household - comparison of fuel spend without solar PV system

Year	1	2	3	4	5	…	10	20
Cost of fuel during daytime outages	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558)	$ (1,558)	…	$ (1,558)	$ (1,558)
Cost of fuel during nighttime outages	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090)	$ (1,090)	…	$ (1,090)	$ (1,090)
Discounted Costs	$ (2,407)	$ (2,188)	$ (1,989)	$ (1,809)	$ (1,644)	…	$ (1,021)	$ (394)
							Net Present Cost (NPC)->	**$ (22,544)**

Household Solar PV system WITHOUT battery, generating 2.4kWh/d excess electricity

Year	0	1	2	3	4	5	…	10	20
Cost of solar PV system, **NOT financed**	$ (3,780)	$ -	$ -	$ -	$ -	$ -	…	$ -	$ -
Cost of operation and maintenance	$ -	$ (189)	$ (189)	$ (189)	$ (189)	$ (189)	…	$ (189)	$ (189)
Revenue from selling excess electricity	*$ -*	*$ 256*	*$ 256*	*$ 256*	*$ 256*	*$ 256*	…	*$ 256*	*$ 256*
Total cost	$ (3,780)	$ 67	$ 67	$ 67	$ 67	$ 67	…	$ 67	$ 67
Discounted cost	$ (3,780)	$ 61	$ 55	$ 50	$ 45	$ 41	…	$ 26	$ 10
								Net Present Cost (NPC)->	**$ (3,213)**
								Cost saved over project life ->	**86%**

HOUSEHOLD FINANCING OPTION

Amount borrowed	$ 3,780
Loan interest rate	15%
Loan term	36 months (3 years)
Payment due	monthly
Discount Factor	28.85
Monthly loan payment	131.03
Monthly fuel cost (use of fuel during sundown)	*90.83*
Average Monthly PV O&M cost	*15.75*
Total customer monthly payment	*237.62*
Income from selling excess electricity generated	*-21.30* *
Reduced customer monthly payment burden	*216.32*

SOLAR SYSTEM DETAILS

Daily load (kWh/day)	6
Peak capacity (kW)	1.5
Project life, yrs	20

*diesel fuel spend for a small business approx. $0.71/kWh. Daily household energy own use from solar during sun-up hours = 3.6kWh/d. Estimate selling back 2.4Wh/d excess generated for 1/2 of what diesel spend would have been for the business if operating 25 working days each month)

FINANCING THROUGH FUEL SAVINGS - Household Solar PV system WITHOUT battery, generating 2.4kWh/d excess electricity

Year	1	2	3	4	5	…	10	20
Cost of solar PV system, **financed**	$ (1,572)	$ (1,572)	$ (1,572)	$ -	$ -	…	$ -	$ -
Cost of operation and maintenance	$ (189)	$ (189)	$ (189)	$ (189)	$ (189)	…	$ (189)	$ (189)
Revenue from selling excess electricity	*$ 256*	*$ 256*	*$ 256*	*$ 256*	*$ 256*	…	*$ 256*	*$ 256*
Total cost	$ (1,506)	$ (1,506)	$ (1,506)	$ 67	$ 67	…	$ 67	$ 67
Discounted cost	$ (1,369)	$ (1,244)	$ (1,131)	$ 45	$ 41	…	$ 26	$ 10
							Net Present Cost (NPC)->	**$ (3,343)**
							Cost saved over project life ->	**85%**

From a business standpoint, the cost of power access from a diesel generator would be more expensive than from the proposed HSS-based microgrid. The World Bank reports that over 70% of businesses in Nigeria own or share a generator and source nearly 60% of their electricity from a generator (Enterprise Surveys, The World Bank, n.d.). Diesel fuel spend for a small business is estimated at $0.71/kWh (ref Table 17). Table 19 and Table 20 provide a daily estimate of the excess electricity generated that may be sold back to the business, at an estimated cost of half of what the business would have spent on diesel. Assuming a negotiated price of half what a small business owner would have paid for similar electricity generation from a diesel generator, the business saves half of their spending in this area, and the households gain an extra source of income. This scenario presents a win-win situation for both parties. Where space allows, another option for the business owner is to invest in purchasing a solar PV system for their own use, where additional electricity needed over time may be sourced from the HSS-based microgrids. In this scenario, the business owner may also participate in the HSS-based microgrid to sell its excess electricity to homes during weekends when the business may not be open and when usage from the residential sector is expected to be higher. Some examples of small to medium-sized businesses that may benefit from sourcing electricity from HSS-based microgrids are shown in Table 21.

Table 21: Examples of small to medium-sized businesses that can benefit from SHS-based microgrids.

Examples of Commercial Load for a Small to Medium Size Business

Assumes working hours in daytime, from 9am - 6pm (9 hours); Estimated total duration of grid power outage during business hours = 3.2 hours (reference Table 14)

Small office example (eg: accounting firm, real estate, internet café, etc)

Rating Source*		Appliance	Power Rating (W)	Quantity	Hours Used	Total Active Power Used (W)	Energy Consumed (Wh)	Total (kWh)
1	1	Lighting Bulb -Energy Saving	15	2	9	30	270	
1	2	Air conditioner, small (1HP)	746	1	9	746	6714	
2	3	Desktop Computer	100	4	9	400	3600	
2	4	Printer (Inkjet)	20	1	1	20	20	
2	5	Paper Shredder	200	1	0.5	200	100	
2	6	Fax	70	1	0.5	70	35	
						Daily total energy consumed:	10739	10.74
						Estimated daily energy from non-grid source:		**3.82**

Small Restaurant/Café example, eg: catering to lunch time customers

Rating Source*		Appliance	Power Rating (W)	Quantity	Hours Used	Total Active Power Used (W)	Energy Consumed (Wh)	Total (kWh)
1	1	Lighting Bulb -Energy Saving	15	2	9	30	270	
1	2	Standing Fan	70	2	9	140	1260	
1	3	Medium size refrigerator	100	1	9	100	900	
2	4	Rice Cooker	200	2	4	400	1600	
2	5	Pressure Cooker	700	1	4	700	2800	
						Daily total energy consumed:	6830	6.83
						Estimated daily energy from non-grid source:		**2.43**

Barber shop example

Rating Source*		Appliance	Power Rating (W)	Quantity	Hours Used	Total Active Power Used (W)	Energy Consumed (Wh)	Total (kWh)
1	1	Lighting Bulb -Energy Saving	15	2	9	30	270	
1	2	Ceiling Fan	85	1	9	85	765	
1	3	Standing Fan	70	1	9	70	630	
2	4	Electric shaver/clippers	15	4	7	60	420	
1	5	Medium size refrigerator	100	1	9	100	900	
1	6	Television	100	1	9	100	900	
						Daily total energy consumed:	3885	3.89
						Estimated daily energy from non-grid source:		**1.38**

* Source of power rating information: (1) Ikeja Electric (Lagos, Nigeria) (Ikeja Electric, n.d.); (2) Generatorist (Generatorist, 2020).

5.3. The Pros and Cons of Solar PV Home System based Microgrids

There are several benefits to implementing microgrids based on household solar power systems. The Home Solar PV System (HSS) based microgrids can provide for a business model where end-users can be compensated for electricity produced by their system and consumed by other end-users in the microgrid, as well as for electricity provided directly to the national grid or businesses. The ability to generate income from their HSS also means that households are incentivized to use electricity more efficiently to maximize their earnings by reducing their consumption and selling more electricity. Another particularly important benefit for urban areas is that this decentralized generation from rooftops is better suited for densely populated areas than centralized solar panel installations, which occupy large areas of land.

5.3.1. Pros of HSS-based Microgrids

Electricity generated from household solar power systems, combined with the distributed microgrid generation concept, has several advantages. These include the additional generation of power. The production of additional electricity may allow adding to or freeing up generation resources for the utility company. According to the Energy Sector Management Assistance Program (ESMAP), in Nigeria, "local photovoltaic systems have the potential to fill in the energy shortfall while the federal government shores up national energy production and policy" (Omisore, 2011). Another advantage of solar home system based microgrids is that they support grid stability. Creating a distribution system for local use of the electricity avoids the losses associated with the transmission lines, as currently experienced by the Nigerian national grid. Decentralized generation can assist in stabilizing the grid, allowing for more reliable access to electricity for customers. An advantage for the prosumer is the ability to generate additional income, thereby creating an additional income stream for the household. Furthermore, there is an opportunity for customer savings on fuel cost compared with solely running the more widely used diesel generators for self-generation. The distributed microgrid can help support the commercial sector by providing access to more reliable electricity. This, in turn, supports job creation for the larger community through a more vibrant commercial sector. Another advantage is the positive environmental impact solar PV systems can provide as a cleaner energy source that does not emit greenhouse gas (GHG), thereby reducing local pollution and health hazards.

5.3.2. Cons of HSS-based Microgrids

While there are several benefits of electricity generated from household solar power systems, there are challenges associated with this as well. These challenges include a potential impact on the microgrid network profitability if the sell-back price to the grid is unattractive compared to selling directly to a business or neighbor. The detailed design and economics for each geographical location will have to be done to maximize profitability for the HSS-based microgrid member households, such as the design work proposed by Chiu et al. (Chiu, Sun, & Poor, 2015). Furthermore, there will need to be a well-defined energy balance amongst the microgrid members to ensure profitability, clearly informing who pays who. In general, those generating and supplying excess electricity to the microgrid earn, while those drawing from the microgrid (residential and business alike) pay.

Another challenge exists around regulation. Regulation on solar systems in Nigeria is still evolving. In November 2017, the Nigerian Electricity Regulatory Commission (NERC) released the 'Eligible Customer Regulation.' Key highlights of the new policy and regulations allow end-users to combine multiple sites and apply to the commission for eligibility status to contract with Generating Companies (GenCos) to supply electricity. However, the regulation also mandates technical and financial obligations that end-users may be challenged to meet (Detail Commercial Solicitors, Volume 4, 2018). For HSS-based microgrids, it may be more beneficial to supply local businesses directly. A potential disadvantage for utility companies is the potential loss of revenue. Utility companies may be negatively impacted as consumption from the grid is replaced by self-generated power. However, in the context of Nigeria, this is likely to be less of an issue as additional sources of power generation are more likely to help stabilize the overloaded grid and thus be beneficial to individuals and utility companies alike. Another challenge exists in the form of grid stability. When tied back to the grid, while solar home system based microgrids may help stabilize the grid, there is a potential that the increased use of various RE power sources utilizing different equipment may threaten grid stability. This may be mitigated by having a central/main microgrid, with the requisite technical specifications, as the connection point to the national grid, feeding the excess electricity from the collection of member households.

5.4. Service Sector Growth

Aside from increased access to power benefitting the status quo of existing businesses in Nigeria, the reduction in power outages and increased access to electricity for the commercial sector can have wider implications in terms of propelling new businesses not already present in Nigeria or without significant footprint, thereby growing certain sectors faster. To examine this theory, examples are taken from some developing nations, assessing the impact more access to electricity has had on their commercial sector.

China's access to electricity has been growing, and with it, a significant shift from construction and manufacturing to the service industry. China's GDP can broadly be described to be contributed by three broader sectors or industries: primary industry (agriculture), secondary industry (construction and manufacturing), and tertiary industry (the service sector). A 2014 report indicated China's primary industry accounted for 10% of GDP, while the secondary industry accounted for 44%, and the tertiary industry for 46% (Bajpai, 2014). China's service sector has doubled in size over the last two decades to account for about 46% of GDP, surpassing China's secondary industries for the first time. While growing at a rapid rate, the services sector's share of GDP in China is still much lower than that of countries like the U.S. (79%), Japan (73%), Brazil (69%), and India (57%). However, China's service sector is expected to continue to grow and play a bigger role in powering the world's second-largest economy, as increasingly affluent Chinese consumers desire more diverse and better-quality services (Yamei, 2017).

In April 2018, the Electric Power Research Institute (EPRI) published a report in collaboration with many stakeholders to examine the forces that are transforming the world's energy systems (Electric Power Research Institute, 2018). Key insights from the EPRI report were that in the United States, electricity has grown from 3% of final energy in 1950 to approximately 21% today, and continues to grow. This growth has been driven primarily by lighting, cooling, refrigeration, entertainment, and communications. For developing countries like Nigeria, still in the earlier wave of economic growth from electricity, using the United States' earlier growth as a proxy of what to expect, an area of possible expansion in Nigeria outside of the basic necessities is in the area of entertainment. The growth of the entertainment industry can greatly contribute to Nigeria's economic growth. According to the U.S. Department of Commerce Bureau of Economic Analysis, the sector of Arts, entertainment, recreation, accommodation, and food services contributes over 1.5 billion

USD to the US economy, or 5% of GDP, and is increasing. According to the Nigerian Gross Domestic Product Report Q4 & Full Year 2018 issued by the National Bureau of Statistics, the ‘Arts, Entertainment and Recreation’ and ‘Accommodation and Food services’ sectors contributed approximately 1.2% to the real GDP for the whole of 2018 (National Bureau of Statistics, 2019). There is an opportunity for real economic growth in Nigeria by expanding the Arts, entertainment, recreation, accommodation, and food services sector. More electricity results in less food spoilage and greater food access options. Through the availability of more and reliable electricity, consumers can expect better and more comfortable accommodations, which can increase economic growth.

Chapter 6: Policy Implications and Enablers

Chapter 6 discusses and recommends policies for enabling the adoption of solar PV systems in Nigeria's urban communities. In this chapter, policy proposals are made that specifically address the electrification concepts proposed earlier in this thesis, i.e., policies that enable securing residential solar PV systems, incentivize its use, and promote collective generation to help power the commercial sector and further bolster the economy.

6.1. Policy Implications in Relation to Enabling Solar PV Through Fuel Savings

Enabling uptake of household solar PV systems can make a tremendous impact in electricity access for more Nigerians, spur economic growth, and greatly reduce or eliminate the use of diesel generators. The uptake of residential solar PV systems can be facilitated significantly by effective policy and conducive enabling frameworks. Supportive policies that enable HSS and their connection to the grid can provide significant benefits such as the production of additional electricity that frees up the limited utility resources, which can assist in stabilizing the grid and improving energy diversity and security with little burden on the government. Furthermore, it can incentivize customers to be more energy-efficient where there is an opportunity to offset the cost of electricity drawn from the grid by selling their excess electricity to the grid. However, key components for enabling uptake of home solar PV systems are (1) Education and workforce training and (2) making financing options more accessible. By effecting appropriate policy, the government can improve access to more reliable electricity while reducing and possibly eliminating the use of diesel generators in urban areas. This chapter proposes enabling policies that may be most effective in Nigeria.

6.1.1. Incentivize Education Sector and Provide Workforce Training

To establish and sustain the use of solar PV systems across communities, having the requisite skill sets available in the community will be critical. Policymakers can play a role by incentivizing the education sector and providing workforce training that will help provide the necessary support base and framework for ongoing maintenance of solar PV systems. The sustainability of solar PV systems can be achieved where support hubs are established within a reasonable distance of community-based micro-grids to allow for adequate support.

6.1.1.1. Education Sector Overview and Opportunities:

This section shares some background on the Nigerian higher education system, its status, and challenges, focusing on engineering education. Next, an assessment is done on Renewable Energy Engineering (REE) in Nigeria, its challenges, and how this can be more widely deployed through enabling policies.

Nigeria's education system is divided into four main stages - Kindergarten, Primary education (six years), Secondary education (Junior and Senior Secondary, three years each), and Tertiary education (typically four years).

The Renaissance Capital issued a 2013 report on the socio-economic profile of Nigeria's states (The Renaissance Capital, 2013). The report showed Nigeria has the largest population of out-of-school youth in the world, with a stark contrast in the primary and secondary school attendance and completion rates in the northern part of the country versus the south. The report showed that most households with six or more people were concentrated in the country's northern part. It also showed that the net primary school completion rate was over 50% in most southern states and below 20% in most northern states. Similarly, secondary school attendance rates were highest in the southern states, at 60% or more, and lowest in the northern states, with the majority at 20% or less.

While the numbers and statistics tell one story, it is important to understand some of the underlying issues that affect the school attendance numbers in the northern states. The militant jihadist group Boko Haram which first erupted in 2009 in Borno State, is most prevalent in the northern states. The 2013 Renaissance Capital report highlights some of the issues in the northern states, stating that Boko Haram "claims to want to implement sharia [Islamic law] in Nigeria and has killed thousands of people in suicide bombings and commando-style raids." The report states, "the fact that a majority of the youth in Borno State is undereducated makes the area fertile hunting ground for terrorist groups like Boko Haram." While school attendance rates in the northern part of Nigeria were previously comparatively lower than other southern states, the tragedy of the Boko Haram situation has further widened the education gap. This is an issue that must be a top priority for the Nigerian government, for people to live without fear for their safety, and for society at large to effectively function. School attendance is bound to suffer where there is a fear for personal safety in the community.

Several issues are faced by a largely uneducated population, many of which factor into the lower standard of living experience. In the context of its effect on the proliferation of renewable energy in Nigeria, poor education indicators are a deterrent to investors seeking skilled labor. While the northern part of Nigeria has a high proportion of uneducated, according to the Renaissance Capital report, education levels in the south and southwestern part of the country are likely to “spur ever-faster growth.” The report further concludes that “the greater expansion of secondary education in the south implies that the most educated workforce in the coming years will also be apparent in this region, where at least 60% of children complete secondary school education. It is regions like this that are developing the necessary skills that we believe will position them at the forefront economically in Nigeria and Africa to start taking jobs from China.” While the southern part of Nigeria shows an expansion in secondary school education, the government must intervene to ensure whole sections of the country are not left behind, particularly in the northern part of Nigeria. This must be done by first addressing the safety issue. Next, adopting a strategy that includes an education campaign will be useful, in addition to enforcing policies on minimum education requirements for children and youth, coupled with safe access and public funding for education.

According to the Africa-EU Renewable Energy Cooperation Programme (RECP) (The Africa-EU Renewable Energy Cooperation Program (RECP)), as of 2014, there was only one university with an academic program in renewable energy (RE) in Nigeria, with another in planning. Funding is needed to rapidly expand these programs, with incentives provided to make this a study of choice for the next generation of engineers. The proposed added funding needed here would be smaller than other investments as this should naturally feed into part of the Nigerian government’s traditional role of providing education to its citizens. However, there is an opportunity to make education in RE a key focus area of study for the country. Additionally, the chance for joint international school partnerships in this area has the opportunity for high reward. Akin to programs between the US and European universities, more collaboration should be sought after between western and African universities. Governments both locally and internationally can support this by enabling foreign student exchange program access and funding, focusing on the RE area of study.

6.1.1.2. Workforce Training in Renewable Energy

The Renaissance Capital report states that the working-age population is concentrated in the south. Looking at employment by sector, most of Nigeria's working population is employed in Agriculture, manufacturing, and trade, which make up about two-thirds of the country's employed population. Almost one-third (31%) of Nigeria's employed population of 49 million in 2009, is involved in the agriculture, forestry, and farming sector. The wholesale and retail trade sector employs a quarter of the country's employed population, and manufacturing employs 11%. While oil and gas production only employs 0.3% of Nigeria's employed population, it is significant as it generates 15% of the country's GDP.

For renewable energy systems to effectively proliferate in Nigeria, a sizeable part of the population needs to be educated in and employed in jobs that will support the design, manufacturing, installation, maintenance, and repair needed in this industry. The effective propagation of solar radiation conversion technologies must start with upskilling the local people in this sector. The upskilling proposed is mainly in the area of engineering and design rather than manufacturing. This is because solar PV systems are likely to become a commodity in the future, and its manufacturing is currently largely dominated by China. Zhu et al. (Zhu, Xu, & Pan, 2019) describe China's strategy in solar PV development. The manufacturing of PV panels is currently largely done in China, in factories that have relatively easier access to the materials for the manufacturing process. China has captured a large share of the global PV market, accounting for 33% of the global solar PV capacity in 2017. Its solar PV cells' production increased from 1% in 2000 to 66% in 2017, and nine of the largest fifteen solar PV suppliers are Chinese. China is also the biggest exporter of solar PV cells. In 2012, while China's solar PV capacity growth was only 12%, it produced 61% of solar PV cells, indicating nearly 80% was exported. Attempting to anchor solar PV manufacturing sites to a country like Nigeria is not likely to be the most effective use of the country's resources in expanding this sector, given the existing major players in the market.

Based on the dominance of countries like China in the PV manufacturing space, it is expected that in countries like Nigeria, the margins from manufacturing will be relatively small compared to what can be achieved on the engineering and design side. So, while much of the technology itself may be imported, there is an opportunity for Nigeria to develop the know-how that can be used in-country and provided as a service to other African countries. Developing expertise in the engineering and design of solar PV systems, where local engineers develop the solution, will affect a step-change in expanding this sector in Nigeria and Africa.

Both theory and practice are essential to building expertise in the engineering and design of solar systems. In addition to local colleges and universities expanding their curriculum in RE, having state-funded local power plants will help develop RE skills, provide economical services to the community, and employment for what is expected to become a fast-growing industry in Nigeria. The operations and maintenance of solar PV systems are critical for its deployment. In addition to providing job opportunities in this area, it will also require local training and certification. The government can support this by embarking on a pointed campaign aimed at people with trade skills, such as electricians, that can be trained in the maintenance and repair of solar PV systems.

6.1.2. Accessible Financing Options

Enabling the uptake of household solar PV systems can be significantly facilitated by financing availability, given the high initial capital cost. This section addresses how more funding options can be made available to more Nigerians.

6.1.2.1. Bank or other Commercial Loan Funding

Compared to diesel generators, the relatively high initial capital investment cost of solar PV systems can make it prohibitively expensive for many Nigerians. According to a 2017 salary survey provided by SalaryExplorer (SalaryExplorer, n.d.), the average monthly salary in Nigeria is 538,926 NGN (1,762 USD), with a maximum of 5,000,000 NGN (16,350 USD) and a minimum of 37,000 NGN (120 USD). The median monthly salary is 300,000 NGN (980 USD)[3]. Enabling the installation of household solar PV systems can be significantly facilitated by financing availability, given the high initial capital cost. This section reviews various financing schemes that can affect transformational change in the adoption of household solar PV systems when coupled with supportive policies.

[3] Exchange rate used is the average 2017 exchange rate as quoted by The World Bank, which is 305.79 Naira (305.79 NGN) to 1 dollar (1 USD) (The World Bank)

Bank loans or other commercial loan funding options can support the purchase of solar PV systems in Nigeria. While these types of funding options are exercised by many in developed countries, they pose several challenges for many developing nations. With bank loans, a loan is secured based on collateral. Unfortunately, those unable to self-fund the installation of solar PV units are also those less able to secure bank loans, especially in the absence of an effective national system of identifying consumers with good versus bad credit. Furthermore, loans are not common for many Nigerians, including in certain religions, where interest-based loans are forbidden. Other commercial funding options may be explored, for example, supplier-provided financing where a supplier essentially loans out the solar unit or consumers draw from a central unit and pay based on their usage. These pay-as-you-go systems are becoming more popular in Nigeria and are likely to provide a solution for lower-income consumers. However, the availability of commercial providers offering affordable solutions is still scarce. This is because of the burden of the cost of doing business in Nigeria – the cost of importing foreign components as well as foreign expertise to sustain the viability of the business. Appropriate government backing may help ease the burden for commercial providers of such pay-as-you-go systems. This thesis proposes using customers' fuel savings towards a payment plan for purchasing solar PV home systems. As shown in the earlier household examples, this provides a potential option for banks and other commercial institutions to provide loans for solar PV systems with some assurance of repayment based on no additional cost to the user. This is made possible where customers can pay towards the loan using the money saved that would otherwise have been spent on fuel for a diesel generator. Furthermore, customers can build a credit history for potential future loans. As suggested earlier, locations like Enugu, which show a shorter payout time for a solar PV system, could be a choice location for a pilot that can be extended to other locations following successful implementation.

6.1.2.2. Government Funding Through Subsidies

Government subsidies have been used in many developed countries for gaining rapid growth in a sector. Government subsidies can encourage commercial and residential consumers to adopt renewable energy systems for electricity generation, generally whereby business and individual consumers are provided with a government tax break to install and/or utilize renewable energy systems for electricity generation. Government subsidies have been most used in developed countries and met with mixed reviews on the achieved results (Concan, n.d.). Where government funding structures are robust enough to provide subsidies for renewable energy use, there is a good chance that that sector will grow faster, though not without potential adverse side effects. However, as noted by Eberhard and Shkaratan, the level of subsidies needs to be "fiscally affordable," such as understanding the cost of a 'one-off subsidy' that disappears versus a 'use-of-service subsidy' which continues indefinitely and may cost more overall (Eberhard & Shkaratan, 2012).

Typically, the revenue generated through taxes is a major source of government revenue. However, this is largely not the case in many countries in Africa, making government subsidies not a viable option for those countries. A June 2016 PWC report informs that while taxation is typically a more reliable and predictable source of revenue, this can be challenging in regions where the rate of compliance is low (Oyedele, n.d.). The PWC report cites the Joint Tax Board, which states there are ten million people registered for personal income tax purposes in all the states in Nigeria. The ten million registered for tax purposes are a fraction of the labor workforce of 77 million at the end of 2015, according to the National Bureau of Statistics (NBS). From another viewpoint, Joseph Okwori and Abubakar Sule (Okwori & Abubakar, 2016) propose that the reason Nigeria largely lacks a reliable revenue source from taxes is due to "corruption and mismanagement." Currently, the Nigerian government would be hard-pressed to generate sufficient revenue from taxation to support subsidies.

Nigeria's revenue is from two primary sources, (1) oil revenue, which accounts for approximately two-thirds of the country's revenue, and (2) non-oil revenue. The Nigerian government is by and large unable to meet its traditional functions, such as providing public goods, maintaining law and order, or even regulating trade and business to safeguard social and economic maintenance (Azubike, 2009). With the steep fluctuations in oil prices in recent years, reliance on oil revenue alone is not sustainable. Given the government's traditional revenue source constraints, attempting to extract more from oil revenue to fund renewable subsidies is unlikely to prove fruitful. A possible source of funding for renewable energy may come from the international community by taking advantage of carbon emissions taxes.

6.1.2.3. Government Funding Through Carbon Emissions Trading

Cowan, Inglesi-Lotz, and Gupta (Cowan, Chang, Inglesi-Lotz, & Gupta, 2014) assess the direction of causality between economic growth, electricity consumption, and CO2 emissions as an important consideration in implementing energy policies. The authors assert that in the case where electricity consumption causes economic growth, the country should implement expansive energy policies. If electricity also causes CO2 emissions, then the country should instead invest in increasing electricity efficiency to decrease emissions without negatively impacting economic growth. The challenge for many developing countries is access to funding to invest in increasing electricity efficiency and cleaner energy systems. A possible source of funding the government can take advantage of is international carbon emissions trading. The Kyoto Protocol established in 1997 is an international treaty where most developed nations agreed to legally binding targets for their emissions of the six major greenhouse gases: Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF_6). Each participating country agreed to CO_2 emission quotas, known as "Assigned Amounts," to reduce their overall emissions. The Protocol defines various mechanisms designed to allow the predominantly industrialized countries to meet their emission reduction commitments with reduced economic impact. In Article 12 of the agreement, one of these mechanisms provides for the “clean development mechanism” or CDM. Under this article, the participating countries can invest in projects that limit emissions in developing countries and use certified emissions reductions (CERs) generated against their own Assigned Amounts (Haites, 2000). With Nigeria being one of the largest importers of diesel generators globally (Frost & Sullivan, 2011) and with one of the highest use of gensets for electricity, the Nigerian government could capitalize on the CDM initiative to help fund household solar PV systems. This will help reduce greenhouse emissions associated with running diesel generators.

The World Bank estimates that 4.5 million households in Nigeria own generators (The World Bank, 2014). In the World bank analysis, of the households that reported purchasing fuel for power production, approximately half a million households purchased diesel (14%), and nearly 3 million purchased gasoline for power production. However, with the removal of subsidies on gasoline in Nigeria, the number of households purchasing diesel generators could rise. The analysis results indicate that about 0.16 million tons of Carbon Dioxide (CO_2) was emitted from diesel generators operated in the residential sector in 2010.

A rough estimation can be made on carbon emissions funding that can be achieved using the CDM initiative. The Enertech metering campaign study indicated the average household consumption, including power outage periods, was 3710 kWh/year (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.). The average power access for the study's geographical areas was 13 hours, indicating 11 hours of power outages that could result in the use of generators. If the household power consumption was attributed to the use of diesel generators during the period of outage (i.e., 45% of the day), then the average power generation from gensets is approximately 3035 kWh/year. The carbon dioxide emissions from diesel is 0.27 $kgCO_2$/kWh (Quaschning). Therefore, 3035 kWh/year would amount to 820 $kgCO_2$/y. Multiplying this by 468,000 households running diesel gensets, this amounts to 384 million $kgCO_2$/y or 0.4 million tons of CO_2/y. Given the 2019 average price of CO2 emissions at $25/ton (Investing.com), Nigeria could secure about $10 million in carbon emissions trading per year, which could, in turn, be used for funding household solar PV systems. A funding scheme can be established based on the amount of CO2 emissions abated from the installation of the chosen solar PV design.

6.1.3. Conducive Solar PV Market

There are policy lessons to be learned when it comes to reducing the burden to individual and commercial consumers in the purchase and maintenance of solar PV systems. Miller and Hope (Miller & C., 2000) discuss policy lessons when lending for off-grid solar power by looking at the World Bank's loans to India, Indonesia, and Sri Lanka. The authors share key lessons and recommendations, including not charging import duties and local taxes on PV modules and complete systems as these create an additional burden on the consumer. This is a potential enabling policy to further reduce barriers to purchasing these systems. In another example, assessing the rapid growth of solar PV in China, Zhu et al. (Zhu, Xu, & Pan, 2019) attribute China's significant growth in this area to two main factors, (1) economic optimization and (2) enabling factors.

With the economic optimization principle, a bottoms-up view of the least-cost renewable technology will tilt users towards that option to achieve economic optimization or cost minimization. In the China example, the dramatic cost reduction in solar PV made that technology the preferred choice when compared to a competing renewable option in wind power. China played a key role in lowering the cost of solar PV, with the authors concluding that “China's low market entry barriers played the most important role in encouraging the emergence of new firms and thus fierce market competition.”

The enabling factors for China’s solar PV growth allowed bottoms-up stakeholders to make least-cost decisions, leading to a more optimized solar PV development trajectory. Zhu et al. list three enabling factors. The first enabling factor is called ‘cost-conscious renewable energy demand,’ and in principle, is driven by the companies’ desire to maximize profits. Government policies that give renewables higher priority to access the electric grid enable this but remain a challenge for companies if the incentive for solar PV does not offset cheaper electricity from other sources e.g., coal in China. The second enabling factor is called ‘policy and goal evolution by implementation selection.’ This includes policies that stimulate domestic demand for solar PV, such as feed-in-tariffs, benchmark pricing, and showcasing successful solar PV projects and their benefits. The third enabling factor is the ‘constrained solar lobby.’ The low barrier for firms to enter the solar PV market in China also brings stiff competition that can lower the profit margins to levels that have led some firms to exit the market. The issues faced with strong competition was further exacerbated by the global financial crisis in 2008 and political wrangling between China and the US and Europe. China’s solar PV market took a big hit in the export market. However, the severe smog event in Beijing and North China in January 2013 brought about strong public support for air pollution control and shifting from coal to cleaner energy. This resulted in China further increasing its solar PV capacities with manufacturing, mainly supporting the domestic market.

The policy lessons learned from India, Indonesia, Sri Lanka, and China provide good insight into what policies may be most effective in supporting a conducive solar PV market. The Nigerian government should leverage these findings to help reduce barriers and rapidly increase Nigeria's solar PV market.

6.2. Policy Implications in Relation to Powering the Commercial Sector Through Urban Swarm Electrification

The causal relationship between electricity consumption and economic growth in Nigeria was explored by Okorie and Manu (Okorie & Manu, 2016), using Johansen co-integration and

VAR-based techniques. The results show that there is a positive relationship between electricity consumption and economic growth in Nigeria in the long run. The Granger causality test is a way to investigate causality between variables in a time series and is a probabilistic account of causality using empirical data sets to find patterns of correlation. Okorie and Manu's application of the Granger causality test to the Nigerian case revealed a unidirectional causal relationship between electricity consumption and economic growth. The authors recommend increasing power demand, including alternatives to the power supply by the national grid, should be made more competitive to spur economic growth. Akomolafe and Danladi (Akomolafe & Danladi, 2014) reach a similar conclusion in their multivariate investigation of electricity consumption and economic growth in Nigeria. Their study revealed that in the long run, electricity consumption is positively related to the real gross domestic product in Nigeria.

Enabling uptake of household solar PV systems can make a tremendous impact both in the residential and commercial sectors. Uptake can be facilitated by effective policy and conducive enabling frameworks. For example, if policymakers guarantee the purchase of the excess electricity generated, these systems become much more affordable for urban households. Failure to have an appropriate policy for home solar PV systems can have both short- and long-term consequences. Consequences include reduced uptake in the installation of new solar PV systems; a reduction in existing home solar PV systems due to poor maintenance and lack of supportive infrastructure; continued and increased use of diesel generators, which increases greenhouse gas (GHG) emissions, as well as the associated health and environmental effects.

By effecting appropriate policy, the government can support reducing and possibly eliminating the power outages currently experienced by the commercial sector. Some of the policy issues and enabling recommendations are further discussed below.

6.2.1. Flexible Financing Options

Flexible financing options can greatly facilitate the installation of household solar PV systems given the high initial capital cost. While these systems have a high initial investment cost, they require low maintenance, and its modularity means that the system size may be increased as demand and financing become available. However, the high initial investment cost for HSS is a big deterrent for many households. Various financing options were previously discussed in earlier section 6.1. In this section, in the context of making HSS more available for powering the commercial sector, this thesis further recommends effective policies that guarantee an income stream by selling electricity to the grid or neighboring businesses. For example, one approach may be financing that can allow offsetting the initial cost of the PV systems over time with the income generated from selling electricity. Another flexible financing option can be made possible by the fuel savings from households that eliminate or reduce their existing use of diesel generators. Yet another funding option may be supplier-provided financing, where a supplier loans out the solar unit and consumers pay based on their usage or pay towards the unit's outright purchase over time. Given that the median monthly salary of Nigerians is 300,000 NGN (980 USD) (SalaryExplorer, n.d.), what is evident is that some form of financing scheme, whether government or privately backed, is essential for the wider adoption of home solar PV systems.

6.2.2. Fit-For-Purpose Minimum Technical Requirements

As more individuals and businesses look to solar-generated electricity for improved electricity availability, a key consideration should be what standards need to be set in place, both on the technical side and regulation, to allow connection to the grid and the sustainability of these systems. Both technical and regulatory capacity is needed to ensure that HSS is installed correctly, that distribution networks can accommodate HSS-based microgrids and that appropriate regulation is developed and implemented. Taking a longer-term view on what standards need to be set in place is particularly important as solar PV use rapidly grows. It will be important to establish minimum technical requirements for systems connected to the grid to help ensure the quality and performance of the feed, as well as the reliability of the supply once it is online. In the microgrid concept proposed in this thesis, grid stability issues related to excess electricity can be mitigated where there is a central/main microgrid that is connected to the national grid or business, and that microgrid meets the stringent requirement for feed-in. Solar home system owners would, in turn, be required to meet minimum requirements, but less stringent and less costly, to be connected to the microgrid to obtain the right to participate in and gain the financial benefits of the HSS-based GenCo. By doing so, individual households could be alleviated from covering the cost of more demanding requirements for connecting to the grid or local business directly.

6.2.3. Feed-In Tariffs

Establishing a Feed-in Tariff (FIT) that guarantees that excess electricity produced will be bought at a fixed price for a given period can help expand the utilization of home solar PV systems. Based on the FIT experience of Japan (Kimura, 2017), Germany (Futurepolicy.org, n.d.) and the Netherlands (Dijkgraaf, van Dorp, & Maasland, 2014), ten years should support establishing renewable energy (RE), and specifically solar PV among residents, and incentivize them to purchase solar PV systems that meet the feed-in system's technical requirements. It will also incentivize self-generators to be more energy efficient to maximize the surplus electricity that can be sold. In the Netherlands, solar PV has undergone a "growth spurt," driving the cost of PV systems down and becoming a competitive electricity source (Dijkgraaf, van Dorp, & Maasland, 2014). FITs are recognized as a major driver for the development of the solar PV market in Europe, where FITs with higher returns on investment usually have a higher impact on the development.

In the Nigerian urban community-based microgrids concept shared in this thesis, the government can support a FIT model. With such a model, households with solar PV systems form a HSS-based microgrid system and effectively act as a Generating Company (GenCo). As such, they should also receive similar benefits that have so far been reserved for the privatized GenCos generating power from ground-mounted PV plants that utilize a large land area. It will be beneficial if HSS-based microgrids can also take advantage of the government's proposed commitment to buy any excess power generated, where the urban community-based GenCos also gain access to more favorable rates for feed-in tariffs. The wholesale contract prices for GenCos with feed-in tariff for electricity generated from solar PV plants is significantly higher than other renewable sources (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015). Table 22 reflects the Feed-in Tariff for electricity generated from various sources for the period 2012-2016. Assuming a FIT equivalent to those offered by the Nigerian government to the privatized GenCos was also offered to HSS-based microgrids, this would make this option more economically attractive for households to adopt. Alternatively, HSS-based microgrids can connect directly to local businesses, where competitive market prices may be reached for supplying businesses with power.

Table 22: Multi-Year Tariff Order (MYTO) II Feed-In Tariffs - Wholesale Contract Prices (Naira/MWH). Source (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015).

	2012	**2013**	**2014**	**2015**	**2016**
Hydrogen plants, small up to 30MW	23,561	25,433	27,456	29,643	32,006
Land-mounted wind power plants	24,543	26,512	28,641	30,943	33,433
Solar PV plants, ground mounted, fixed	67,917	73,300	79,116	85,401	92,192
Biomass power plants	27,426	29,623	32,000	34,572	37,357

Chapter 7: Conclusions and Further Work

7.1. Conclusion: Enabling Solar PV Through Fuel Savings

This thesis espouses the use of home solar PV systems in urban communities and proposes how these high capital investment systems may be secured at no additional cost to the user through fuel savings and effective financing options. This proposal stands to eliminate or significantly reduce the use of diesel generators, which has risks to people's health and the environment. Middle-class Nigerians in urban communities are targeted in this thesis. They represent a demographic with the highest demand for electricity and with income levels that can be incentivized to adopt solar PV systems. This stands to have a knock-on effect that should enable diffusion of solar PV systems across the country and lead to furthering its use in areas not connected to the grid. This fosters renewable energy deployment and frees up government resources to further support the off-grid communities.

The use of home solar PV systems has a strong potential for increasing electricity availability and reducing or eliminating power outages in urban areas. The combination of home solar PV systems, power from the grid, and a much-reduced use of the existing stock of generators already owned by many urban households can help create the necessary balance in urban communities to achieve continuous power supply. While there has been a sharp decline in the cost of solar PV systems over the years, the initial investment cost still poses a sizeable barrier in developing countries like Nigeria. This thesis proposes policy recommendations to enable the diffusion of residential solar PV adoption with a proposal that eases the financial burden of the initial investment cost for solar PV systems.

This thesis presents a practical and implementable option for enabling access to a cleaner, renewable source of energy through solar PV systems in urban communities. This can be achieved at no additional cost to users by using fuel savings and adequate financing. By doing so, the use of diesel generators, and their adverse health and environmental risks, are significantly reduced or eliminated. While this thesis has focused on the diffusion of renewable energy systems in Nigeria, the approach proposed can be replicated in other geographies. By taking on board and effecting strategies like this one, having a practical and credible pathway for implementation, Nigeria and other similar economies can accelerate their journey towards achieving improved living standards and positive economic, health, and environmental impact.

7.2. Conclusion: Powering the Commercial Sector Through Urban Swarm Electrification

The adverse economic impact due to power outages in Nigeria is enormous. In the private sector alone, losses due to electrical outages averaged 16% of annual sales. A key enabler for Nigeria's economic growth will be access to more reliable electricity. This thesis presents a conceptual framework of urban household solar PV-based microgrids as a feasible and implementable option to enable more reliable power access for the commercial sector. It does so by framing how a microgrid made up of household solar PV systems can form a balancing network for more reliable power access. While this thesis presents one opportunity amongst others in this space, by taking on board and effecting strategies like this, Nigeria and other similar economies can start to build a pathway towards achieving increased clean electrification and positive economic and environmental impact. The use of solar PV home systems to form a microgrid for electrification has strong potential for increasing electricity availability and reducing or eliminating power outages experienced by businesses across Nigeria. The combination of solar PV home systems and power from the grid can help create the balance needed to achieve a more reliable power supply for the commercial sector.

This thesis also addresses policy issues related to the proposal and recommends policy enablers for the diffusion and adoption of residential solar PV, the foundation of which is needed for an effective distribution network. The policy recommendations include expanding the contract prices for feed-in-tariffs currently offered for ground-mounted solar PV plants also for microgrids based on solar home systems. This should allow HSS-based microgrids to operate as GenCos with the benefit of being able to sell electricity to the national grid or directly to businesses. Additionally, offering more financing options is proposed to ease the financial burden of the initial investment cost for solar PV systems.

There are some limitations to this work that provide grounds for further research. For example, the approach taken in this work was an exploratory methodology with a proposed next step of testing through quantitative methods. Testing this approach in a community in Nigeria or a similar developing country would be an appropriate next step. Furthermore, the approach suggested by this work most supports businesses that are closest to the urban areas, thereby being somewhat disadvantageous for businesses in the outskirts of urban areas or in rural areas. Expanding the available options for businesses outside of the urban areas will help achieve the benefits of economic growth across all areas of Nigeria. A further area of research would be a detailed analysis of the expected growth rate of solar PV adoption in the residential sector and the resulting amount of additional electricity generated and made available to the commercial sector. This next step can be done whilst reviewing the cost of creating and accelerating such a distributed network system against the tradeoffs and cost of an alternate means of electricity generation.

7.3. Overall Thesis Conclusion

The motivation for this thesis work was to develop a feasible method to improve power access in Nigeria by leveraging the free renewable energy resources in the country. In order to achieve this, this thesis looked at the power outage problem in Nigeria, the effect on the residential and commercial sectors, and the barriers to reliable power access in the country. It next looked at what practical approach can be undertaken to achieve the desired result of more reliable access to power.

Three main research questions were asked and answered in this thesis. The research questions asked were as follows:

1) Is it feasible to build and establish a solar PV home network in urban communities in Nigeria in an economically sustainable way for more reliable continuous power access?
2) Can a home solar PV system based microgrid support increasing electricity reliability to power the commercial sector, improve productivity, and promote economic growth?
3) What policies may be most effective in enabling diffusion and adoption of solar PV home systems for residential use and support powering the commercial sector?

The first research question was addressed by establishing the power access issues that persist in Nigeria and options for more reliable power access. A case was made for home solar PV systems as a feasible option for generating more reliable power. Furthermore, this thesis work addressed the persistent challenge on a credible pathway to make solar PV systems financially accessible to more Nigerians. The proposed framework presents a credible pathway for urban households to obtain a solar PV system through fuel savings, at no additional cost, thereby establishing an affordable, sustainable way to grow solar PV's implementation and wider adoption. Plus, a key positive effect is a resultant reduction in or elimination of the use of diesel generators, which poses both environmental and health risks.

A comprehensive literature review was done to provide additional backing for the feasibility of the thesis proposal. The literature review included solar PV projects already implemented in Nigeria and the sub-Saharan region, reviewing these projects' successes and failures. While the benefit of solar PV is well established, the affordability, sustainability, and growth potential of these systems, in Nigeria, to allow for more reliable power access, is not. Drawing on learnings from the actual implemented RE projects, this thesis ascertains what key further contributions can be made in this area and the pitfalls to avoid. The resulting proposal builds on this foundation to determine a credible and implementable solution for growing solar PV technology adoption for many Nigerians while tackling the system's affordability and sustainability challenges.

The second research question is addressed on how an established home solar PV system based microgrid can be used to power the commercial sector reliably, affordably, and competitively. A case was made that by forming an urban community-based microgrid made up of residential home solar systems, the excess electricity generated can be used to power the commercial sector. This would most apply during periods of low demand in residences (weekday daytimes), where there is high demand in the commercial sector. Based on the high revenue losses seen due to power outages in the commercial sector, the framework proposed is feasible and provides an opportunity for more reliable power access from an HSS based microgrid, which in turn, could significantly stimulate economic growth.

Finally, this thesis addressed the third question on effective and enabling policies for the proposed improvements in the residential and commercial sectors. By looking at what has been successfully implemented in other countries, a proposal is made on viable options that can be employed in Nigeria with a high chance of success. Also, looking at Nigeria's specific opportunities and challenges, further policy enablers and recommendations are made that can help progress the step change needed in the adoption of more renewable energy systems, and in particular solar home PV systems, to benefit both the residential and commercial sectors.

There is further research work that can and should be done. First and foremost, this includes an implementation of the proposed approach with a test group in Nigeria, preferably in the Enugu area, which shows a lot of promise as it has a short payout time for a solar PV system.

In theory, residential uptake of solar PV systems should increase in direct correlation to access to financing that converts fuel savings into payment options for the system. For powering the commercial sector, the proposed approach would also benefit from a pilot study. Such a study should include a test group of households forming an urban community-based microgrid and supplying the excess electricity to the commercial sector. Getting direct results of how this can be used to power nearby businesses in urban communities, including the expected increase in power access reliability and lower operating cost, should provide a strong use case for wider implementation. Finally, further work is suggested to study the applicability of the proposed approach in different geographical areas, both within Nigeria, more widely in sub-Saharan Africa, and potentially other regions globally that may also be challenged with unreliable power access in their urban communities.

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Appendix

A. International Energy Agency – Key Energy Statistics, 2018

Table A- 1: Energy Consumption for Nigeria and 4 Peer Countries

2018 Data					
	Nigeria	Bangladesh	Brazil	Indonesia	South Africa
Industry	7505	9410	26430	34884	13360
Transport	22689	4172	75242	50157	24551
Residential	105592	15546	83449	54378	19214
Commercial and public services	3412	667	12704	6028	6096
Other	1705	2461	26796	8727	8123
Total	140903	32256	224621	154174	71344
Population, 2018	*1.96E+08*	*2.42E+08*	*2.09E+08*	*2.68E+08*	*5.8E+07*
Consumption per capita	*0.72*	*0.13*	*1.07*	*0.58*	*1.23*

B. Enertech monitoring data for Lagos

Table B- 1: Residential power access and energy use for Lagos, Nigeria

				100%	Grid on	Grid off
Hour of Day	No Grid Power Access, %	Minutes of no access to grid	Average Load, Watts	Average Energy use, 100% on, kWh	Average Energy use, when access to grid only, kWh	Average Energy use from gen when no access to grid power, kWh
1.00	20.78	12.47	802.17	0.80	0.64	0.17
2.00	23.07	13.84	736.96	0.74	0.57	0.17
3.00	24.88	14.93	722.46	0.72	0.54	0.18
4.00	25.24	15.14	787.68	0.79	0.59	0.20
5.00	24.64	14.78	845.65	0.85	0.64	0.21
6.00	30.90	18.54	823.91	0.82	0.57	0.25
7.00	37.89	**22.74**	849.28	0.85	0.53	**0.32**
8.00	36.21	**21.72**	863.77	0.86	0.55	**0.31**
9.00	39.34	**23.60**	849.28	0.85	0.52	**0.33**
10.00	38.13	**22.88**	802.17	0.80	0.50	**0.31**
11.00	37.41	**22.45**	860.15	0.86	0.54	**0.32**
12.00	35.18	**21.11**	932.61	0.93	0.60	**0.33**
13.00	31.51	**18.90**	976.09	0.98	0.67	**0.31**
14.00	29.58	**17.75**	986.96	0.99	0.70	**0.29**
15.00	30.66	**18.40**	986.96	0.99	0.68	**0.30**
16.00	30.66	**18.40**	954.35	0.95	0.66	**0.29**
17.00	23.68	**14.21**	1026.81	1.03	0.78	**0.24**
18.00	26.45	**15.87**	972.46	0.97	0.72	**0.26**
19.00	23.68	14.21	1088.41	1.09	0.83	0.26
20.00	21.39	12.83	1055.80	1.06	0.83	0.23
21.00	19.58	11.75	1001.45	1.00	0.81	0.20
22.00	21.39	12.83	932.61	0.93	0.73	0.20
23.00	20.66	12.40	889.13	0.89	0.71	0.18
24.00	19.70	11.82	838.41	0.84	0.67	0.17
	Hrs running genset during daylight period	**3.97**			**Estimated demand when no power from grid during daylight period**	**3.62**
	Total hrs running generator	6.73	Energy usage per day	21.59	15.56	6.03
			Energy usage per month	647.57	466.80	180.77
			Energy usage per year	7878.71	5679.39	2199.32

*Sunrise to sunset period from approximately 6:30am-6:30pm (shown in bold and gray).

C. Enertech monitoring data for Abuja

Table C- 1: Residential power access and energy use for Abuja, Nigeria

				100%	Grid on	Grid off
Time of Day	No Grid Power Access, %	Minutes of no access to grid	Average Load, Watts	Average Energy use, 100% on, kWh	Average Energy use, when access to grid only, kWh	Average Energy use from gen when no access to grid power, kWh
1.00	35.53	21.32	1202.80	1.20	0.78	0.43
2.00	34.34	20.60	1136.64	1.14	0.75	0.39
3.00	32.33	19.40	1155.73	1.16	0.78	0.37
4.00	31.10	18.66	1125.19	1.13	0.78	0.35
5.00	31.78	19.07	1079.39	1.08	0.74	0.34
6.00	32.74	19.64	1079.39	1.08	0.73	0.35
7.00	35.14	**21.08**	1066.67	1.07	0.69	**0.37**
8.00	35.48	**21.29**	924.17	0.92	0.60	**0.33**
9.00	36.89	**22.14**	814.12	0.81	0.51	**0.30**
10.00	38.01	**22.81**	850.38	0.85	0.53	**0.32**
11.00	40.27	**24.16**	865.65	0.87	0.52	**0.35**
12.00	42.47	**25.48**	911.45	0.91	0.52	**0.39**
13.00	44.52	**26.71**	1008.78	1.01	0.56	**0.45**
14.00	48.15	**28.89**	999.24	1.00	0.52	**0.48**
15.00	48.29	**28.97**	987.79	0.99	0.51	**0.48**
16.00	45.89	**27.53**	1064.12	1.06	0.58	**0.49**
17.00	44.20	**26.52**	1071.76	1.07	0.60	**0.47**
18.00	43.38	**26.03**	1094.66	1.09	0.62	**0.47**
19.00	40.32	24.19	1060.31	1.06	0.63	0.43
20.00	31.92	19.15	1129.01	1.13	0.77	0.36
21.00	24.21	14.53	1178.63	1.18	0.89	0.29
22.00	22.28	13.37	1209.16	1.21	0.94	0.27
23.00	28.77	17.26	1279.77	1.28	0.91	0.37
24.00	33.84	20.30	1304.58	1.30	0.86	0.44
	Hrs running genset during daylight period	**5.03**			**Estimated demand when no power from grid during daylight period**	**4.91**
	Total hrs running generator	8.82	Energy usage per day	25.60	16.30	9.30
			Energy usage per month	767.98	489.10	278.88
			Energy usage per year	9343.77	5950.75	3393.01

*Sunrise to sunset period from approximately 6:30am-6:30pm (shown in bold and gray).

D. Enertech data for Enugu, Benin, Bauchi and Sokoto

ENUGU HOUSEHOLD DEMAND

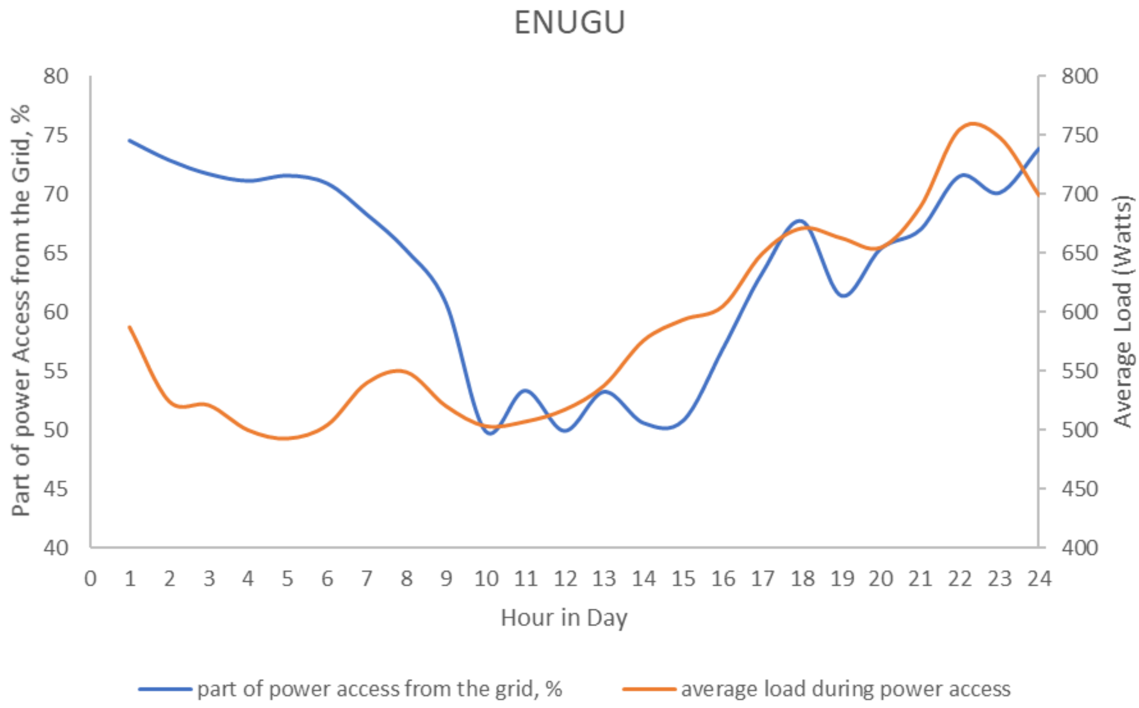

Figure D- 1: Enugu - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

Table D- 1: Average Energy Used for Various Load Cases and Power Access Periods for Enugu Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (kW)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	14.1	0.755
Average grid power access throughout day	64%	15.3	9.0	0.755
CASE 1: Average No-grid power access throughout day	36%	8.7	5.1	0.755
Sun-up period only, 6:30am-6:30pm				
Assuming 100% power access from the grid during sun-up period of day	100%	12.0	6.8	0.671
Average grid power access during sun-up period of day	57%	6.9	3.9	0.671
CASE 2A: Average No-grid power access during sun-up period of day	43%	5.1	2.9	0.671
Sun-down period only, 6:30pm-6:30am				
Assuming 100% power access from the grid during sun-down period of day	100%	12.0	7.3	0.755
Average grid power access during sun-down period of day	70%	8.4	5.1	0.755
CASE 2B: Average No-grid power access during sun-down period of day	30%	3.6	2.2	0.755

Table D- 2: Cost of diesel fuel for use cases - Enugu

Diesel Generator Use Cases		**CASE 1: outages throughout day**	**CASE 2A: outages when sun-up**	**CASE 2B: outages when sun-down**
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		8.7	5.1	3.6
Electric production in kWh		8.7	5.1	3.6
Consumption fuel in liter/day		9.6	5.6	4.0
Total cost per day	USD/d	9.3	5.4	3.8
Total cost per year	USD/yr	3388	1986	1402

BENIN HOUSEHOLD DEMAND

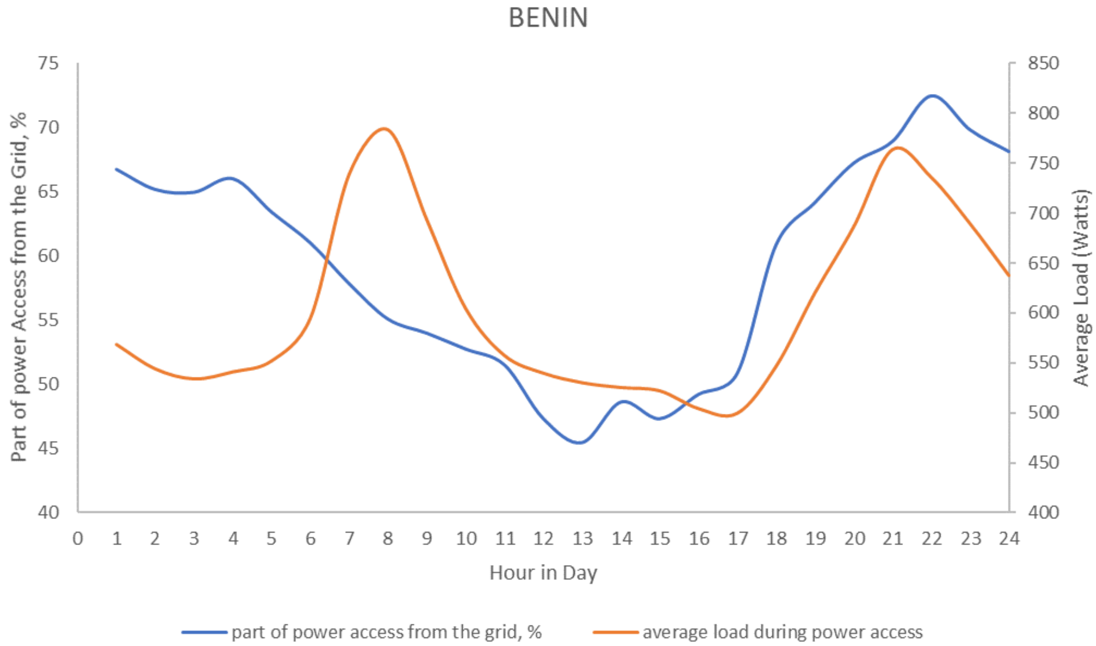

Figure D- 2: Benin - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

Table D- 3: Average Energy Used for Various Load Cases and Power Access Periods for Benin Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (kW)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	14.5	0.784
Average grid power access throughout day	59%	14.2	8.7	0.784
CASE 1: Average No-grid power access throughout day	41%	9.8	5.9	0.784
Sun-up period only, 6:30am-6:30pm				
Assuming 100% power access from the grid during sun-up period of day	100%	12.0	7.0	0.784
Average grid power access during sun-up period of day	52%	6.2	3.7	0.784
CASE 2A: Average No-grid power access during sun-up period of day	48%	5.8	3.4	0.784
Sun-down period only, 6:30pm-6:30am				
Assuming 100% power access from the grid during sun-down period of day	100%	12.0	7.5	0.764
Average grid power access during sun-down period of day	67%	8.0	5.0	0.764
CASE 2B: Average No-grid power access during sun-down period of day	33%	4.0	2.5	0.764

Table D- 4: Cost of diesel fuel for use cases - Benin

Diesel Generator Use Cases		**CASE 1: outages throughout day**	**CASE 2A: outages when sun-up**	**CASE 2B: outages when sun-down**
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		9.8	5.8	4.0
Electric production in kWh		9.8	5.8	4.0
Consumption fuel in liter/day		10.8	6.4	4.4
Total cost per day	USD/d	10.5	6.2	4.3
Total cost per year	USD/yr	3817	2259	1558

BAUCHI HOUSEHOLD DEMAND

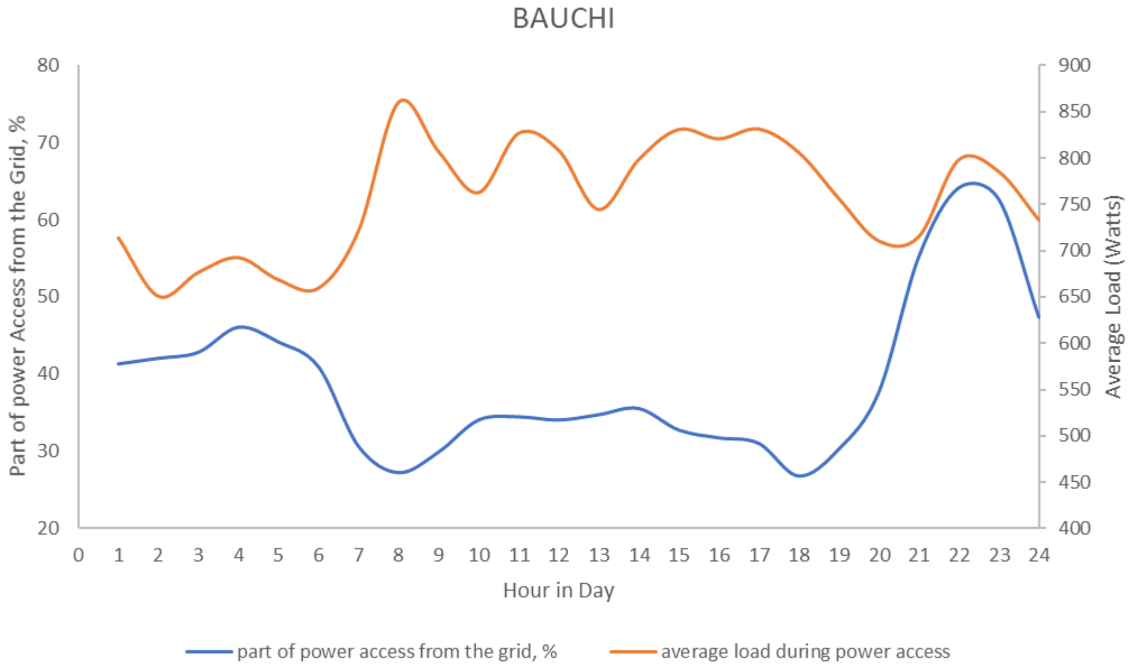

Figure D- 3: Bauchi - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

Table D- 5: Average Energy Used for Various Load Cases and Power Access Periods for Bauchi Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (Kw)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	18.2	0.861
Average grid power access throughout day	39%	9.4	7.1	0.861
CASE 1: Average No-grid power access throughout day	61%	14.6	11.1	0.861
Sun-up period only, 6:30am-6:30pm				
Assuming 100% power access from the grid during sun-up period of day	100%	12.0	9.6	0.861
Average grid power access during sun-up period of day	32%	3.8	3.1	0.861
CASE 2A: Average No-grid power access during sun-up period of day	68%	8.2	6.6	0.861
Sun-down period only, 6:30pm-6:30am				
Assuming 100% power access from the grid during sun-down period of day	100%	12.0	8.6	0.798
Average grid power access during sun-down period of day	46%	5.5	4.0	0.798
CASE 2B: Average No-grid power access during sun-down period of day	54%	6.5	4.6	0.798

Table D- 6: Cost of diesel fuel for use cases - Bauchi

Diesel Generator Use Cases		**CASE 1: outages throughout day**	**CASE 2A: outages when sun-up**	**CASE 2B: outages when sun-down**
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		14.6	8.2	6.5
Electric production in kWh		14.6	8.2	6.5
Consumption fuel in liter/day		16.1	9.0	7.2
Total cost per day	USD/d	15.6	8.7	6.9
Total cost per year	USD/yr	5686	3194	2531

SOKOTO HOUSEHOLD DEMAND

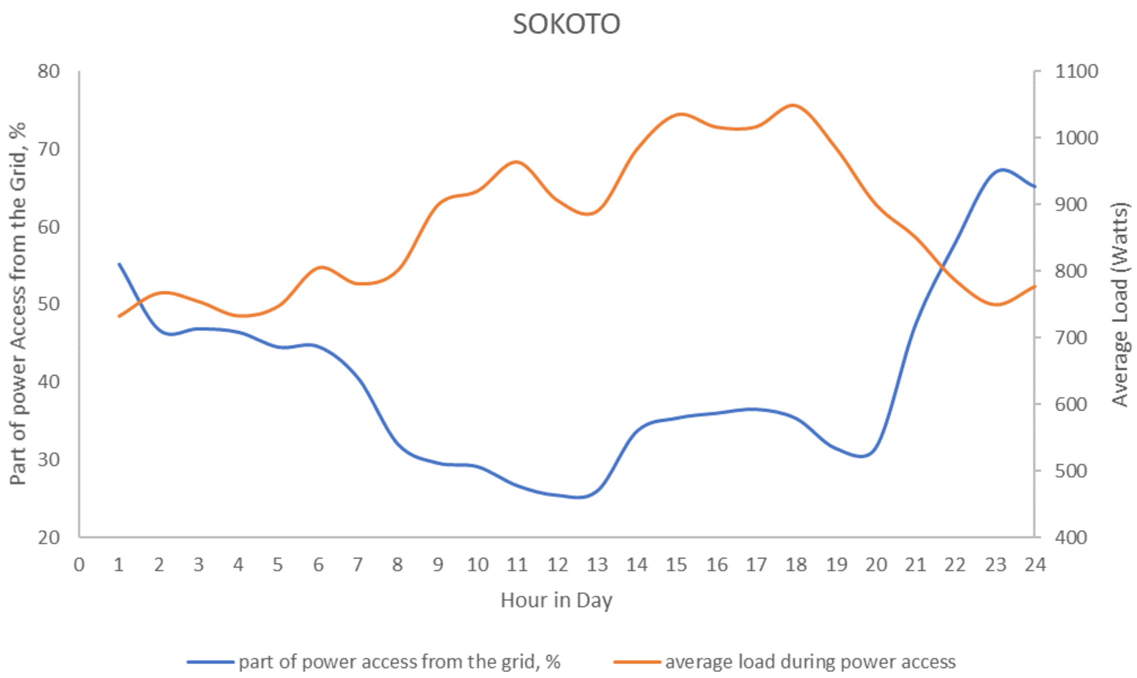

Figure D- 4: Sokoto - part of power access vs. average load during power access. Adapted from source (Energy Commission of Nigeria; Federal Ministry of Environment; United Nations Development Programme; Global Environment Facility, n.d.).

Table D- 7: Average Energy Used for Various Load Cases and Power Access Periods for Sokoto Households

	Grid power Access	Hours	Average Energy Use, kWh/d	Average Peak capacity (kW)
Full day				
Assuming 100% power access from the grid throughout day	100%	24	20.9	1.049
Average grid power access throughout day	40%	9.7	8.3	1.049
CASE 1: Average No-grid power access throughout day	60%	14.3	12.6	1.049
Sun-up period only, 6:30am-6:30pm				
Assuming 100% power access from the grid during sun-up period of day	100%	12.0	11.3	1.049
Average grid power access during sun-up period of day	32%	3.9	3.6	1.049
CASE 2A: Average No-grid power access during sun-up period of day	68%	8.1	7.6	1.049
Sun-down period only, 6:30pm-6:30am				
Assuming 100% power access from the grid during sun-down period of day	100%	12.0	9.6	0.985
Average grid power access during sun-down period of day	49%	5.9	4.6	0.985
CASE 2B: Average No-grid power access during sun-down period of day	51%	6.1	5.0	0.985

Table D- 8: Cost of diesel fuel for use cases - Sokoto

Diesel Generator Use Cases		CASE 1: outages throughout day	CASE 2A: outages when sun-up	CASE 2B: outages when sun-down
ratio fuel consumption l/kWh		1.1	1.1	1.1
Cost of fuel per liter l		0.97	0.97	0.97
calculated Cost kWh		1.07	1.07	1.07
Number of hours running h/d		14.3	8.1	6.1
Electric production in kWh		14.3	8.1	6.1
Consumption fuel in liter/day		15.7	8.9	6.7
Total cost per day	USD/d	15.3	8.6	6.5
Total cost per year	USD/yr	5569	3155	2376

Table D- 9: Solar PV design overview

Location	Case	Daily Load (kWh/d)	Peak (kW)	LCOE (USD/ kWh)	Up-front Cost (USD)	Battery Replace-ment Cost (present cost) (USD)	Total Capital Cost (USD)	O & M Cost (USD)	Solar Capacity (kW)	Storage Capacity (kWh)
Enugu	Case 1	5.5	1.0	0.42	4362	420	4782	239	1.35	3.01
Enugu	Case 2A	3.0	1.0	0.33	2184	0	2184	109	0.64	0
Benin	Case 1	6.0	1.0	0.62	9990	1003	10993	550	3.28	7.19
Benin	Case 2A	3.5	1.0	0.34	2414	0	2414	121	0.81	0
Bauchi	Case 1	11.5	1.0	0.46	7445	631	8076	404	2.20	4.53
Bauchi	Case 2A	7.0	1.0	0.20	3007	0	3007	150	1.24	0
Sokoto	Case 1	13.0	1.5	0.43	6941	655	7596	380	1.79	4.70
Sokoto	Case 2A	8.0	1.5	0.22	3780	0	3780	189	1.33	0

Table D- 10: Enugu Net Present Cost (NPC) Assessment

CITY	ENUGU	
ANNUAL FUEL COST	$	3,388
MONTHLY FUEL COST	$	282
Project life, yrs		20
Battery life, yrs		10
Battery cost, USD	$	400
O&M, % of total capital cost		5%
Discount rate		10%

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITH BATTERY - ENUGU				
Diesel Generator, NPC over 20 years	**$**	**(28,844)**		
Solar PV system WITH battery, NPC over 20 years	**$**	**(6,818)**	***76%***	**cost savings**
Solar PV system WITH battery, <FINANCED>, NPC over 20 years	**$**	**(6,812)**	***76%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	4,782		
Loan interest rate		15%		
Loan term (months)		21		
Payment due	monthly			
Monthly loan Payment	$	260		
Monthly fuel cost (100% fuel replacement)	*$*	*-*		
Averge Monthly PV O&M cost	*$*	*20*		
Total customer monthly payment	*$*	*280*		

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITHOUT BATTERY - ENUGU				
Solar PV system WITHOUT battery, NPC over 20 years	**$**	**(3,114)**	***89%***	**cost savings**
Solar PV system WITHOUT battery, <FINANCED>, NPC over 20 years	**$**	**(3,083)**	***89%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	2,184		
Loan interest rate		15%		
Loan term (months)		16		
Payment due	monthly			
Monthly loan Payment	$	151		
Monthly fuel cost (use of fuel during sundown period)	*$*	*117*		
Averge Monthly PV O&M cost	*$*	*9*		
Total customer monthly payment	*$*	*277*		

Table D- 11: Benin Net Present Cost (NPC) Assessment

CITY	BENIN
ANNUAL FUEL COST	$ 3,817
MONTHLY FUEL COST	$ 318
Project life, yrs	20
Battery life, yrs	10
Battery cost, USD	$ 400
O&M, % of total capital cost	5%
Discount rate	10%

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITH BATTERY - BENIN				
Diesel Generator, NPC over 20 years	**$**	**(32,496)**		
Solar PV system WITH battery, NPC over 20 years	**$**	**(15,672)**	***52%***	**cost savings**
Solar PV system WITH battery, <FINANCED>, NPC over 20 years	**$**	**(16,494)**	***49%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	10,993		
Loan interest rate		15%		
Loan term (months)		57		
Payment due	monthly			
Monthly loan Payment	$	271		
Monthly fuel cost (100% fuel replacement)	*$*	*-*		
Averge Monthly PV O&M cost	*$*	*46*		
Total customer monthly payment	*$*	*317*		

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITHOUT BATTERY - BENIN				
Solar PV system WITHOUT battery, NPC over 20 years	**$**	**(3,442)**	***89%***	**cost savings**
Solar PV system WITHOUT battery, <FINANCED>, NPC over 20 years	**$**	**(3,404)**	***90%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	2,414		
Loan interest rate		15%		
Loan term (months)		15		
Payment due	monthly			
Monthly loan Payment	$	177		
Monthly fuel cost (use of fuel during sundown period)	*$*	*130*		
Averge Monthly PV O&M cost	*$*	*10*		
Total customer monthly payment	*$*	*317*		

Table D- 12: Bauchi Net Present Cost (NPC) Assessment

CITY	BAUCHI
ANNUAL FUEL COST	$ 5,686
MONTHLY FUEL COST	$ 474
Project life, yrs	20
Battery life, yrs	10
Battery cost, USD	$ 400
O&M, % of total capital cost	5%
Discount rate	10%

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITH BATTERY - BAUCHI				
Diesel Generator, NPC over 20 years	**$**	**(48,408)**		
Solar PV system WITH battery, NPC over 20 years	**$**	**(11,514)**	***76%***	**cost savings**
Solar PV system WITH battery, <FINANCED>, NPC over 20 years	**$**	**(11,504)**	***76%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	8,076		
Loan interest rate		15%		
Loan term (months)		21		
Payment due	monthly			
Monthly loan Payment	$	440		
Monthly fuel cost (100% fuel replacement)	*$*	*-*		
Averge Monthly PV O&M cost	*$*	*34*		
Total customer monthly payment	*$*	*473*		

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITHOUT BATTERY - BAUCHI				
Solar PV system WITHOUT battery, NPC over 20 years	**$**	**(4,287)**	***91%***	**cost savings**
Solar PV system WITHOUT battery, <FINANCED>, NPC over 20 years	**$**	**(4,238)**	***91%***	**cost savings**
<FINANCING ASSUMPTIONS>				
Amount borrowed	$	3,007		
Loan interest rate		15%		
Loan term (months)		14		
Payment due	monthly			
Monthly loan Payment	$	235		
Monthly fuel cost (use of fuel during sundown period)	*$*	*211*		
Averge Monthly PV O&M cost	*$*	*13*		
Total customer monthly payment	*$*	*459*		

Table D- 13: Sokoto Net Present Cost (NPC) Assessment

CITY	SOKOTO
ANNUAL FUEL COST	$ 5,569
MONTHLY FUEL COST	$ 464
Project life, yrs	20
Battery life, yrs	10
Battery cost, USD	$ 400
O&M, % of total capital cost	5%
Discount rate	10%

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITH BATTERY - SOKOTO			
Diesel Generator, NPC over 20 years	**$ (47,412)**		
Solar PV system WITH battery, NPC over 20 years	**$ (10,829)**	***77%***	**cost savings**
Solar PV system WITH battery, <FINANCED>, NPC over 20 years	**$ (10,796)**	***77%***	**cost savings**
<FINANCING ASSUMPTIONS>			
Amount borrowed	$ 7,596		
Loan interest rate	15%		
Loan term (months)	20		
Payment due	monthly		
Monthly loan Payment	$ 432		
Monthly fuel cost (100% fuel replacement)	*$ -*		
Averge Monthly PV O&M cost	*$ 32*		
Total customer monthly payment	*$ 463*		

CASE: DIESEL GENERATOR vs SOLAR PV SYSTEM WITHOUT BATTERY - SOKOTO			
Solar PV system WITHOUT battery, NPC over 20 years	**$ (5,389)**	***89%***	**cost savings**
Solar PV system WITHOUT battery, <FINANCED>, NPC over 20 years	**$ (5,342)**	***89%***	**cost savings**
<FINANCING ASSUMPTIONS>			
Amount borrowed	$ 3,780		
Loan interest rate	15%		
Loan term (months)	17		
Payment due	monthly		
Monthly loan Payment	$ 248		
Monthly fuel cost (use of fuel during sundown period)	*$ 198*		
Averge Monthly PV O&M cost	*$ 16*		
Total customer monthly payment	*$ 462*		