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MEETING ENERGY DEMAND FOR CRITICAL HEALTH CARE IN
DEVELOPING ECONOMIES: A CASE STUDY MODELLING
RENEWABLE ENERGY SYSTEMS

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ABSTRACT

Most of the world's fastest population growth is occurring in cities of developing countries. With this growth comes higher demand for energy and modern energy services. However, the utility grids in many developing countries are unreliable with dire consequences for economic and social wellbeing with the health sector in these nations experiencing some of the most severe impacts. Review of WHO-sponsored and other related research documents reveals that there is a gap in current frameworks for healthcare energy provision. Existing frameworks for measuring and improving access and quality of electricity for healthcare facilities lack essential demand-side elements to identify potential levels of energy requirements. Research to further define demand-side requirements and optimal power supply technologies in different settings is required.

Consequently, this research initiated a multi-dimensional energy framework to address this gap using Nigeria as a case study. First, a focus group of experts was recruited to assess essential electricity demand for an energy intensive treatment based on WHO's SARA compendium of health services. Second, a post-energy assessment criticality analysis was conducted to create a lower level energy demand based on the most essential (or critical) applications in the treatment. Third, renewable energy technologies (RETs) were modelled in microgrid systems to determine the most viable systems in terms of cost effectiveness, reliability and environmental sustainability.

Results show that two levels of energy demand for health services - essential and critical - can be created using a criticality assessment method. An Event Resilience Index of 0.34 was derived i.e. an energy system should power 34% of essential equipment in a secondary or lower level health facility for it to be resilient to unexpected power outages. On the supply-side, DER systems in settings with high solar but low hydro potentials in Nigeria require backup generators to ensure reliability and lower costs based on pre-set benchmarks (CoE of $\leq \$0.14/\text{kWh}$ and emission of $\leq 1000 \text{ gCO}_2\text{-eq/kWh}$) without producing unhealthy levels of pollutant emissions. Systematically determined reduced loads can be powered economically using fully renewable power resources. Furthermore, the modelling of energy resources in Nigeria's six geopolitical zones revealed that Nigeria has significantly more microhydro potential than wind.

Keywords: Cost of energy; criticality; energy demand; grid power; health facility; Nigeria; optimisation; pollutant emission; power supply; renewable energy.

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LIST OF ABBREVIATIONS

BRICS	Brazil, Russia, India, China and South Africa
CCHP	Combined Cooling, Heat and Power
CHP	Combined Heat and Power
CPV	Concentrating Photovoltaics
DER	Distributed Energy resource
DG	Distributed Generation
DMap	Data Map
DSM	Demand Side Management
ESS	Energy Storage System
FiT	Feed-in-Tariff
FMEA	Failure Mode and Effect Analysis
gCO ₂ -eq/kWh	Grams of CO ₂ Equivalent per kWh Electricity Generated
GCS	Glasgow Comma Scale
GHG	Green House Gas
HACCP	Hazard Analysis and Critical Control Point
HAWT	Horizontal Axis Wind Turbine
HFMEA	Healthcare Failure Mode and Effect Analysis
HOMER	Hybrid Optimization of Multiple Energy Resources
HydroK	Hydrokinetic Turbine
ICE	Internal Combustion Engine (<i>ICE Generator</i> also refers to <i>Diesel Generator</i> in this study)
IEEE	Institute of Electrical and Electronics Engineers
MDGs	Millennium Development Goals
NASA	National Aeronautics and Space Administration (USA)
NOCT	Nominal Operating Cell Temperature
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory (USA)
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
PV	Photovoltaic

RCA	Root Cause Analysis
RE	Renewable Energy
RES	Renewable Energy Source
RET	Renewable Energy Technology
SARA	Service Availability and Readiness Assessment
SPA	Service Provision Assessments
SSA	Sub-Saharan Africa
SSM	Supply Side Management
STC	Standard Test Conditions. PV manufacturers rate the power output of their PV modules at standard test conditions, which are a radiation of 1 kW/m ² , a cell temperature of 25°C, and no wind. Standard test conditions do not reflect typical operating conditions because full-sun cell temperatures tend to be much higher than 25°C.
UH	Unburned Hydrocarbon
USAID	US Agency for International Development
VAWT	Vertical Axis Wind Turbine
WHO	World Health Organisation
WTP	Willingness to Pay
	<u>Nigeria Regions</u>
NC	North Central
NE	North East
NW	North West
SE	South East
SS	South South
SW	South West

1 INTRODUCTION

This chapter introduces the motivation for this research. A background to energy poverty in the developing regions of the world and its effects on healthcare is presented. Furthermore, the classification of energy-dependent applications and the different levels of energy supply in healthcare are presented. The specific impacts of unreliable power supply on these applications are identified. Also, the potential for filling the energy gap created by unreliable grids is presented. Finally, the terms of reference of the research are highlighted including the illustration of the structure of the PhD thesis.

1.1 Research Motivation

The motivation for this investigation into the potential for renewable energy use in critical health applications is based on the effects of unreliable power supply on healthcare provision in low income regions of the world. This is explored through the nature of the power sector in developing and less developed countries; power requirements in health facilities; impacts of unreliable power on health and healthcare provision and; potential for renewables to bridge the gap.

1.1.1 Problem Statement

Energy poverty has been a major global issue for years with 1 billion people still living without electricity (The World Bank, 2018a). Energy poverty has been defined as the absence, shortage or difficulty in accessing modern energy services (Bonan, Pareglio and Tavoni, 2016). 3 billion people use polluting fuels to cook and provide heating, with adverse effects on health and quality of life. The situation is not expected to improve significantly by 2030 with 1 billion people still lacking access to electricity (IEA, 2017). Most of the predicted improvements are expected to come from Latin America, developing Asia and the Middle East but no progress in Sub-Saharan Africa.

These systems, such as nuclear, coal, oil or gas fired plants, can be expensive to set up and run. They also require a level of technical knowhow to manage, which many developing countries do not have. The paucity of technical knowledge and poor management have led to the deterioration of existing power infrastructure in developing countries like Nigeria. These have led to years of unreliable power

supply that have stifled development, impacted poorly on health and overall quality of the lives of citizens. The health sector is one of the areas where the effects are most obvious, however, there is little coverage of these in literature.

Furthermore, reliable, environment-friendly and sustainable energy provision is increasingly becoming a necessity in modern societies. While it is necessary to expand energy generation capacities to cater to an increasing world population, the health and environmental impacts of many known energy sources are proving costly. Citizens of many industrialised nations are now demanding responsible energy generation in the face of growing evidence of global warming due to increasing CO₂ emission. 25% of this emission comes from electricity generation alone (US EPA, 2016).

The developed world is beginning to champion the efforts towards diversifying energy supply sources using distributed renewable sources with a view to reduce the environmental impacts of conventional central power systems. With most of the world's population growth occurring in developing countries (Pandey, 2016)¹, this provides a unique opportunity for developing countries to dial down, or skip altogether, the expensive and problematic expansion of centralised grid power. But intermittency is a major concern associated with renewable power resources and technologies.

Nevertheless, current research efforts have identified that creating a mix of these resources in combination with energy storage systems, called distributed energy resources (DER), has the potential to produce reliable power supply. But there is a catch. DERs can be expensive to acquire, set up and operate.

To this end, WHO (2015a) used a traditional framework for assessing healthcare energy requirements to determine a reduced level of energy demand and proposed the use of energy-efficient devices to cut the cost of distributed energy systems. However, this can only work for new healthcare facilities. Existing healthcare facilities in low income settings will not be able to overhaul their entire suite of equipment and devices to reduce energy demand.

¹ As much as half of the world's population by 2050 is projected to be living in only nine countries, all developing countries except for the USA.

Furthermore, Apichonnabutr and Tiwary (2018) advanced an upgrade to the traditional framework by assessing trade-offs between economic and environmental performance using a household hydro-based microgrid. This allowed for a primary and deferred load scenario based on a simple stakeholder engagement survey.

The above methods presented solutions that are either prohibitively expensive to implement for existing facilities or inadequate for a healthcare facility requiring a balance between multiple health and financial outcomes. Therefore, this research proposes a multilevel energy demand assessment method that includes a criticality assessment to create four levels of demand scenarios. This forms the basis for another multilevel assessment of optimal supply options based on economic and environmental factors.

A key problem this research aims to address is the low uptake of renewable energy technologies for essential services in developing countries despite advances made in the field and the opportunities they present for settings with unreliable or no grid access. Intermittency and cost are some of the most common reasons postulated in literature. This research aims to address intermittency through hybridisation of RETs and cost through structured prioritisation of critical loads.

1.1.2 Background to the Power Sector in Developing Countries

In 2008, approximately 1.47 billion people, 22% of the world's population, had no access to electricity globally. Of this figure, only 3 million reside in the OECD and transition economies, the rest are from developing nations (Gwénaëlle et al., 2009). Although this figure has since improved as a result of China's rapid economic growth, over the years, only 30% of the population in sub-Saharan Africa (SSA) has access to electricity (EIA, 2015a; Scott and Seth, 2013).

Lack of access varies considerably from region to region. For example, over 80% of people living without access to electricity reside either in sub-Saharan Africa or in South Asia. While SSA constitutes approximately 14% of the total population of developing nations, it accounts for 40% of the population without access to electricity (EIA, 2015a).

Even where there is access, the bane of irregularity and inadequacy, acts as a major constraint to economic development and to quality of life (Escribano et al., 2010). It is estimated that an average of 4.9% of annual sales are lost due to power outages with especially high losses encountered in businesses in Nigeria. The situation is, however, much better in sub-Saharan South Africa, one of five major emerging national economies (Müller-Krumholz, 2014).

Figure 1-1 shows a comparison between national electricity generation and population among OECD, BRICS, Africa and two sub-Sahara countries. While high power generation per capita is not, by itself, an indicator of national development, it is a key factor in overcoming poverty and improving access to modern healthcare. The wealth and development status of a nation and its citizens is closely linked to the type and extent of access to energy (EnDev, 2018). Extensive access to electricity has enabled countries like China and India to rapidly industrialise, move a large proportion of their citizens into the middle class, and provide modern healthcare service.

In developing countries where the reliability of power supply is dire, the use of back-up electric generators adds significantly to the cost of businesses and services. In 2012 alone, the cost fuel for back-up electric generators is estimated to be about \$5 billion across businesses and homes in sub-Saharan Africa (IEA, 2014). Incentive for private investment is also removed due to reduced utility revenues (non-payment) associated with unreliable grid supply. This is despite studies showing that willingness to pay (WTP) for reliable electricity is high in developing countries and it exceeds the long-run marginal cost of supply (World Bank, 2008). It is also difficult to raise tariffs when reliability and quality of provision is poor, thereby adding further constraints to the availability of investment funding.

Access to reliable electricity has been identified as a prerequisite for economic development within the objectives of the Millennium Development Goals (EnDev, 2017). By extension, economic development reduces poverty and economic prosperity can help to buy good health services. Over 50% of health care facilities in some developing countries have no electricity or lack reliable power supply (Adair-rohani et al., 2013; WHO, 2012). Unreliable electricity compels health care providers to depend on polluting and inefficient sources to supply power required

for lighting at night, electric medical equipment, heating for sterilisation and electricity for administrative functions.

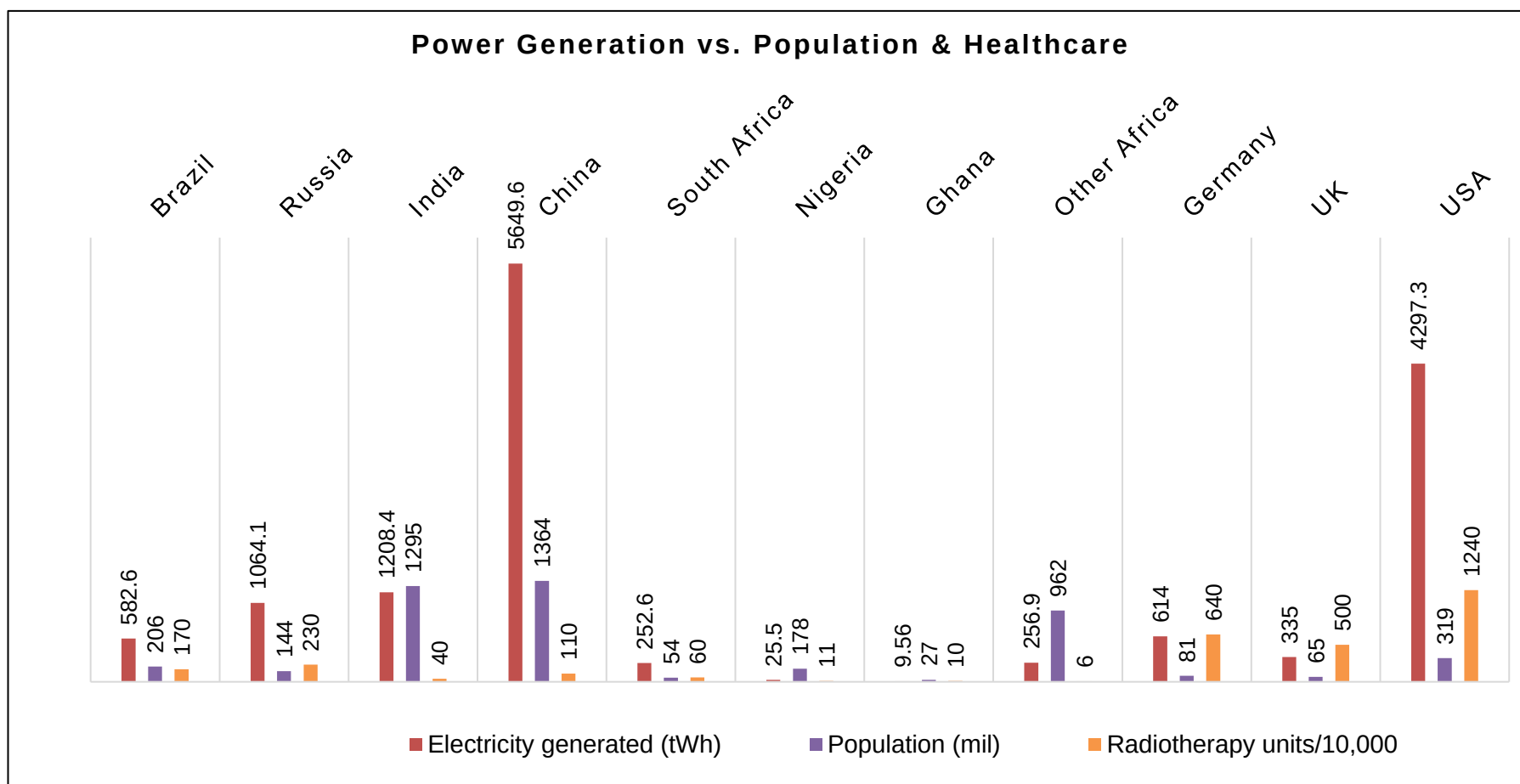


Figure 1-1: Annual national power and healthcare statistics, BRICS, Sub-Sahara Africa & OECD (WPR, 2016; EIA, 2015a; WHO, 2014a)

1.1.3 Energy Requirements in Health Facilities

Hospitals are the most energy intensive buildings per square meter after fast food restaurants (Heather and Erin, 2014). To put things in perspective, buildings in the United States account for 50% of all energy consumption, healthcare buildings make up less than 1% of total commercial buildings yet, they consume 5.5% of total commercial building energy (EIA, 2015b; Heather and Erin, 2014).

Hospitals are some of the most complex types of buildings. Every hospital is an amalgamation of an extensive variety of functional units and services as depicted in Figure 1-2. Treatment and diagnostic functions include emergency rooms, surgery, clinical laboratories and imaging. Hospitality services include housekeeping and food service. Other functions relate to the fundamental care or bed-related services and the attendant administrative functions for each service category. As a result, hospitals are heavy water and energy users, and they produce significant amount of waste.

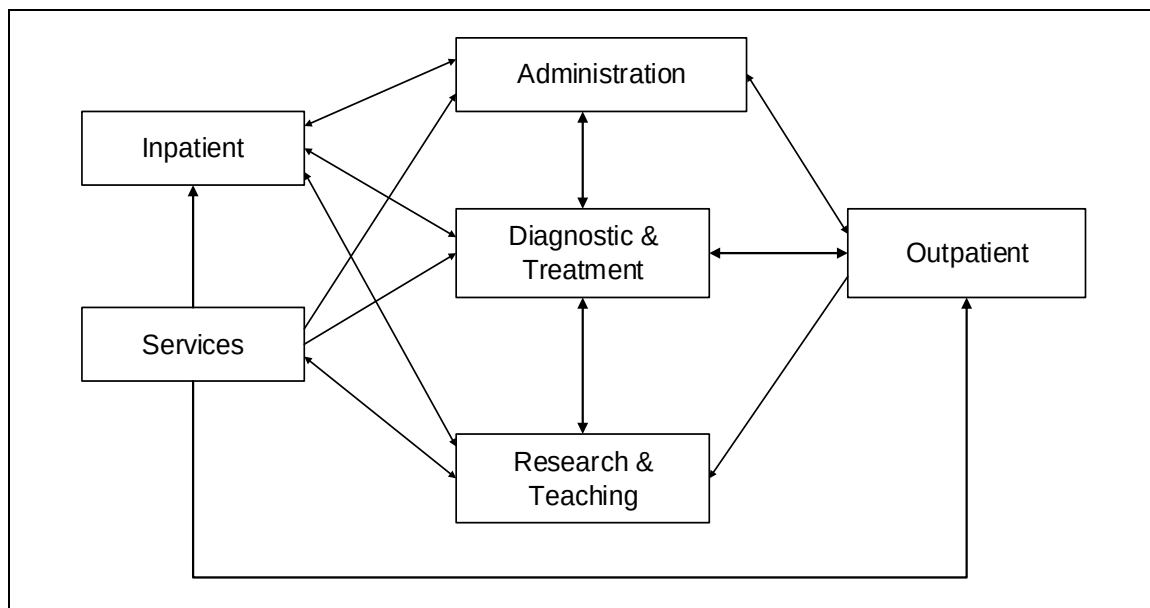


Figure 1-2: General hospital relationships (Source: Researcher's elaboration based on design guidelines in ACEM, 2014)

The functional units in a hospital usually face competing priorities and needs. Therefore, idealised settings and inveterate professional preferences must be balanced against statutory requirements, bona fide functional needs (internal traffic and relationship with other departments) and the financial wellbeing of the facility

(Alan et al., 2015). In settings with limited resources, the need to channel resources to the most critical functions is crucial.

Clinical functions are directly related to lifesaving activities, hence, the need to prioritise them when allocating limited resources. In settings where power supply is not constant or reliable, it is necessary to implement pre-designed procedures to ensure available power is supplied to the most critical spaces and equipment. This research is therefore aimed at investigating competing energy supply solutions for critical applications in a typical healthcare facility in a developing country.

1.1.3.1 Energy Demand Classification

Energy demand for clinical functions can be broadly divided into electricity and thermal needs as highlighted in Table 1-1. A health centre may offer a wide variety of services, such as immunisations, surgical operations, basic emergency treatment and obstetric care. Each of these would require trained staff, medicines and specific equipment. A systematic definition of critical energy requirements in relation to every aspect of health service provision has not been undertaken (WHO, 2015a). Nevertheless, health infrastructure surveys such as WHO's Service Availability and Readiness Assessment (SARA) have detailed inventories of available equipment in healthcare facilities.

Table 1-1: SARA classification of energy requirements (WHO, 2015a)

Electricity needs	Thermal energy needs
Infrastructure	Cooking and water heating
Medical devices	Sterilisation and incineration of medical wastes
Appliances for specific services	Space heating

Therefore, the assessment of essential electric power supply needs in a healthcare setting can be based on the SARA health service classifications. The groupings illustrated in Table 1-2 includes: (i) infrastructure such as lighting, water supply, sterilisation and communication; (ii) medical devices such as ultrasound scanner, anaesthesia machine and electrocardiograph (ECG); and (iii) support appliances for specific services such as surgical services, blood transfusion and vaccination.

Table 1-2: Classification of essential electrical equipment. Source: Researcher's elaboration of SARA (WHO, 2015a)

Infrastructure	Medical devices	Specific services
Lighting	X-ray equipment	Vaccine refrigerator
ICT	ECG recorder	Neo-natal incubator
Waste management	Suction apparatus	Haematology analyser

In this study, lighting is separated from general infrastructure, which are not regarded as critical, because it is: common to all the spaces; critical in most areas of the health facility and; can be easily isolated from other equipment (see Figure 1-3). Services such as sterilisation, requiring thermal energy that can be generated using electricity, are included in the classification.

According to the WHO (2015a), SARA and similar infrastructure survey tools are employed at national and international levels to conduct detailed monitoring of equipment available in health facilities with regards to their provision of specific services. However, a better definition of equipment electricity requirements is required. This would help drive the design of suitable supply-side solutions to prioritise the most essential needs of a facility, rather than just gaining an understanding of the overall energy requirements.

The development of more energy-efficient medical devices that can operate from solar panel sources and low-power battery has led to new opportunities to improve energy access through demand-side interventions. Examples include solar-powered direct-drive vaccine refrigerators, obstetrics devices such as fetal heart monitors and LED microscopes.

Direct-drive refrigerators convert solar energy to power a cooling system that produces ice or some other phase-change material rather than storing energy in a battery. This keeps the refrigerator at a stable temperature when solar power is not available while removing the cost of battery replacement (WHO, 2015a). More systematic review and continuous updating of the energy performance requirements for essential technologies is therefore necessary. Hence, this

research advances a systematic method of assessing electrical energy demand and supply scenarios for varying levels of criticalities in health facilities.

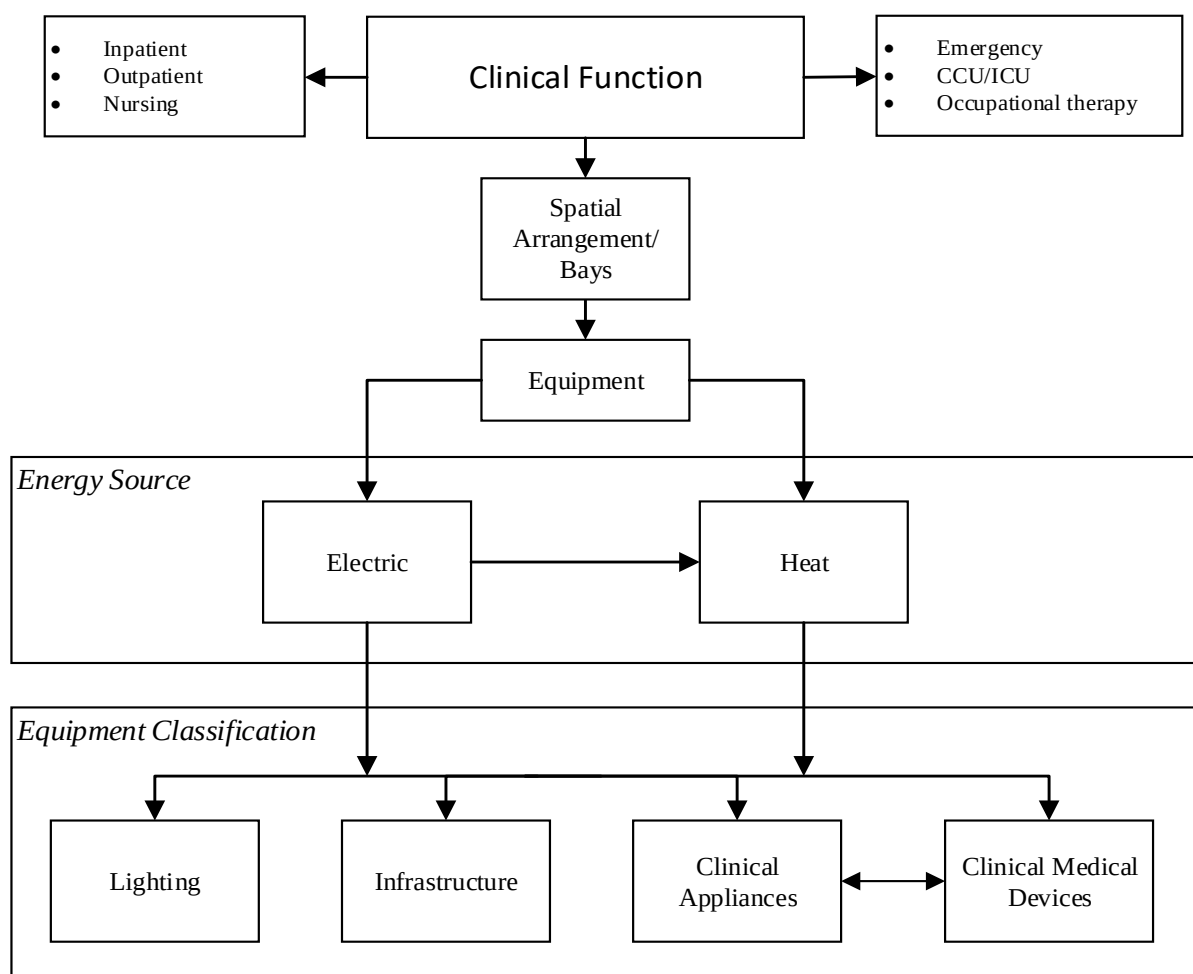


Figure 1-3: Clinical services equipment classification. Source: Researcher's elaboration of NHS Estates (2013)

Besides electricity for medical devices, appliances and facility support functions (such as communication and water pumping), health facilities have thermal energy needs for sterilisation, incineration of wastes, cooking, space and water heating. Such needs are more significant in larger health facilities delivering more complex health services or offering inpatient services. Heat energy production are not considered in this research.

Nevertheless, thermal energy needs may be met using electricity and, increasingly, by high-efficiency co-generation of heat and power (CHP) systems in health facilities grid-connected settings. It is more common for thermal energy needs to be supplied through direct combustion of traditional and fossil fuels such

as biomass, diesel, gas, and coal using on-site boilers. Furthermore, inexpensive thermal solar panels can provide hot water for space heating and hygiene purposes. The improvement of building energy efficiency can greatly reduce thermal energy needs as well as electricity requirements (WHO, 2015a). Hence, this study includes a systematic approach to the reduction of energy demand in health facilities.

1.1.3.2 Multilevel Energy Supply

Since there are various levels of energy demand requirements in health facilities, it is also reasonable to have a multilayer approach to providing electricity for these loads. Supply side management solution proposed in WHO (2015a) involved the design of optimal supply systems for two healthcare energy demand scenarios. One contains electrical loads of conventional devices while the second contains energy-efficient devices. Olatomiwa et al. (2016) generated optimised systems for a singular rural clinic load profile.

However, it is reasonable to create different levels of supply scenarios to satisfy different levels of hospital energy demand. This research is therefore proposing a multilevel supply side management solution that relies on the following:

- Structured assessment of criticality of electrical applications to create four levels of electrical load demand
- A calculated minimum resilience factor based on above assessment²
- Potential to generate income from the sale of excess energy produced
- Low actual emissions rather than net emissions (includes CO₂ emissions saved through renewable power generation)

The above conditions are required for the supply solution to meet higher measures of affordability and sustainability than those achieved in earlier studies. There is a persistent dependence on fossil fuel-based power supply in developing countries like Nigeria, instead of transitioning to an economy based increasingly on renewable power supply.

² The assumption here is that, a facility that can afford a conventional power system that includes a diesel generator should be able to finance a microgrid that can meet a certain percentage of its total load.

Indeed, analysis of Nigeria's Vision 20: 2020 (NPCN, 2010), containing infrastructure development plans from 2010 to 2020, shows that a lot more focus is placed on rehabilitating and expanding existing grid infrastructure. The power infrastructure plan of Vision 20: 2020 is aimed at increasing power generation capacity from 3,700 MW in 2010 to 35,000 MW in 2020. It includes a 3-year power generation target of up to 16,000 MW by 2013 from 3,700 MW in 2010. The plan shows that 44% of total generation target is based on the rehabilitation of existing transmission distribution networks and the construction of new gas and coal-fired power plants. On the other hand, a paltry 2.45% of this target is based on solar, wind and small/micro hydro combined.

In November 2018, Nigeria's installed power generation capacity was up to 12,522 MW, 78% of the 2013 target of 16,000 MW (Power Africa, 2018). Of this installed generation capacity, 10,142 MW is thermal, and 2,380 MW is hydro. Nevertheless, Nigeria is only able to generate about 4,000 MW on most days (Power Africa, 2018).

As of 2015, Nigeria has 1 MW and 30 MW of mini-grids and solar home systems respectively, 0.25% of installed capacity (BloombergNEF, 2018). There is little or no indication of progress on the non-large hydro renewable power targets. This possibly suggests that renewable power is still considered either too expensive to be robustly deployed, or too intermittent to play a major role in solving the problem of unreliable power supply in Nigeria. In 2015, 75% of power demand in Nigeria, representing 13,800 MW, is met through self-generation, mainly using diesel (BloombergNEF, 2018),

Meanwhile, the power element of Vision 20: 2020 was upgraded to Electricity Vision 30:30:30 in 2017 (Yunus, 2018). The policy targets 30,000 MW power generation capacity by 2030, 30% of which is expected to come from renewable sources. Considering the significant lack of progress in meeting renewable power generation targets of Vision 20:2020, there is need for other methods of intervention to be considered if the renewable targets of Vision 30:3-30 are to be met. This study proffers the optimisation of distributed power supply configurations for pre-determined energy demand levels as a systematic approach to affordably and sustainably bridge this gap in supply.

1.1.4 Impacts of Unreliable Power Supply on Healthcare

In energy poor settings and in many SSA countries, the argument for adequate and reliable power supply overshadows that for energy efficiency and low carbon emission. These nations contend with limited access to reliable power supply. Several publications have highlighted that aggregate energy demand is strongly correlated with population and wealth of nations (Ayres and Warr, 2010; Braimah and Amponsah, 2012; Flavin and Aeck, 2005; Gwénaëlle et al., 2009; Oseni, 2012; Tainter, 2011; Vera and Langlois, 2007; Watson et al., 2012). Therefore, to be able to sustain increasing economic activities and other daily routines, many developing countries have resorted to the extensive use of internal combustion electric generators with serious financial and health implications.

Accurate analysis of the impacts of unreliable power supply and the use of fossil-fuel-burning generators on healthcare in developing countries is scant (Adair-rohani et al., 2013; WHO, 2015a). However, the effects on economic functions can be said to have received some coverage. Nevertheless, there is consensus within literature that, while scheduled power outages may be acceptable for the periodic maintenance of power systems, unscheduled power failures are very disruptive and can pose serious threats to lives, businesses and properties (Marnay, 2014; Saviva Research, 2013; Tam, 2016). It is the devastating effects of rampant power outages on healthcare facilities in developing countries that formed the basis for the undertaking of this research.

The predilection of contemporary research to attach significant importance to short-term economic sensibilities (e.g. payback period, return on investment, and average payment period) has led to the relegation of the effects of technical and administrative shortcomings in these countries. For example, Nigeria has, for decades, thrown significant amounts of money at its power problems with little or no long-term success (Nkordeh et al., 2017). This can be attributed to a lack of focus on the management of central power infrastructure. Therefore, it is important to explore possible solutions at lower levels of power provision pending the resolution of administrative and technical issues at the national level.

It is noteworthy that, besides the impacts on economic functions and health outcomes in hospitals, there are other areas such as level of sophistication of

services and safety of staff and visitors. A review of research papers in the fields of energy, healthcare and health impacts in developing countries revealed multi-tiered effects of unreliable power on health services as shown in Figure 1-4. It is noted that, the impact of unreliable power supply worsens as one journeys from the top through the lower levels of healthcare provision. Ultimately, a lower level of provision combines the adverse effects produced at each of the levels above in addition to its inherent impacts.

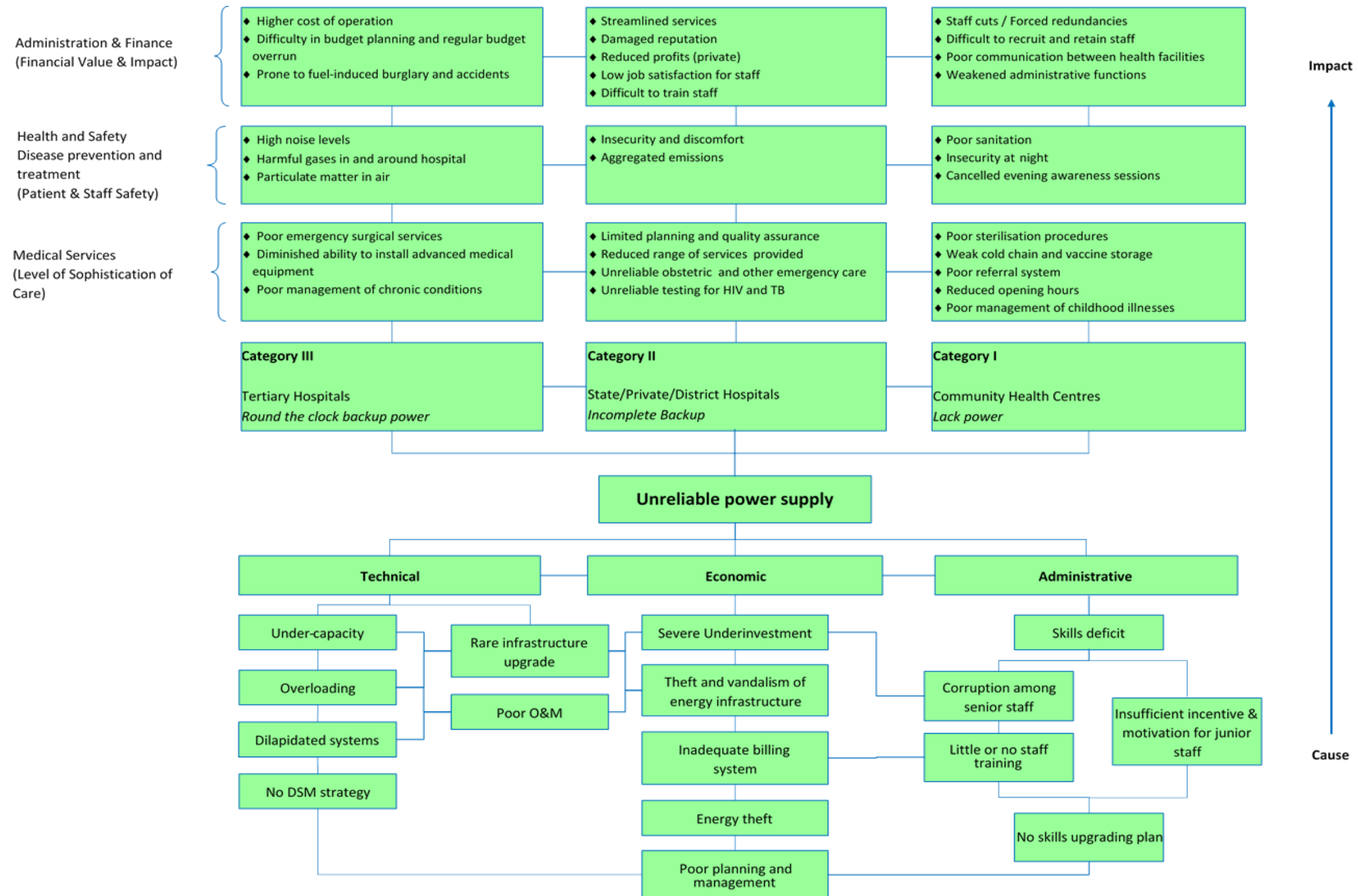


Figure 1-4: Problem Tree showing the causes of unreliable power supply and its impact on different tiers of health care facilities in developing countries. Source: Based on researcher's review of Welland (2017); WHO (2015a); Adair-Rohani et al. (2013); Lawrence and Hancock (2010); Sambo (2008); Künzli et al. (2000)

1.1.5 Potential for Renewable Energy and Load Prioritisation

Recently, the evolution of renewable energy has met and surpassed expectations in countries like China, Japan, Germany and the US. This suggests that renewable energy is a viable alternative for many developing countries. In China alone, over 190GW of renewable power capacity (excluding hydropower) has been added between 2004 and 2013 (REN21, 2014). Similarly, India and Brazil have added more than 20GW and 8GW of renewable power capacity respectively in the same period. These can be compared to the entire installed generation capacity of 28GW of the entire sub-Saharan Africa excluding South Africa in 2013 (The World Bank, 2016). The renewable energy success stories in Europe, China and other places where energy use intensity is high suggest that the energy gap in many developing countries can be bridged using renewable sources.

Several barriers to reliable access to modern energy services among the world's poorest have been identified including high upfront cost of energy conversion technologies and grid connection charges, cost-recovery difficulties, poor performance of equipment, and technical capacities for operation and maintenance (Watson et al., 2012). Despite frequent references to the importance of resolving these economic and technical barriers to energy access, evidence for intervention is weak. The weakest evidence relates to political and cultural barriers (Darmani et al., 2014; Painuly, 2001; Scott and Seth, 2013).

Some of the barriers to large scale deployment of RETs relating to economic and technical factors can be solved using microgrids. A microgrid is an assembly of energy loads, distributed generation units and energy storage systems all acting under the command of a master controller enabling it to function both in tandem with the central grid or in island mode (Parhizi et al., 2015). Using the microgrid is a method that can improve the resilience of a power system or act as a stand-alone supply source in instances where primary power supply is unreliable (Tam, 2016). Although rapid technological advancements have provided a myriad of options to make the control and operation of microgrids work, they still present as expensive alternatives for facilities in low-income regions.

Therefore, it is necessary to carry out accurate demand assessment, prioritisation of critical applications and optimal microgrid planning to ensure microgrid deployments are economically viable. These constitute the foundations for the objectives of this study.

1.2 Research Aim and Objectives

In view of the above research motivation and background, the aim of this research is to identify sustainable microgrid options for prioritised critical healthcare applications plagued by unreliable power in resource-constrained settings.

To achieve the stated aim, the following objectives have been identified:

1. To identify, classify and conduct demand assessment in kWh for essential electrical applications in a healthcare setting affected by unreliable power supply using a treatment case.
2. To prioritise critical treatment applications in a pre-assessed treatment case using health failure mode and effect analysis to create lower levels of energy demand.
3. To conduct a techno-economic analysis of competing distributed energy resources (DERs) by optimising multiple hybrids of conventional and renewable power supplies with energy storage systems (ESS) to determine the most cost effective and environment friendly microgrid options for treatment applications identified.

1.3 Scope of Research

The definitions of the scope of this research include:

- A single treatment case is used to identify, classify and conduct demand assessment used in modelling different distributed generation scenarios in multiple locations;
- Resource-constrained locations considered are limited to the six geopolitical regions of Nigeria to have a nationwide coverage that allows for comprehensive comparisons;
- Viable distributed energy resources are measured under economic, technical (reliability and resilience) and environmental (pollutant emissions) parameters;

- Microgrid considerations include using a combination of renewable energy sources (specifically solar PV, wind and microhydro), energy storage systems (Lithium-ion batteries) and conventional power sources (grid and internal combustion engine generator only);
- Sustainability in this research refers mainly to supply-side management (SSM) of distributed energy resources. It encompasses economic viability of power generation options, readily available renewable energy sources, low emission of pollutants and affordable operational costs;
- A minimum and maximum demand scenario was modelled to consider conventional and energy efficient devices respectively for the demand-side management.

1.4 Thesis Outline

Figure 1-5 illustrates the structure of this research according to subject areas and the chapters where these are covered. Each chapter of this thesis from this point forward starts with the section of the structure presented in Figure 1-5 that is relevant to it.

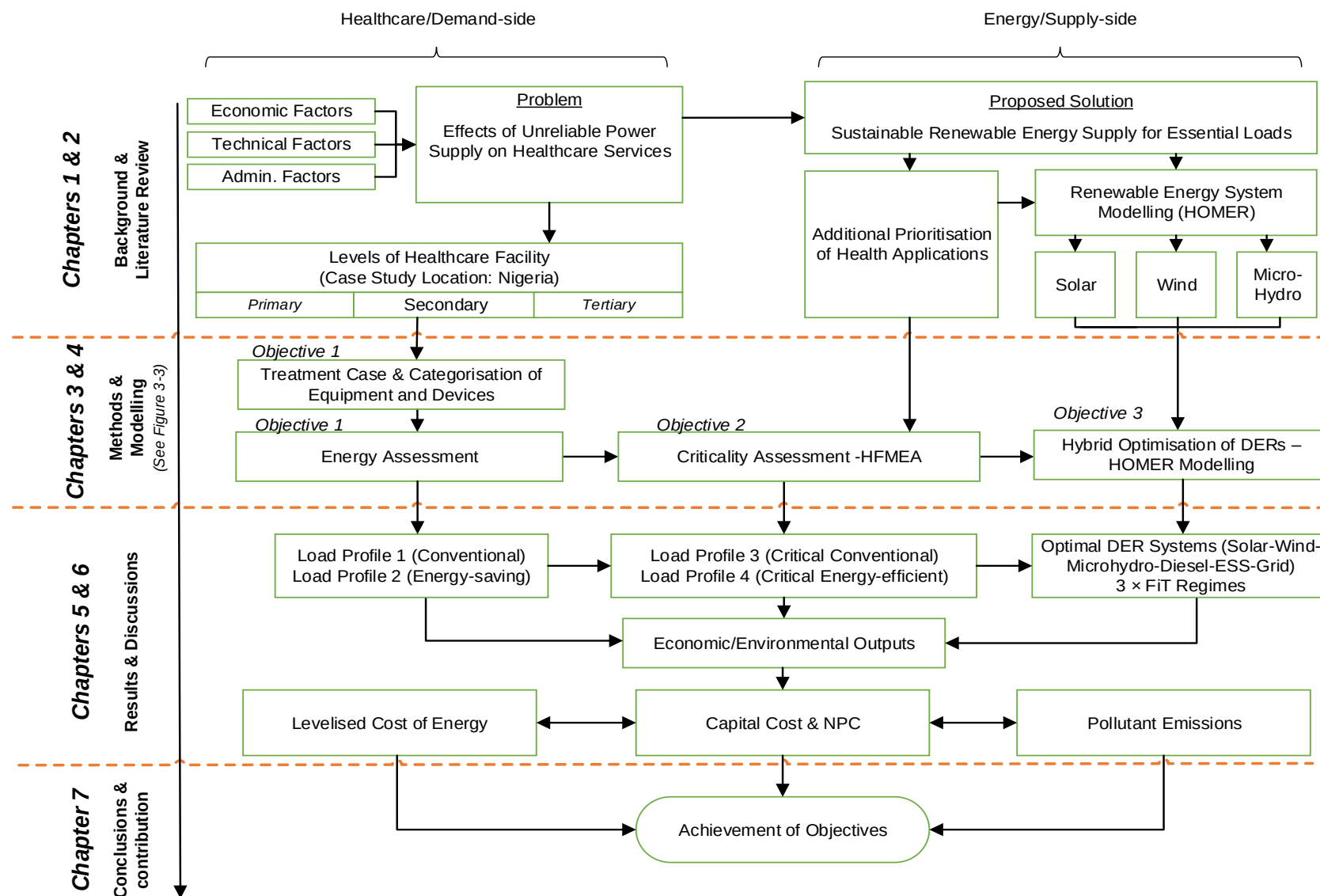


Figure 1-5: Thesis structure

Chapter 1 presents the background into the motivation for this research by exploring the nature of the power sector in developing countries; power requirements in health facilities; impacts of unreliable power on healthcare provision; and potential for renewables to bridge the gap. The terms of reference and scope of this research are also presented.

In Chapter 2, a review of the themes covered within the boundaries of the research is presented. It highlights research gaps within these themes and how this study contributes to knowledge by bridging these gaps. Furthermore, the six cities used in this study are explored in relation to their geography and their renewable energy potential.

Chapter 3 contains the details of the methods applied in assessing energy demand, assessing critical loads, and optimising renewable energy technologies in power supply systems. These are all embedded in the new framework for assessing healthcare energy demand and supply systems. Limitations of each method are also presented.

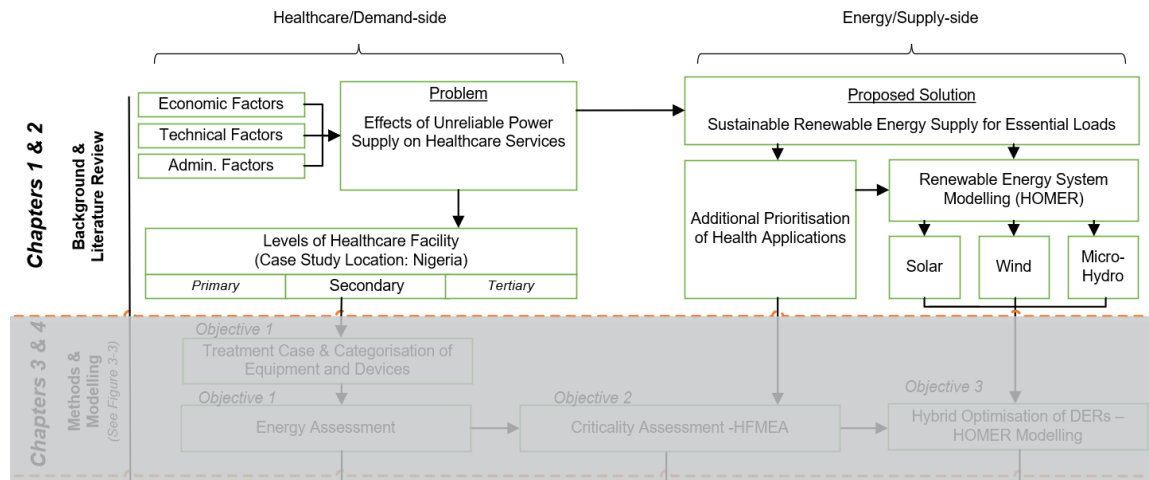
In Chapter 4, the HOMER modelling technique used in the analysis of energy resources in selected case study cities is presented including the description of the process of determining optimal power supply systems.

Chapter 5 presents the results of the determination of energy demand profiles and criticality assessment. These include an initial energy assessment using a case treatment and the prioritisation of treatment applications in the treatment process using the Health Failure Mode Effect and Analysis (HFMEA) methodology. A second energy assessment is carried out on the prioritised treatment applications derived from the HFMEA process. The results of the energy assessments provided the basis for the optimisation of potential DER systems in Chapter 6.

Chapter 6 presents the analysis of the effects of natural and techno-economic variables affecting optimised deployment of distributed energy resources in health facilities. It includes load demand and feed-in-tariff sensitivity analysis. Results are compared with literature on each city's renewable energy potentials.

In Chapter 7, the summary and conclusions of the research findings are drawn. Recommendations for future work are also presented.

2 LITERATURE REVIEW



2.1 Introduction

This chapter brings together the subjects of healthcare provision and energy provision. It presents a review of the current state of power supply in developing countries with emphasis on how power supply issues affect health and different levels of healthcare services. Economic, technical and administrative issues were explored in relation to unreliable power supply including impacts on different levels of health services, as presented in the previous chapter (see Figure 1-4). Further review of existing frameworks aimed at achieving improved energy supply outcomes in healthcare is conducted with a view to advancing them. The conceptual framework that underpins this research is also introduced. Advancing recent frameworks for selecting optimised autonomous energy system will improve the decision making process for stakeholders.

2.2 State of Central Grids in Developing Countries

A review of data from developing countries such as China, India and sub-Saharan Africa (SSA) revealed that commonly faced grid issues faced include: insufficient grid capacity to meet immediate demands; ageing grid infrastructure and grid expansion efforts lagging anticipated demands; and unsustainable primary fuel sources (Pandey, 2016). Where there is substantial RE potential, insufficient grid upgrade investments and slow pace of existing projects result in inadequate rate of RE integration into the energy mix. The review revealed further that China and India have a common energy issue in their reliance, to a large extent, on fossil

fuels as primary energy source for electricity generation. Whereas, in sub-Saharan Africa, the primary energy source for large sections of the population is biomass for heating and cooking needs.

Consequently, SSA is not considered much of an energy related emitter of CO₂ when compared with China and India due to low level industrial activities and fossil fuel consumption. This is possibly one of the reasons why national energy policies in sub-Saharan Africa are focused more on expanding generation capacity than on reducing GHG emissions (Aliyu, Modu and Tan, 2018). However, it is well documented that biomass usage in SSA is highly inefficient with negative public health and environmental implications (EnDev, 2017; WHO, 2015a).

From the foregoing, a change of approach is necessary to expand and improve energy access in developing countries. A commonly proposed approach is the integration of renewable energy sources (RES) into the national grid to expand access and achieve global sustainability goals. While this approach has been successfully deployed in developed countries, inherent issues in the national grids of developing countries pose significant challenges (Pandey, 2016). The use of smart grids is necessary for the integration of alternative energy sources with conventional power systems (von Behaim, 2017). Although smart grids present attractive opportunities, there are significant hurdles to overcome for smart grids to be successfully implemented in developing countries as shown in Table 2-1.

Removing national political and techno-economic barriers, five key aspects of concern for grid development in developing countries identified by von Behaim (2017) include: network losses; power outages; population served; consumer tariffs; and integration of new (renewable) generation capacity. On the other hand, the main concern for localised generation of renewable energy is intermittency (Connolly et al., 2010; Fizaine and Court, 2015; Tam, 2016). Since grid access will continue to be an issue in the foreseeable future, localised hybrid systems (solar PV with diesel generators) have been touted as viable alternative. However, there are few empirical evidences of financial viability and environmental suitability of these options (Olatomiwa, Mekhilef and Ohunakin, 2016; WHO, 2015a). Investigating these evidences for a specified location is one of the key objectives of this research.

Table 2-1: Opportunities and challenges in implementing smart grids in developing countries. Source: von Behaim (2017)

Opportunities	Challenges
Early stage grid development allows developing countries to technology 'leapfrog' and directly install smart grid technologies when building up their transportation and distribution network.	Utilities in developing countries are often capital-constrained, limiting their ability to invest in smart grid projects, even economically ones.
Potential for innovative energy services such as linking payments to the mobile communications network or using mini/micro grids for rural electrification.	Upper limit on chargeable utility tariffs to guarantee user-affordability. Therefore, difficult to recover O&M for smart grid system.
By recording electricity loads across the power lines smart grids can be used to track and reduce technical and power theft losses.	Lack of detailed and reliable data E.g. user demography and systems operation data. Such data is not readily available in all developing countries.
	Regulatory and institutional issues often limit innovation. E.g. regional standards, harmonising different power networks, and data privacy.

2.3 State of Power Supply in Health Facilities in Developing Countries

Evidence, both anecdotal and scientific, indicate that access to electricity in health care facilities is partial and unreliable in developing countries. A developing country is regarded as a non-industrialised, poor country that is aiming to develop its resources. While a developed country refers to an industrialised country with a highly developed economy (Gillaspy, 2018). While there is a plethora of literature on the state of electricity access in developing countries, peer-reviewed literature or data on energy access for health facilities in developing countries is scant (Mwachumu, 2017).

A WHO-led investigation by Adair-Rohani et al. (2013) discovered ‘nationally representative data’ for only 14 developing countries worldwide. Out of these, 11 were sub-Sahara African countries. The findings showed that there is extensive lack of electricity access in health facilities as shown in Figure 2-1. On the average, a quarter of these facilities have no electricity access in the 11 African countries while only an average 28% of health facilities have reliable electricity supply (Adair-Rohani et al., 2013). Reliable supply being access without outages of more than 2 hours in the past week (WHO, 2015a).

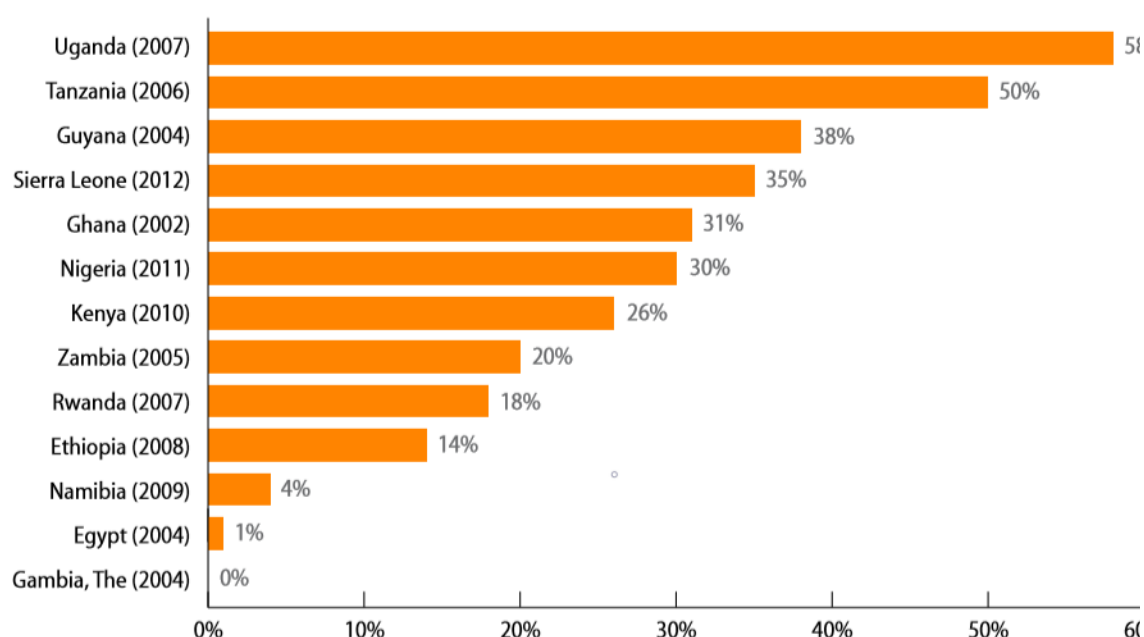


Figure 2-1: Health facilities with zero electricity access. Source: WHO (2015a) and Adair-rohani et al. (2013)

The need for wider coverage, improved quality and frequency of collection of data on the subject of electricity access for health facilities in developing countries is important (Suhlrie et al., 2018; Welland, 2017; WHO, 2015a; Adair-Rohani et al., 2013; Dalglish et al., 2013). To this end, the US Agency for International Development (USAID) created the Service Provision Assessments (SPA). The WHO also developed the Service Availability and Readiness Assessment (SARA) tool to measure infrastructure and equipment availability in health facilities. SARA is utilised in this study to classify energy use applications. To increase energy access, by improving energy efficiency and increasing the use of renewable energy, the Sustainable Energy for All (SEforAll) initiative was launched by former United Nations (UN) Secretary-General, Ban Ki-moon (Suhlrie et al., 2018). This

study focuses on improving electricity access in health facilities using renewable energy.

2.4 Nigerian Healthcare System

The Nigerian healthcare system is organised into primary (primary health centres and posts), secondary (state general and private hospitals) and tertiary (teaching and specialist hospitals) levels of health facilities (Home Office, 2018; Welcome, 2011). The Federal Government's responsibilities include development of health policies, regulation and healthcare provision at the tertiary level. The State and Local Governments are responsible for provision and management of healthcare at the secondary and primary levels.

It is very difficult to present an accurate figure of the number of health facilities in Nigeria due to a lack of structured documentation and data collection (Omoluabi, 2014). A 2015 study by the Embassy of the Netherlands in Nigeria puts the number of hospitals in Nigeria at 24,000. A report by the US Department of Commerce, International Trade Administration states that, in 2014, there were around 3,534 hospitals in Nigeria. Of these, 950 were public sector managed.

However, figures in Welcome (2011) show that there are 20,278 primary health centres and posts, 33,303 general hospitals (secondary) and 59 teaching hospitals and federal medical centres. Further down the years, the 2005 Federal Ministry of Health (FMOH)'s census estimated a total of 23,640 health facilities. 85.8% (20,283) of these are primary healthcare facilities, 14% (3,309) secondary and 0.2% (47) tertiary. There are approximately 9,000 private health facilities, including 2,600 private hospitals. These private facilities provide at least 70% of healthcare facilities in Nigeria (Home Office, 2018; ITA, 2017).

In 2014, Nigeria had approximately 134,00 hospital bed, equating to 0.8 per thousand populations³. This is seen as well below the rate for the region in Africa.

³ Compare with 2.2 beds per '000 population in Brazil (2014), 4.2 China (2012), 8.3 Germany (2013), 0.9 Ghana (2011), 0.7 India (2011), 8.2 Russia (2013), 2.8 South Africa (2005), 2.8 United Kingdom (2013) (Source: The World Bank, 2015a)

Although the number of hospital bed has grown at a compound annual growth rate (CAGR) of 3.8% since 2009, a slightly higher rate than population growth, the improvement is insufficient to significantly improve the population to bed ratio (ITA, 2017). The estimated CAGR of the number of doctors in Nigeria is 2.7% from 2009 to reach 66,555 in 2014 (Home Office, 2018; ITA, 2017). However, Nigeria's stock of practicing doctors is approximately only 35% of the official figures because official statistics were never updated since 1963 (Omoluabi, 2014). Omoluabi (2014) estimates that Nigeria's ratio of physician to 1000 population is 0.17, one of the lowest in Africa. This is partly due to the migration of healthcare personnel to other countries in search of higher pay, and better working and living conditions (Innocent, Uche and Uche, 2014).

There is a disproportionate distribution of healthcare practitioners in Nigeria. The North East, with 14% of Nigeria's population, has just 4% of the nation's doctors. Whereas, the South West, with 20% of the population, has 43.9% of practicing doctors. Furthermore, the North West, with a higher population than the South West region, has only 20% of the country's physicians (Omoluabi, 2014). This unequal distribution of health practitioners is also evident between rural and urban areas. Most of Nigeria's population (55%) are based in rural areas but medical practitioners are concentrated in secondary and tertiary hospitals situated in the urban areas (Home Office, 2018).

Provision of healthcare in Nigeria is deeply fragmented, characterised by a very small fraction of services coming from an integrated and organised centre (Innocent, Uche and Uche, 2014). Although there is a referral system in place between the three levels of healthcare, it is not always respected (Home Office, 2018). Complaints that can be managed at the primary level are often dealt with at the tertiary level because of weakness at the other levels occasioned by inadequate personnel and infrastructure such as electricity and clean water.

In Nwakeze and Kandala (2011), the authors noted that the lack of basic infrastructure such as an inefficient transport system (particularly with poor road network), erratic power supply, inadequate water supply, obsolete medical equipment, weak legal and regulatory framework are some of the factors limiting access to health care in Nigeria. Basic health indicators such as infant and

maternal mortality rates are very poor. There were 65 infant mortality per 1,000 live births in 2017 and 814 maternal mortality per 100,000 live births in 2015 (The World Bank, 2018b). Although there are many factors contributing to poor healthcare access and provision in Nigeria, this study is focussed on the provision of reliable and sustainable power supply for health facilities.

2.5 Effects of Unreliable Power Supply on Nigeria's Health Services

Effective healthcare delivery is a desirable and crucial social service. However, the delivery of satisfactory healthcare is heavily reliant on reliable and adequate power supply (Adair-rohani et al., 2013; Mcguire, 2015; WHO, 2015a). The issue of chronic power shortage in Nigeria is well-covered in literature (Ikhisemojie, 2016). In many parts of Nigeria, grid power supply is unreliable and frequently unavailable especially in rural areas (Nwanya, Sam-Amobi and Ekechukwu, 2016).

Consequently, most hospitals in Nigeria depend on alternative petrol or diesel-powered generating sets (Odiawa, 2017a). Hence, a significant portion of the operating costs of these facilities and patient bills is related to power generation. The realisation of effective critical healthcare delivery in hospitals, especially those in rural areas, is therefore adversely affected (Nwanya, Sam-Amobi and Ekechukwu, 2016). There are instances of surgical operations carried out under smartphone camera flashlights because the backup generator had developed a fault (Odiawa, 2017a; UNDP, 2015).

Hospitals in major cities like the Federal Capital Territory (FCT) Abuja are not spared either. For example, an investigation of the New Township Health Centre in Abaji, Abuja, noted that the lack of steady power supply has affected services adversely and discouraged patients' attendance (Owoseye, 2018). A technician in the hospital stated that, on days when there is power supply, the facility enjoys a maximum of four hours of electricity a day. Although relatively well-equipped, the hospital is unable to provide crucial services run round the clock due to lack of uninterrupted power supply. Every member of staff would normally have a personal torchlight to attend to patients at night for services such as child births.

Sometimes, staff at the hospital would pull funds together to fuel the backup generator to pump water and run test during weekends (Owoseye, 2018).

Nevertheless, renewable energy systems have become increasingly attractive viable alternative power sources for primary health facilities (Nwanya, Sam-Amobi and Ekechukwu, 2016; Odiawa, 2017b; Owoseye, 2018). With intervention from international donor and funding organisations, the provision of healthcare by many rural or primary facilities has been enhanced (UNDP, 2015). For example, through the Energy Efficiency Programme by the United Nations Development Programme Global Environment Facility (GEF-UNDP), a stand-alone PV station was installed in the Cottage Hospital in Uke Community, Karu Local Government Area of Nasarawa State (UNDP, 2015).

In large Nigerian health facilities such as, secondary and tertiary hospitals, the commonly adopted alternative to the poor central grid is the use of diesel or petrol-fuelled generators (Ikhisemojie, 2016; Odiawa, 2017b). The burning of fossil fuels in hospital environments tends to exacerbate pre-existing conditions and contribute to the onset of new ones. Toxic fumes from the ICE engines contribute significantly to air pollution resulting in inflammation of the conjunctiva, sinusitis, asthma and the introduction of lead into the body of humans and animals (Ikhisemojie, 2016).

Although battery-assisted devices and solar power are increasingly deployed in primary health facilities, the scale of deployment of alternative energy sources in Nigerian hospitals is too small to power an entire health facility (Odiawa, 2017b). Furthermore, the critical energy performance parameters for allocating energy to medical care and monitoring how hospitals use energy supply are non-existent (Nwanya, Sam-Amobi and Ekechukwu, 2016). This research therefore aims to provide a criticality assessment procedure fit for the purpose of allocating energy to priority services.

2.6 Classification of Health Facilities by Service Provision and Electricity Access

Classification of health facilities vary from country to country based on structure of health systems, healthcare policies and socio-economic development alignment.

Several classification frameworks exist along the lines of national and organisational standards. Some categorisations are presented in Table 2-2.

Table 2-2: Comparative categorisation of health facilities by service provision

Categorisation by a national healthcare system		Categorisation by selected organisations		
Kenya	Nigeria	USAID Powering Health	EC ENABLE Project	WHO
Hospitals	Tertiary hospitals	Category III health clinics (antiretroviral treatment clinics)	Provincial/ general hospitals	Regional/ provincial hospitals
Health centres	Secondary hospitals	Category II health clinic (blood banks, pharmacies)	District hospitals	District hospitals
Primary care facilities including: • Maternity clinics • Dispensaries	Primary (Community) health centres	Category I health clinic (health posts, blood banks, pharmacies, standalone labs)	Subdistrict/cottage hospitals	Health centres
-	-	-	Health centres	Health posts
(USAID/Measure Health, 2010)	(Welcome, 2011)	(USAID, 2013)	(European Commission, 2006)	(WHO, 2015a)

Although there are common measures of level of care between the categorisations, the examples presented above exemplify the intricacy of developing a universal standard. The Nigerian categorisation considered in this study is also presented in the problem tree in Figure 1-4.

The health facility used in assessing energy demand in this study is in the Nigerian secondary hospital category. This is the equivalent of WHO's district hospital and USAID's category II health clinic. District health centres normally offer a broader range of services to larger populations than health posts or clinics. They provide more patient beds and more advanced health care such as accident response, diagnosis and treatment of infectious diseases and complex obstetric procedures (WHO, 2015a).

Category II health clinics require between 10 to 20 kWh/day of electrical energy. They contain approximately 60 to 120 beds and run all the equipment found in category I facilities such as:

- Lighting for the facility
- Running one or more refrigerators to maintain the cold chain for medical supplies such as blood and vaccines
- Basic lab equipment including a centrifuge, microscope, haematology mixer and incubator.

In addition, category II facilities accommodate communication and IT devices, more sophisticated diagnostic facilities, and have separate refrigerators for food storage and cold chain (USAID, 2013).

Categorising hospitals by electricity access involves using a multi-tier framework proposed by the World Health Organisation. In the framework, as the tiers increase, the level of electricity supply improves across nine attributes indicating progressive ability to provide medical services in a reliable, affordable and sustainable manner (WHO, 2015a). Provided that the electricity systems are functioning, and fuel is available for generators, the combined power supplies from both primary and secondary sources are considered when determining these attributes as shown in Table 2-3.

The World Bank (2015a) estimates Nigeria's grid availability at 50%, that is, an average availability of 12 hours daily. The tier 3 facility with intermediate access and duration of supply greater than or equal to 8 hours per day, but less than 16 hours, is comparable. Therefore, the tier 3 secondary hospital in Nigeria is used for the case study facility in this research.

Table 2-3: WHO's multi-tier measurement of electricity supply in primary and secondary health facilities. Source: WHO (2015a)

Attributes	Tier 0 No access	Tier 1 Minimal access	Tier 2 Basic access	Tier 3 ⁴ Intermediate access	Tier 4 Advanced access	Tier 5 Full Access
Peak power capacity Watts (W)	<5	5–69	70–199	200–1999	2000–9999	≥10000
Daily energy capacity Watt hours [Wh] per day	-	20–279 Wh per day	280–1599 Wh per day	1600–31 999 Wh per day	32–220 kWh per day	>220 kWh per day
Duration of supply Hours per day	-	≥4	≥4	≥8	≥16	≥23
Evening peak hours supply Hours per day	–	–	≥2	≥2	4	4
Cost-effectiveness (affordability)* Lifetime costs per kilowatt hour	–	≤ 5 times benchmark	≤ 3 times benchmark	≤ 2 times benchmark	≤ 1.5 times benchmark	≤ 1 times benchmark
Quality No/poor/unstable voltage	–	–	–	Adequate	Adequate	Adequate
Reliability No outages of more than 2 hours in the past week	–	–	–	-	Adequate	Adequate
Operational sustainability Adequate operation and maintenance budget) [#]	–	–	–	Adequate	Adequate	Adequate
Environmental sustainability and health (g CO ₂ -eq /kWh) ⁵	–	≤2400 g CO ₂ -eq /kWh	≤1400 g CO ₂ -eq /kWh	≤1000 g CO ₂ -eq /kWh	≤850 g CO ₂ -eq /kWh	≤500 g CO ₂ -eq /kWh

* The grid tariff applicable to health clinics located in the nearest electrified area is taken as a benchmark for affordability

[#] Electricity is not vulnerable to interruption because of unpaid utility bills and/or lack of budget for fuel purchases; maintenance; lack of spare parts or (PV) battery replacement

⁴ Tier 3 or Category II (USAID) or Secondary hospital (Nigeria) is selected for this study.

⁵ g CO₂-eq /kWh: These thresholds refer approximately to mean emissions factors of oil-based and renewable power generation technologies in WHO (2015a)

One of the key limitations of the multi-tiered measurement framework is its focus on tracing energy access primarily from the supply side and less on the demand side of access. It allocates the attributes of electricity supply required but overlooks the energy requirements of necessary healthcare services. Indeed, this gap is common among current frameworks employed in selecting power supply systems (see Section 3.2 Conceptual Framework). Although useful for guiding regional or national assessments and investment in power systems, the multi-tiered framework does not provide an approach for determining an absolute minimum energy demand for any given level of health facility to provide its most basic functions.

This research aims to bridge this gap by employing a health risk assessment tool (HFMEA) to determine two tiers or levels of equipment (conventional and energy saving) and service (overall and critical) energy demand profiles. These result in four energy demand profiles for: 1) conventional equipment for total service availability (maximum energy demand scenario); 2) energy-efficient equipment for total service availability; 3) conventional equipment for critical services only; and 4) energy-efficient equipment for critical services only (minimum demand scenario).

2.7 Effects of Unreliable Power Supply on Health Services and Health

Access to electricity, including a reliable supply, is important as a crucial enabler for the delivery of modern health services. Lighting is important for night-time emergency care and other critical services like child and maternal healthcare. The procedures for these services become dangerous under poor lighting conditions afforded by candles or kerosene lanterns at night when there is no electricity (Adair-Rohani et al., 2013; Lim et al., 2012). Yet, electricity supply is often unavailable, limited and unreliable especially in lower level health facilities in developing nations (Dalglish et al., 2013).

Refrigeration is also an electricity-dependent application required for the preservation of blood, vaccines and medicines in health facilities. Disruption in power supply introduces flaws into the cold chain resulting in vaccine spoilage (Olatomiwa et al., 2016). This has been identified as a key issue and a major source of setback to the full implementation of the Global Immunisation Vision and Strategy (Kamara et al., 2013).

Energy poverty has also been shown to be responsible for high incidence of surgical site infections in developing countries which, is nine times higher than in developed nations (Chaparro, 2016). Modern healthcare devices such as x-ray scanners, heart monitors, and laboratory equipment require electricity to function. Meaning that, the estimated 1 billion people in the world served by health facilities with poor or no electricity (WHO, 2017a) have limited or no access to modern healthcare. Where there is access to electricity, unreliable supply causes interruptions, and sometimes damages, in the use of essential diagnostic and medical devices.

Facilities with electricity access have been found to be more attractive for the employment and retention of skilled health workers (WHO, 2015a). Poor electricity access is shown to strongly correlate with absenteeism among healthcare employees (Babinard and Robert, 2006). Modern health services such as mobile and tele-healthcare are also enabled through electricity access including the facilitation of public health education and orientation (Chaparro, 2016).

(a)



(b)



Figure 2-2: (a) Open fire autoclaving using firewood in a health facility in Malawi (Mwachumu, 2017); (b) Hospital staff cooking over wood fire in Ethiopia (WHO, 2015a)

Furthermore, regular access to clean energy such as electricity has broader impacts on human health. WHO (2018) estimates that 3 billion people still cook using open fires and inefficient stoves that utilise solid fuels and kerosene. These cooking practices generate high levels of household air pollution such as particulate soot that can penetrate deep into human lungs. Women and children are particularly prone to exposure because they spend the most time undertaking household chores (WHO, 2018). As illustrated in Figure 2-2, many cooking activities and heating applications in health facilities in developing countries are dependent on these practices with severe consequences for patients and staff.

Reliable supply of electricity reduces the use of these traditional fuels for cooking and lighting (WHO, 2014b, 2017a). However, long periods of power outages, which are widespread in developing countries, force people to use alternative energy sources which expose them to dangerous pollutants. 3.8 million people die prematurely every year due to illnesses linked to household air pollution produced by the inefficient use of conventional fuels for cooking (WHO, 2018).

Figure 2-3 illustrates the differences in national populations that are reliant on clean energy fuels. The effect of exposure to pollutant air emissions from the burning of unclean fuels domestically and unregulated fossil fuel use can be associated with high

mortality rates in countries with low reliance on clean fuels and poor emissions control and regulation (WHO, 2017a). Although evidence suggests that Russia uses fuels cleanly in domestic settings, it has a high mortality rate related to air pollution mainly because of loose control over combustion of fossil fuels.

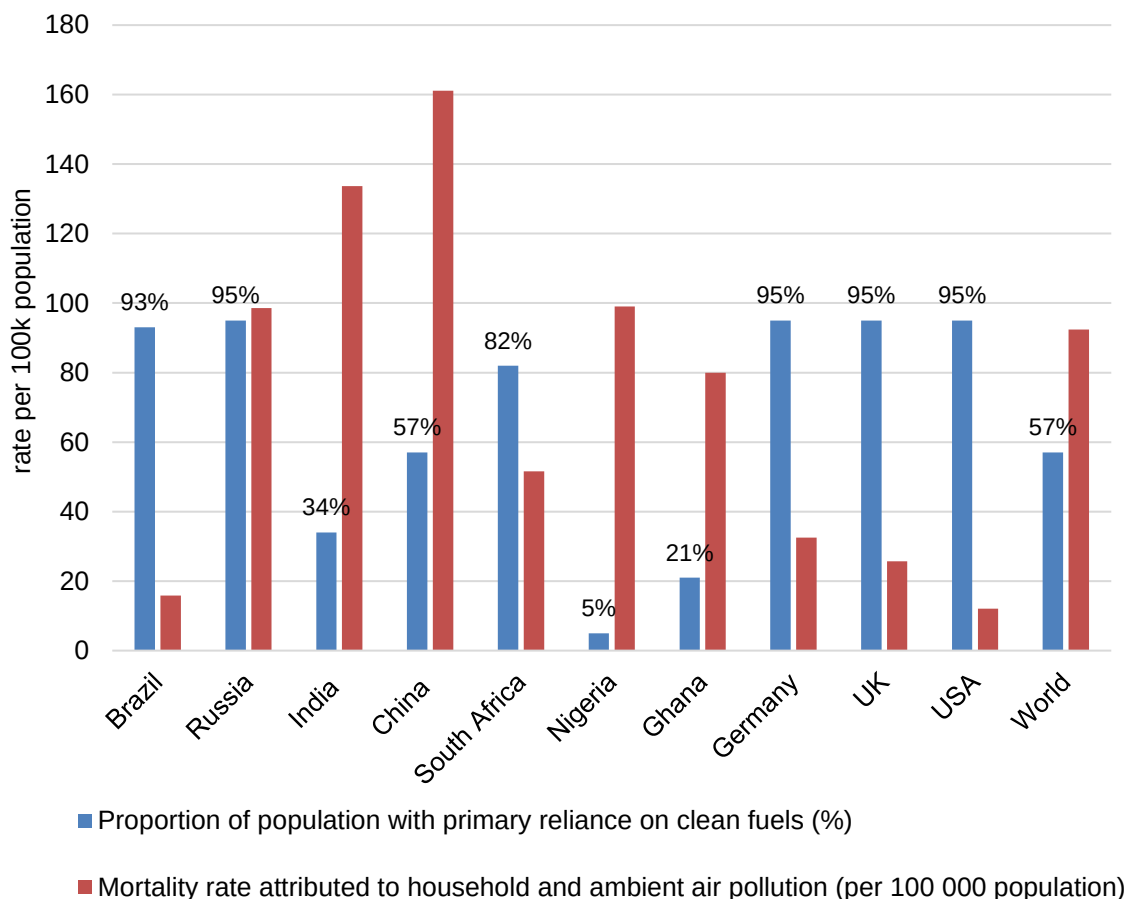


Figure 2-3: National reliance on clean fuels vs. mortality due to household and ambient air pollution. Source: Researcher's elaboration of data from WHO (2017)

Nigeria has a particularly low proportion of citizens (5%) using clean fuels as primary source of energy. Out of this figure, 27% die from pneumonia and 18% from stroke. 27% deaths are due to ischemic heart disease, a condition characterised by narrowed heart arteries starving the heart muscle of blood and oxygen. Chronic obstructive pulmonary disease, a condition of long-term breathing problems and poor air flow, causes 20% of the premature death figure. Carcinogens from household air pollution are responsible for 8% deaths from lung cancer.

2.8 Access to Power Supply vs. Unreliable Power Supply

Health facilities situated close to an electrical grid connection are traditionally reliant on grid electricity as primary source of energy. However, power outages or fluctuations during peak service demand are a major concern even in grid-connected urban settings in developing countries (WHO, 2015a). Health facilities are then forced to choose between remaining without electricity or depend on expensive onsite generators.

In settings that are not connected to the grid, the most common source of power is a stand-alone diesel generator supported with candles, flashlights and kerosene lanterns for lighting (WHO, 2015b). However, generators are expensive to operate and maintain. High cost of fuel, its transportation and storage including unavailable maintenance locally all contribute to making generators unreliable sources of power. Less than 30% of stand-alone generators were functional in a WHO survey of six sub-Saharan African countries (WHO, 2015a).

Studies⁶ have largely focussed on energy access for off-grid settings where 1.2 billion people do not have access to electricity in developing countries. This is important and increasing numbers of rural communities are getting connected (Wolfram, 2017; Olatomiwa et al., 2016). However, there is a lot less coverage of connected settings where reliability of supply is poor (Odiawa, 2017b; Wolfram, 2017). Poor reliability does not only mean occasional flickering of light sometimes, whole communities can experience total power outages for hours and days on end in developing countries (Gertler, Lee and Mobarak, 2017).

⁶ Studies on expansion of rural energy access include: EnDev, 2018; Gertler, Lee and Mobarak, 2017; Juan Pablo, 2012; Lipscomb, Mobarak and Barham, 2013; Suhlrie et al., 2018; Taryn, 2011; Welland, 2017; Winkler et al., 2011; Wolfram, 2017

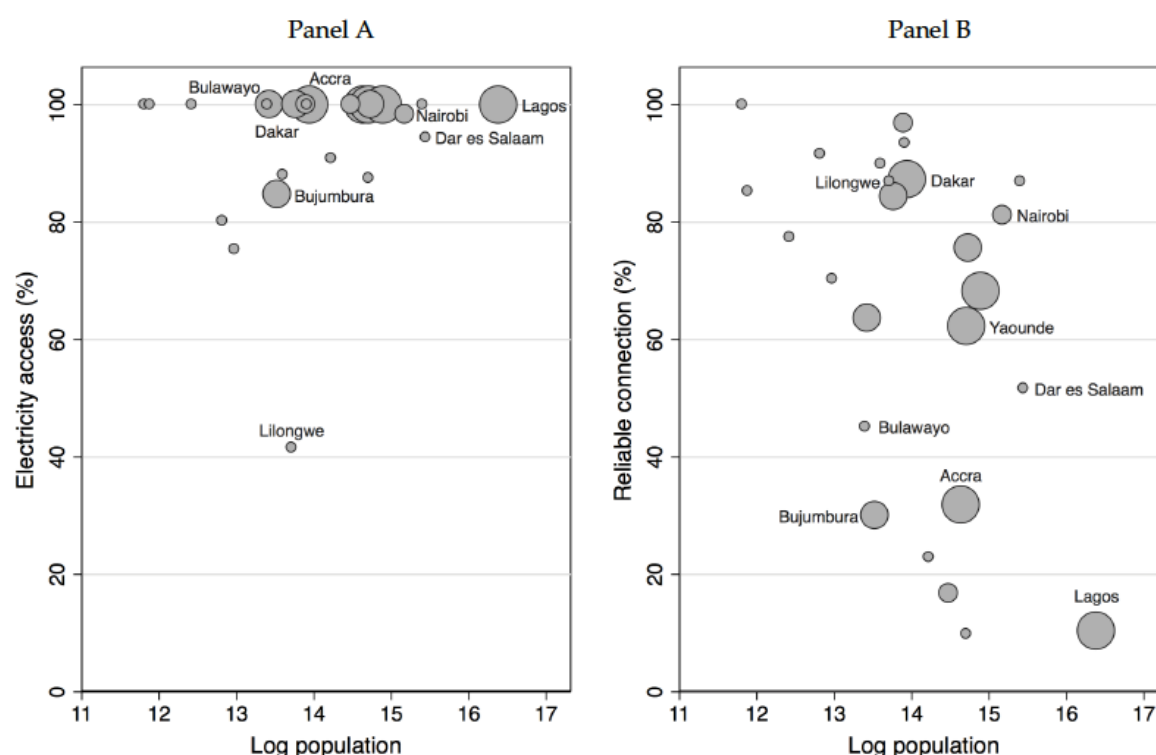


Figure 2-4: Access and reliability of access to electricity in 21 major SSA cities.

Based on Round 6 Afrobarometer data, which were collected in 2015, covering roughly 32,000 households from 21 countries in Sub-Saharan Africa.

Markers/bubbles are scaled to reflect the estimated population density for each city, based on publicly available information (Gertler, Lee and Mobarak, 2017).

Figure 2-4 summarises grid access and reliability data from 21 sub-Saharan African cities (Gertler, Lee and Mobarak, 2017). Panel A illustrates the percentage of city dwellers with access to grid electricity. Many in the cities have close to 100% access and all are above 75% except Lilongwe, the capital of Malawi. Whereas, Panel B depicts the percentage of these city dwellers who report that their grid connections work all the time or most of the time. This is less than 20% in Lagos, Nigeria's largest city of almost 20 million people.

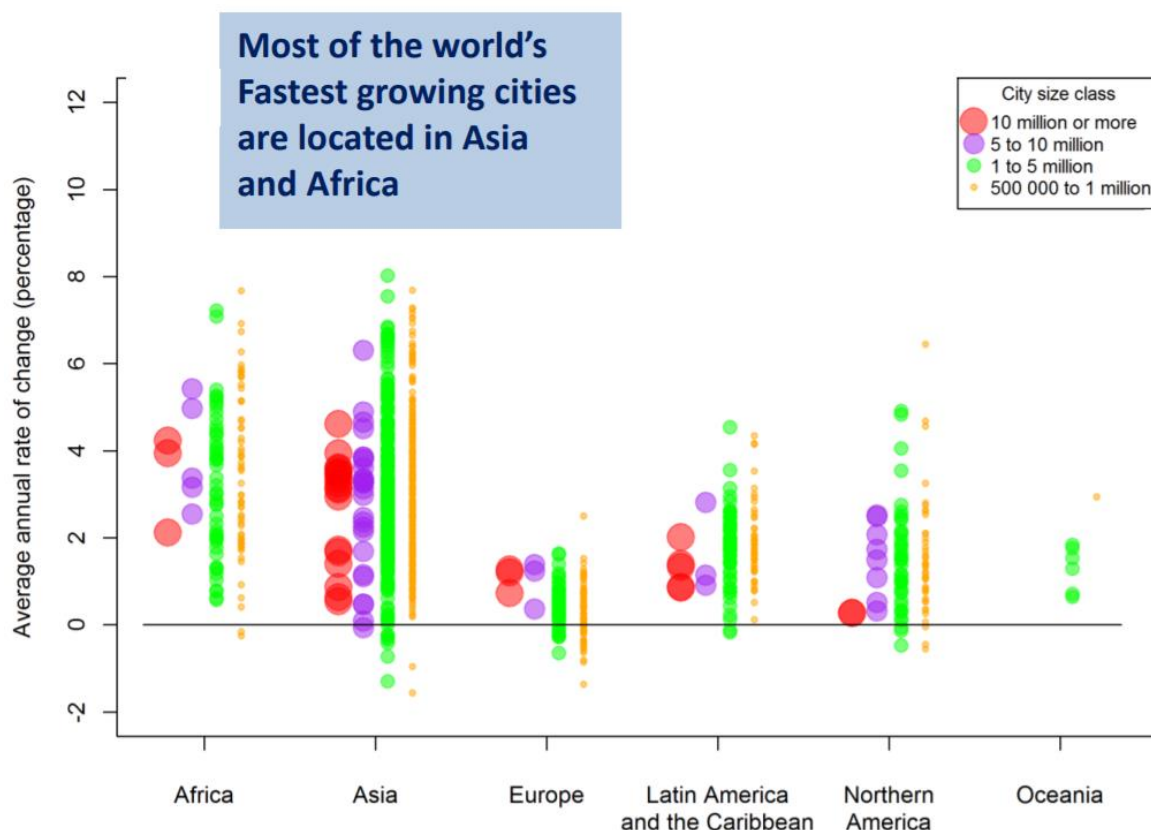


Figure 2-5: Population growth rates of the world's cities 2000 – 2016 (Henning, 2017)

Access to reliable electricity in cities is important because urbanisation is one of the starkest demographic trends in developing countries (Wolfram, 2017). Furthermore, the wellbeing of many in rural communities is tied to an urban economy with remittances from a family member who moved to the city. As illustrated in Figure 2-5, Africa and Asia have the fastest urban migration trends in the world. This means that increasing number of people are contending with unreliable supply of electricity in developing countries of these regions. Hence, the importance of reliability is especially meaningful in urban centres of developing countries where almost everyone is connected to an unreliable grid.

Therefore, this research focuses on settings that are connected to the grid but experience low measures of the required attributes of electricity supply for the smooth running of health facilities. These attributes, set out by the World Health Organisation, are necessary for effective use of electric medical equipment.

2.9 Attributes of Electricity Supply for Health Facilities

Of the nine attributes of electricity defined by WHO (2015a) and presented in Table 2-3, four are considered in this study while the others are assumed to be ideal. The variable attributes employed are described in detail below.

2.9.1 Power Quality

Power quality is generally defined as “any change in power (voltage, current, or frequency) that interferes with the normal operation of electrical equipment” (Seymour and Horsley, 2011). Power quality encompasses various definitions of power disturbances that have been standardised by the Institute of Electrical and Electronics Engineers (IEEE) to include transient disturbances, power interruptions, under-voltage, over-voltage, waveform distortion, voltage fluctuations and frequency variations (IEEE, 2009; Seymour and Horsley, 2011). The definitions and causes of power quality issues are presented in Appendix N. Unreliable power in this research is at least one or more incidents of power quality disturbances.

The proper functioning of medical equipment and services that depend on them can be interrupted or harmed by poor quality electricity. When electric voltage is inadequate, or frequency of supply is fluctuating, many AC-powered devices do not function correctly. Other power quality indicators like surges can damage or wreck medical equipment or cause serious injuries to users.

It is imperative to understand and measure these disturbances in terms of local conditions before making purchase decisions when acquiring protection devices such as surge protectors and voltage stabilisers. Interruptions, low voltage and voltage fluctuations are regarded as rife in developing countries usually because of load shedding, overloaded power systems or long-distance, low-tension cables linking remote areas. It is observed that, power quality may be adequate when voltage drops slightly or voltage fluctuations are uncommon and minor, with little or no impact on device operation (WHO, 2015a).

2.9.2 Reliability

Reliability is a function of power quality but merits separate consideration in health facility contexts. It refers to the occurrence and duration of unexpected power outages

mostly caused by grid failure or disruptions from stand-alone systems (WHO, 2015a). Typically, a health facility will have back-up generators and uninterruptible power supply (UPS) to maintain essential health services, even in developed nations. Lack of reliable power is not the same as “unreliable” power in this research. Unreliable power, as defined in the section above, refers to manifestations of power quality issues.

However, in resource-constrained environments, the cost of providing backup power for every application at the same time is usually prohibitive. Hence, backup sources are procured to support priority applications such as lighting, refrigeration and critical devices. However, no structured process of determining the prioritisation of these application has been found in literature. Therefore, one of the main objectives of this research is to employ a structured approach (the HFMEA) to prioritise applications for alternative power supply. In the results and discussions chapter, the reliability of optimised stand-alone power systems is analysed based on their reliability during long periods of power outages.

Despite the availability of backup power, reliability is considered inadequate when unscheduled interruptions in grid-based power supply are frequent and lengthy. The effects of unreliable power are particularly dire for applications such as anaesthesia machines and may cause damage to equipment and stocks of blood, vaccines and medicines. Determining the effect of an unscheduled power failure is not straightforward and can range from a minor to catastrophic event depending on the timing and length of the unexpected outage. An unexpected outage in the middle of the night when activities are at a minimum might present far less adverse effects compared with a midday power outage.

2.9.3 Affordability or Cost-competitiveness

This refers to the ability of a health care facility to bear the capital and operating cost of its power sources. The cost of power supply varies by source with grid-based supply typically the least expensive and power from stand-alone fossil fuel-based generators the most expensive due to high operating costs. Renewable sources such as wind and solar power applications can present low operating costs, but they come with significant capital outlays to start with.

Affordability in this research is benchmarked against Nigeria's electricity tariff for grid-connected health facilities of \$0.07 /kWh (Opeyemi, 2016). Systems that supply electricity at an average life-cycle cost of energy (CoE) of more than twice this benchmark (that is \$0.14 /kWh) are regarded as unaffordable for a tier 3 facility used in this study (see affordability benchmark for tier 3 facilities in Table 2-3). In addition to capital cost, the economic justification for the selection of optimised systems in Chapter 6 are based on this attribute of power supply.

2.9.4 Environmental Health and Sustainability

The provision of alternative energy supply in developing nations often requires burning fossil and traditional fuels leading to environmental pollution. Environmental damages such as air, water, soil and noise pollution arising from the combustion of fuels can aggravate and damage the health those that are in and around the health facility. This attribute is difficult to ameliorate as it involves trade-offs between providing constant power supply against protecting the health of patients, medical staff, visitors and people living near the health facility from the source of power supply.

Emissions of PM₁₀ and CO₂ per kWh of electricity generation are well-accepted indicators of health impacts and environmental sustainability of an energy system emissions. Due to increasing concerns about air pollution and climate change, particulate matter and carbon dioxide emissions are now being used as measures for assessing and selecting competing power systems in developing countries. The results of these emissions for optimised energy systems are presented and discussed in chapter 6 with the aim of helping decision makers select the most environment friendly system as stated in the research objective 3.

2.10 Factors Responsible for Low Uptake of Renewable Energy Technologies to Counter Power Supply Issues

The factors responsible for unreliable grid power supply in developing countries has been presented in Chapter 1 (see problem tree in Figure 1-4). However, investigations have shown that the potential for alternative energy sources to bridge the gap in central power supplies is huge in developing countries like Nigeria where this issues persist (RECP, 2017a; Sambo, 2009a; Watson et al., 2012; Welland, 2017). Recently, the evolution of renewable energy has met and surpassed expectations in many countries

of the world suggesting that this is a viable alternative for many developing countries. In China alone, over 190GW of renewable power capacity (excluding hydropower) has been added between 2004 and 2013 (REN21, 2014).

It is therefore important to investigate the factors responsible for the persistent energy poverty in developing countries to understand areas to prioritise interventions. A review of published texts⁷ relating to challenges in the deployment of modern energy sources in developing countries yielded similar but differently structured presentation of these issues. From an analysis of these texts, these factors have been synthesised and presented in Table 2-4. An unpublished Delphi survey of healthcare sector stakeholders in Nigeria using these factors and their indicators (see Appendix I) revealed that institutional weaknesses, corruption and vested interests under political and institutional factors are the highest ranked hinderances to successful uptake of alternative power sources. This is followed in ranking by: upfront cost of technology hardware (economic demand-side factor); political (political and institutional); techno-social practices misalignment (cultural/social); low technical capacity (technical); high cost of infrastructure (economic supply-side); political invisibility (political and institutional); O&M costs (economic-demand-side); quality & performance (technical); desirability of RETs (cultural/social); and inadequate cost recovery (economic - supply-side).

Although empirical evidence of the high impact of political and institutional hinderances is weak, all the texts reviewed corroborated the importance of overcoming political, technical and financial hurdles to successfully implement renewable power solutions in developing countries. Much cannot be done politically from an academic perspective. However, technical and financial possibilities can be explored through research. Hence, this study focuses on improving technical and economic outcomes in the exploration of competing renewable energy options. Besides the commonly explored solar and wind technologies in developing countries, a microhydro technology component called the hydrokinetic turbine is considered. The hydrokinetic turbine is regarded as low maintenance with little environmental impact (HOMER

⁷ Reviewed texts include: (Adair-Rohani et al., 2013; Bonan, Pareglio and Tavoni, 2016; Parhizi et al., 2015; Sambo, 2008; Watson et al., 2012; Welland, 2017; WHO, 2015a).

Energy, 2017). Furthermore, the modelling of hybrid DER systems in a microgrid setup is aimed at achieving the lowest costs such as life-cycle cost of energy, net present cost and capital cost.

Table 2-4: Factors responsible for low uptake of RETs in developing countries. Adapted from (Watson et al., 2012)

Type of Barrier	Description/ Category	Literature definition
Economic (demand-side)	Upfront cost	Expensive energy technology hardware as a barrier (for both standalone renewables and diesel gen-sets, and grid extension)
	Maintenance and operational costs	Characterised by high O&M costs of self-provision of electricity and grid extension. There are two arguments to consider under this barrier: i. The inability of low income users to pay for maintenance and operational costs. ii. Whereas, there is high willingness to pay for reliable electricity even in poor areas.
Economic (supply-side)	Inadequate cost recovery	There are numerous reasons for this type of barrier e.g. low population densities, distance and dispersed nature of rural populations, low load factors, and non-reflective tariff structures
	High cost of infrastructure	This barrier is linked to high upfront costs (demand-side) usually linked to lack of access to finance, low income levels of customers, inadequate levels of public capital.
Technical	Quality and performance of technological equipment	Barrier refers to quality and performance of hardware. This is common with SHSs* (low quality equipment and installations) and MFPS**. In the case of grid electricity, this refers to poor performance and unreliability of service.
	Low technical capacity to adequately maintain and operate energy systems	This barrier is referred to in many different aspects, including: low capacity of public utilities to operate and maintain power; low knowledge and skills among local technicians and end users in the case of SHSs and other decentralised energy technologies (MFPS, micro-grids); dependence on donors' technical support; stations and electric networks; and poor managerial skills to provide adequate after-sales services.

Political and Institutional factors	Political	This is referred to as a lack of political will or the presence of political interference. Also, very important is the power of voting blocs which could hamper the implementation of cost effective measures to improve access to energy.
	Institutional weaknesses, corruption and vested interests	These barriers refer to difficult-to-implement sector reforms, inadequate delivery capacity and lack of accountability of energy policy.
	Political invisibility of local population	This barrier refers to the lack of power and mechanisms to bring rural populations/farm-workers/areas unsupportive of ruling party into energy policy deliberation/implementation.
Cultural/Social	Misalignment of technological system design and social practices and users' needs	This barrier arises because energy products (technological designs) do not always cater to regional and local needs, as interventions are designed and implemented from centralised institutions.
	Desirability of energy technologies	These barriers arise from the relative desirability of energy technologies and include the status enhancing role of owning solar PV technology in rural areas and the associated problems of theft. This category also addresses whether off-grid technologies are desirable, and in what circumstances. E.g., solar PV normally provides intermittent electricity and consequently cannot fulfil users' needs or demands.
*SHS – Solar Home System **MFP – Multifunction Platforms		

2.11 Health Energy Framework for Demand and Supply Evaluation

Collaborations between energy and health sectors are necessary in overcoming barriers to alternative sources of energy provision (WHO, 2015a, 2015c). Successfully implemented partnership models in developed countries can be adapted for developing countries. These can help health facilities gain access to more reliable and cheaper energy sources. The implementation of these models can encourage potential investors to participate in these partnerships through institutional commitments from health facilities to repayment of investments (Watson et al., 2012; WHO, 2015a).

Furthermore, the use of a structured framework to evaluate health energy demand and locally available energy resources in health facilities can be attractive to serious long-term investors. The uniform application of such framework nationally can also attract foreign investment. Energy initiatives in health facilities may include identification of immediate and future energy needs and identification of off-grid and microgrid supply solutions. However, the effective provision of energy also dictates that a strong energy supply ecosystem is in place to include enabling laws, regulations, policies governance structures that allow equitable access to energy, its efficient use and effective payment systems (WHO, 2015a). On the demand-side of energy delivery, a health facility should contain an appropriate suite of medical equipment and devices including skilled staff to operate them efficiently. On the supply-side, the facility should be prepared to operate and maintain power generating infrastructure in a way that ensure their operational integrity and longevity.

Figure 2-6 is an energy results chain framework for health services developed by WHO (2015a) to demonstrate the ways by which modern health energy investments lead to improved health service outcomes. These improved outcomes can be mapped directly to the negative impacts of unreliable power supply presented in Figure 1-4. Improved power supply is not the one-stop shop panacea to poor health service delivery in developing countries. However, access to modern energy services, especially electrical medical technologies, can enhance the quality and variety of health services available.

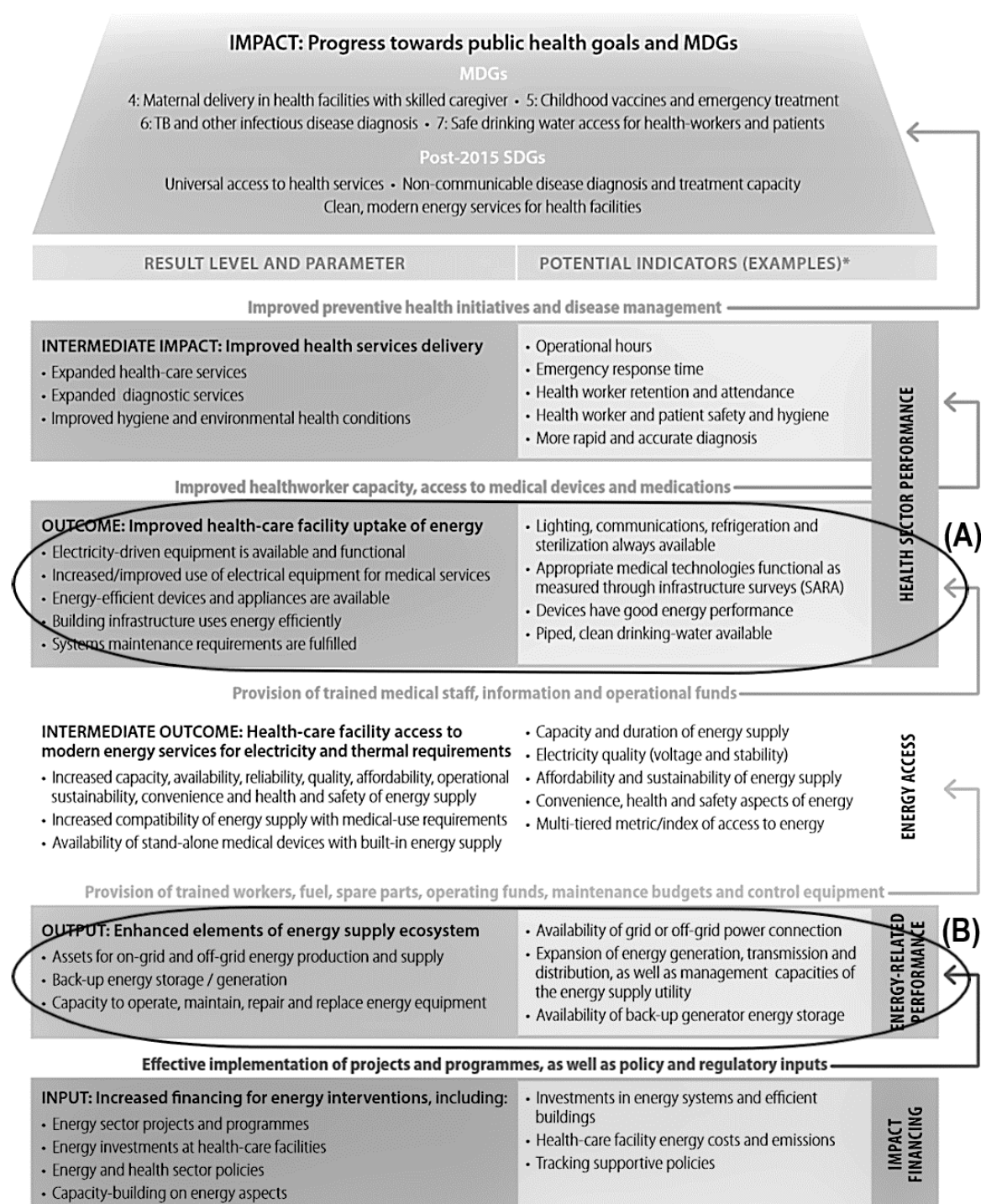


Figure 2-6: WHO's energy chain framework for health services ⁸. (A) - DSM parameters and indicators; (B) - SSM parameters and indicators. Source: WHO (2015a)

⁸ Research conceptual framework based on Sections labelled (A) and (B).

The indicators for improved health facility uptake of energy (see area circled ‘A’ in Figure 2-6) represent the foundation for defining some of the demand-side parameters considered in this research. Supply-side parameters considered are based on the enhanced-elements of energy supply ecosystem in the framework (area circle ‘B’). It is important to note that the framework lacks a definition for the health outcome indicators related to the provision of clean energy. Environmental and health sustainability of supply options are important considerations in this study. The identification of health outcomes for different supply options is an identified area for future work.

Normally, electricity supply planning should be in line with electricity requirements, both for essential building functions and medical applications. However, this is difficult because of complexities in interactions between health applications, variety in health services across countries, and differences in levels of access to medical technologies (WHO, 2015a). As pointed out in Section 2.6 above, many health energy assessment frameworks are supply-side-centric in their bid to reduce costs and improve sustainability. However, demand-side strategies such as procurement of energy-efficient devices and building, and improvement in energy user behaviours can reduce health facility energy demand considerably. This will in turn improve general energy access.

Currently, there is no universally accepted standard for determining the minimum capacity electrical system for health service provision at different levels of the health system (WHO, 2015a). Therefore, this study proposes a two-step process for determining essential loads and critical essential loads for a health facility. Each load category is also divided into two, one with conventional devices and the other with energy-efficient devices. This allows for the definition of thresholds for minimum service provision at the same time making it possible to scale distributed energy supply according to available funds.

Instead of determining essential energy requirements simply based on available suite of equipment in a facility using SARA’s compendium of health services, it may be more apt to use a focus group of local experts to determine a representative emergency treatment case for this purpose. The differences in traditional health energy

assessment process (WHO, 2015a) and the one proposed in this study are presented in Table 2-5. Apichonnabutr and Tiwary (2018) proposed stakeholder engagement survey to determine current and future load demand as an additional step to the traditional assessment methodology.

Table 2-5: Traditional vs. proposed health energy assessment methodologies

Step	Traditional energy demand assessment methodology	New proposed health energy demand assessment methodology	Step
		Establish focus group of local or regional health and facility management experts	1
		Focus group determine representative emergency case requiring highest concentration of electrical medical services	2
1	Create health facility load profile based on equipment and service availability	Create health facility load profile based on identified treatment case	3
		Determine pre-energy assessment criticalities using USAID load classification ⁹ and identify devices with DC alternatives for additional prioritisation requirements	4
2	Determine higher end and lower end load profiles representing conventional and energy-efficient medical devices	Determine higher end and lower end load profiles representing conventional and energy-efficient medical devices	5

To determine essential critical loads, it is important to go beyond the WHO's SARA framework used in identifying general health facility energy needs. The severity of the failure of essential electrical applications can be used to determine how critical an appliance is to a treatment process. Therefore, a post-energy assessment criticality

⁹ See Section 3.4.3 Classification of Treatment Equipment and Devices – SARA and USAID

analysis process is proposed to create even lower levels of energy demand based on prioritised critical applications.

2.12 Event Resilience Index

Resilience is described as the ability to “absorb, adapt to, and / or rapidly recover from a potentially disruptive event” (NIAC, 2009). It may be impossible to completely prevent disruptions to a power system, but it can be designed to withstand and recover from disruptions. Resilience is the attribute of a power system that allows some or all its electric loads to continue receiving power during an event that leads to power failure (Tam, 2016). Infrastructure resilience is the ability to reduce the magnitude, impact, or duration of a disruption (EOP, 2013). The aim of this study is to identify sustainable power generation options that can ensure the resilience of health infrastructure to continue providing critical services in the event of grid power failure. Hence, this study is more about demand-side resilience than the resilience of power supply infrastructure.

In NIAC (2009), critical infrastructure resilience is characterised by three key features. First, *robustness* refers to the ability to maintain critical operational functions during crisis. This can be embedded within building and infrastructure design or in system redundancy and substitution. Second, *resourcefulness* refers to the ability to adequately prepare for, respond to, and manage a disruption as it occurs. This can be in form of appropriate courses of action, training, operation continuity planning, and prioritising actions to minimise or control damage. Third, *rapid recovery* refers to the ability to return to normal operations in the quickest and most efficient manner possible after a crisis. Attributes include competent emergency operation, carefully designed contingency plans, and having the means to get the right people and resources to where they are needed on time.

Resourcefulness and rapid recovery attributes of infrastructure resilience may be too expensive and technical to deploy for health facilities in poor settings. Therefore, for the purpose of this research, robustness of power supply solutions to maintain critical health services is considered. To achieve this, it is important to identify minimum power requirements relative to maximum requirements when creating such power solutions.

In literatures reviewed (Aguirre and Ibikunle, 2014; Alan et al., 2015; Dalglish, Poulsen and Winch, 2013; Parhizi et al., 2015; WHO, 2017a), resilience in electricity provision is usually a supply-side technical and management consideration. However, a demand-side metric for a facility level resilience to different characteristics of power supply can be employed. Although the well-studied poor reliability of grid systems in developing countries is the main cause of the identified research problem, the resilience of facilities to this persistent issue can present a viable solution.

It is important to note that reliability is not the same as resilience. Reliability is the ability of a system to consistently provide service both in quality and quantity (Tam, 2016). A system can be reliable but not resilient to, or able to recover from, disruptions. Unreliable utility grids often lead to unreliable economic and social services. Reliability is often expressed as mean time to failure (MTTF), failure rate, or system average interruption index (SAIFI). Knowing the reliability of a grid can give the opportunity to design systems that are resilient to its outages. However, the data necessary to compute reliability metrics are not available in developing countries like Nigeria.

Therefore, the event resilience index (ERI) tool proposed in Tam (2016) is appropriate for studies in developing countries because it uses local energy demand measurements. The ERI is the ratio between electric loads served after an event and before the event. Gaining an understanding of loads that are critical to the function of a facility can help in designing low cost DER systems to increase its resilience to unexpected power outage.

2.13 Criticality Assessment for Health Application Prioritisation

The cost of providing on-site alternative energy sources to reliably power health facilities in poor environments may be prohibitive. Using USAID (2008) estimates and factoring for inflation, the cost of installation and 1-year maintenance of an alternative power system for a primary facility that requires 15kWh/day of electrical energy using a hybrid system of ICE generator and solar PV with batteries is estimated at \$45,450¹⁰.

¹⁰ Figure based on result of running a HOMER model using USAID (2008) estimates and Nigeria's inflation rate 2016/17.

This might prove too expensive for many primary and secondary healthcare facilities in less developed regions.

In addition, conflicting interests and professional narcissism may make the task of prioritising equipment for alternative power supply an arduous and complex task. Putting the patients' safety at the forefront of a facility's activities means it is important to have a pre-agreed arrangement in place for specific emergency cases. Hence, certain circumstances will arise where it will be necessary to cut power to some less-essential devices to more critical ones to operate.

For instance, it is necessary to carry out some blood tests before carrying out certain surgical operations. The operation process therefore depends on the blood testing process for success. Hence, blood testing equipment has priority over surgical devices in such cases. By using a Failure Mode Effects and Analysis (FMEA)-based risk assessment methodology called Health Failure Mode Effects and Analysis (HFMEA), it is possible to identify and highlight critical processes and accompanying equipment for prioritisation in specific cases.

2.13.1 Justification of Criticality Assessment

Healthcare is expected to bring benefits to patients and their loved ones, however it can put patients, relatives and even staff at risk of adverse events and human errors (Kaafarani et al., 2009). In healthcare facilities, the emergency ward is often the most complex and susceptible to medical errors (NHS Estates, 2013). The conditions in emergency wards dictate that there is little time for critical decision making consequently leading to higher probabilities for adverse events.

In New Zealand, a developed country with an average 99.98% electricity supply reliability (Orion, 2017), traumatic events in about 10% of surgery patients happen in the emergency ward. Although these are not entirely due to power supply issues, it is easy to visualise the health and healthcare impacts of unreliable power on treatment processes in places like Nigeria where reliability is often lower than 50% (The World Bank, 2016).

There is paucity of structured information on the direct effects of power reliability (or unreliability) on treatment processes using electrical equipment. Most literature

reviewed relating to this tend to focus on the effect of power outages on healthcare due to extreme events. The impact of unreliable power on healthcare is highly varied and far reaching (Klinger et al., 2014). However, understanding and ameliorating the direct effects on emergency treatments is crucial to reduce the risk of mortality (ACEM, 2014). This will help in developing structured plans to prevent the failure of the most critical treatment processes that use electrical equipment.

The adverse effects of unreliable power can be reduced by making electricity supply and distribution systems as resilient as possible using redundancy, reconfigurability and robustness measure (Department of Health, 2014). However, poorer countries can less afford such measures. Therefore, prioritisation of critical services and processes using risk prioritisation techniques can become an effective measure.

2.13.2 Health Failure Mode Effects and Analysis (HFMEA)

Prevention of errors in treatment processes is a basic function of improvements in quality of healthcare. HFMEA is one of the most reliable, proactive and systematic approaches to identify and avoid the potential errors before they occur which is specially designed for treatment and healthcare organisations (Cheng et al., 2012; Ibrahimipour et al., 2014). Prioritisation, a key objective of this research, is a major element of most risk assessment approaches (DeRosier et al., 2002). The HFMEA approach is good for identification and prioritisation of risks to improve patient safety and reduce the potential errors of each process before they happen (Taleghani et al., 2016). Equipment prioritisation is based on the outcome of the hazard score.

2.13.3 Traditional FMEA and Origins of HFMEA

Failure Modes and Effects Analysis (FMEA) is a part of Reliability Centred Maintenance (RCM) which originates from the defence and airline industries (Braaksma et al., 2012). It is a systematic, proactive method for evaluating a process to identify where and how failure might occur. It further assesses the impact of possible failures on the process to highlight sections of the process that need intervention the most.

The Health Failure Mode and Effect Analysis was developed by the United States' Department of Veterans Affairs (VA) National Centre for Patient Safety (NCPS) as a

hybrid upgrade of the FMEA for prospective risk analysis in healthcare. HFMEA combines concepts found in FMEA and the Hazard Analysis and Criticality Control Point (HACCP) model from food safety, with tools and definitions from the VA's Root Cause Analysis (RCA) process (DeRosier et al., 2002). A five-step process, it deploys a multidisciplinary team to assess healthcare processes in a proactive manner. HFMEA was successfully rolled out throughout the VA system in 2001 (Shaqdan et al., 2014).

In clinical practice, many reporting systems focus on analysing adverse events after they have occurred while more progressive systems focus on analysing close calls (DeRosier et al., 2002; IHI, 2004). However, evidence shows that the analysis of potential failures, their causes and effects makes it possible to improve existing safety strategies in clinical practice (Veronese et al., 2015). The most advanced systems allow for proactive assessment of vulnerabilities before the occurrence of close calls.

Traditional FMEA is a qualitative method that concentrates on product manufacturing processes such as medical device production. It involves the calculation of a risk priority number (RPN) as demonstrated in Equation (2-1) (Ferencey, Staňák and Bugár, 2011). An RPN is the product of three indexes assigned to each identified failure mode: the occurrence rating (O), severity rating (S) and detectability rating (D). A ten-point scale is used to rate each index with 10 being the most frequent, most severe and least detectable failure mode respectively.

$$RPN = O \times S \times D \quad (2-1)$$

Whereas, the HFMEA team uses process flow diagramming, a hazard-scoring matrix and the HFMEA decision tree to identify and assess vulnerabilities. The HFMEA uses a four-point scale to rate severity and probability (occurrence). For severity, the scale directly represents catastrophic (4), major (3), moderate (2), and minor (1). In addition, specific operational standards are defined for each severity category. Probability ratings include: frequent (4) (several times in 1 year), occasional (3) (several times in 2 years), uncommon (2) (sometimes in 2 to 5 years), and remote (1) (5 to 30 years) (see Appendix A for full severity and probability rating scales definitions). Due to the high frequency of incidences of poor power quality in developing countries like Nigeria, it would be necessary to redefine these probability scale definitions.

In developing the HFMEA, the NCPS discovered that, while FMEA is an apt tool for the evaluation of healthcare devices, it is not conceptually ideal for assessing healthcare processes (DeRosier et al., 2002). For example, the application of the standard definition of severity to healthcare processes consistently scored a 10 because failure of such processes would likely result in patient death or injury. This highlights one of the weaknesses of the RPN approach in that it allocates equal importance weightings to occurrence, severity and detectability. Similarly, for this study, the severity rating for a no-contact device whose output is required for the execution of other processes is the highest possible, 4.

To improve the application of FMEA in healthcare, NCPS staff reviewed the seven-step HACCP management system developed by the Food Drug Administration to protect food supply from biological, chemical and physical hazards (DeRosier et al., 2002). Although HACCP employs the use of questions to investigate system vulnerabilities and decision tree to highlight critical control points, it did not have direct applicability to healthcare processes. HACCP focuses on food processing and handling and some of the investigative questions are not relatable to healthcare. In addition, the definition of critical control points in healthcare poses significant challenges. Nevertheless, the decision tree concept in HACCP is adopted in HFMEA.

Although the HFMEA is adopted in this research, the identification of critical control points is included in the analysis since process failure resulting from unreliable (unavailable or inadequate) power supply to devices is the only consideration, and failure due to human errors are excluded. A Critical Control Point (CCP) is a position or step in a process at which control can be applied to prevent or eliminate a hazard or to reduce it to an acceptable level (DeRosier et al., 2002). In this study, any point in the treatment process or sub-process where a DC powered alternative is available for a device is regarded as a CCP.

For any proactive risk assessment method, prioritisation is a major component and it is the essence of this study. That is, the method seeks to prioritise healthcare equipment for alternative power supply per its criticality to the patient's treatment outcome. Prioritisation is a major aspect of HFMEA and it originated from the RCA process developed by NCPS (Shaqdan et al., 2014). The Safety Assessment Code

(SAC) matrix is a part of RCA designed to prioritise adverse events and close calls. In other fields, the SAC matrix exists as adaptations such as Severity Assessment Code matrix, Risk Assessment Code matrix, or Safety Risk Assessment matrix.

In the Root Cause Analysis process, the severity of an event is classified as catastrophic, major, moderate or minor (Shaqdan et al., 2014). The probability of the event occurring is classified as frequent, occasional, uncommon, or remote. After the determination of the severity and probability, the SAC matrix is used to score and prioritise the event. When used in the RCA process, the matrix score ranges from 1 to 3. However, the Hazard Matrix used in HFMEA in this research uses a score range from 1 to 16 while using the same definitions and concepts. Table 2-6 shows the summary of concepts used in HFMEA and their sources while Table 2-7 shows a comparison between the steps in traditional FMEA and HFMEA.

Table 2-6: Sources of HFMEA features. Source: Researcher's elaboration of DeRosier et al. (2002) and Shaqdan et al. (2014)

Concepts employed	HFMEA	FMEA	HACCP	RCA	Comments
Team membership	✓	✓		✓	-
Diagramming process	✓	✓	✓		-
Failure mode and causes	✓	✓			-
Hazard scoring matrix	✓			✓	This replaced the RPN ($o \times s \times d$) in traditional FMEA with Hazard Score ($o \times s$)
Rating scales	✓	†	✓	✓	1 -10 rating scale for FMEA RPN 1 – 4 for severity and probability for HFMEAS
Severity and probability definitions	✓	†		✓	RPN in Traditional FMEA
Decision tree and criticality points	✓		✓		Decision tree replaced <i>detectability</i> element in FMEA's RPN
Actions and outcomes	✓	†		✓	More detailed in HFMEA using worksheet*
Responsible person and management concurrence	✓	†		✓	More detailed in HFMEA using worksheet*
†Although these components are present in FMEA, they were substantially modified in the HFMEA model					
*Worksheet example presented in Appendix B					

Table 2-7: Comparing steps in traditional FMEA and HFMEA. Source: Based on review of DeRosier et al. (2002) & VA NCPS (2015)

Steps	FMEA	HFMEA
1	Select a process to evaluate with FMEA	Select a process to evaluate with HFMEA
2	Recruit a multidisciplinary team	Recruit a multidisciplinary team
3	Have the team meet together to list all of the steps in the process	Have the team meet together to list all of the steps in the process using a flow diagram
4	Have the team list failure modes and causes	Conduct a Hazard Analysis <ul style="list-style-type: none"> A. List all possible/potential failure modes B. Determine the severity and probability of the potential failure mode (similar to step 5 in FMEA but missing <i>detectability</i>) C. Use the Decision Tree to determine if the failure mode warrants further action e.g. for hazard scores more than 8 (yes/no, non-quantitative <i>detectability</i> embedded in decision tree). D. List all the failure mode causes for each failure mode where the decision is to proceed
5	For each failure mode, have the team assign a numeric value (known as the <i>Risk</i>	Actions and Outcome Measures

	<i>Priority Number, or RPN</i>) for likelihood of occurrence, likelihood of detection, and severity	
6	Evaluate the results	Select person responsible to complete recommended actions and determine management concurrence. Record in HFMEA worksheet.
7	Use RPNs to plan improvement efforts	Follow-up on actions taken
	<ul style="list-style-type: none"> • Use FMEA to plan actions to reduce harm from failure modes • Use FMEA to evaluate the potential impact of changes under consideration • Use FMEA to monitor and track improvement over time 	<ul style="list-style-type: none"> • Follow-up to make sure the actions were implemented and on what date • Revisit probability of failure mode cause using Probability Rating table and enter new rating on HFMEA worksheet • Obtain new hazard score by multiplying severity by the probability and document on the HFMEA worksheet. The new hazard score should now be <8. If not, reconsider recommended actions.

2.13.4 Other Relevant Risk Assessment/Decision-making Analysis Tools

Besides the HFMEA, the Failure Modes, Effects and Criticality Analysis (FMECA) is a potentially relevant assessment for healthcare applications. It adds a criticality assessment to the traditional FMEA. To use FMECA, there is a need to consider the reliability or unreliability of each item (or device in this case) in the process at a given operating time (Savino, Brun and Riccio, 2011). It will involve evaluating factors, other than power availability, within individual devices that may contribute to failure and assigning severity and probability ratings to them. However, this study is not focused on the inherent reliabilities of devices used in the treatment process, it is limited to the effect of unreliable power (unavailable, intermittent or poor quality) on the success of the process.

Another relevant tool is the Multi-Criteria Decision Analysis (MCDA) in healthcare. The MCDA is used to evaluate alternatives and priorities using structured, explicit approaches to the decision making process involving multiple criteria by working with inputs from decision makers and stakeholders. Different types of decision-making applications that employ MCDA in healthcare include benefit risk analysis, shared patient clinician decision making, resource allocation, health technology assessment, portfolio decision analysis, and prioritising patients' access to services (Thokala et al., 2016).

A major drawback of MCDA is the frequent conflict between decision makers involved when prioritising what matters most between alternatives under consideration (Thokala et al., 2016). The HFMEA is more apt concerning selecting equipment to prioritise for power allocation because it includes steps that allow for cooperative evaluation and consensus regarding the effects of failure of a process or sub-process. However, in a study like this, MCDA for healthcare decision-making could be useful when making decisions relating to choosing power backups as it allows stakeholders to allocate and prioritise different criteria, such as cost, output, availability, and environmental impact, when making decisions.

2.14 Microgrids of Renewable Distributed Energy Resources and Energy Storage Systems

Trends (Figure 2-7) show that despite demand-side efficiencies, electric power consumption will continue to rise into the nearest future especially in developing countries (BP, 2017; Gillaspy, 2018). Although annual energy use in industrialised OECD countries is relatively constant, it is growing at around 5% per annum elsewhere driven by economic and population growth (Adam and McCulloch, 2018). To meet modern man's insatiable demand for electricity, analysts anticipate that dispersed or distributed energy resources (DERs) within microgrids will play a major role (Parhizi et al., 2015).

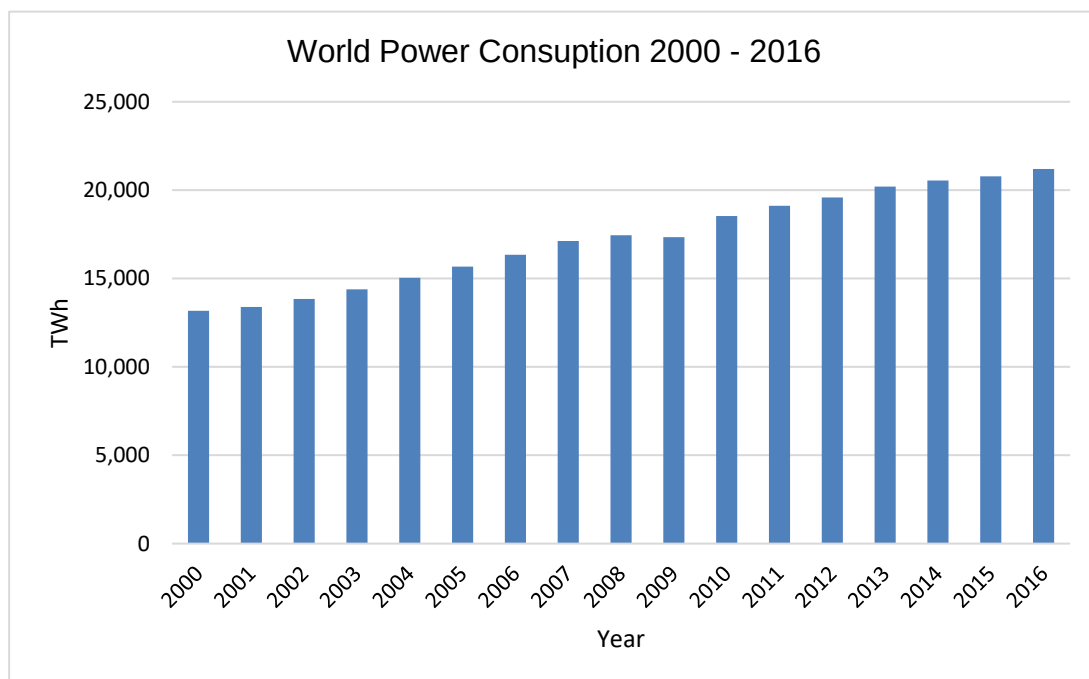


Figure 2-7: World Power Consumption Trend in Terawatt Hour 2000 – 2016.

Data source: (BP, 2011, 2017)

For developed countries, there seems to be a gradual shift in power delivery paradigm from a wasteful centralised system to a more dilute and flexible system of multiple power sources designed to meet local load requirements (Hatziargyriou et al., 2007; Levin and Thomas, 2016). Although renewable energy sources are inherently intermittent, rapid advancement in renewable energy technologies have resulted in increased reliability and lower costs.

Perhaps the most significant change in the power delivery paradigm is the combination of distributed energy resources with energy storage systems to bridge the gap in power quality and reliability requirements between traditional power systems and microgrids (Parhizi et al., 2015). Due to high capital costs, it will seem like there is little incentive for developed economies with reliable central grid to take on DERs. However, another key driver for the adoption of DERs for developed countries is the need to meet their greenhouse gas emissions targets based on progressive agreements within the United Nations Framework Convention on Climate Change (UNFCCC) (Wüstenhagen and Menichetti, 2012). Besides the above benefits of DERs, increased efficiencies from the utilisation of waste heat from the conversion of primary fuel to electricity using combined heat and power equipment also presents a major incentive for energy users (RESHospitals, 2013; WHO, 2015a).

Despite the stated benefits of microgrids, many developing countries are slow to jump on the DER bandwagon. Many sub-Saharan economies like Nigeria are still stuck in the renewable energy intermittency conundrum. The improved power quality and reliability required in critical services can be achieved by optimising DERs and ESSs in grid-connected or island-modes. A quick analysis of distributed energy resource research on Scopus, a leading source of peer-reviewed research papers, revealed only 199 published literature from 19 sub-Saharan African countries compared with the USA's 4,025 and the UK's 1,000.

There is significant opportunity for countries with ailing power infrastructures to build reliable power systems based on distributed resources rather than aiming to expand their inefficient grids (Levin and Thomas, 2016). Many developed countries are now deferring grid expansion to focus on increasing the penetration of distributed generation using microgrids to smoothen out the integration of DERs and existing power systems (Greenpeace, 2015). Furthermore, surveys show that majority of small and medium-sized enterprises in sub-Saharan Africa consider power outages as a major obstacle (Cissokho and Seck, 2013). Healthcare facilities in the region are equally affected despite the criticality of their services to patient outcomes (Adair-rohani et al., 2013b; Lawrence and Hancock, 2010; Sambo, 2008).

Many studies reveal that cost is a major limitation for widespread adoption of DERs in developing countries (Engelken et al., 2016; Gabriel, 2016; Thayer-Hart et al., 2010; Union of Concerned Scientists, 1999). However, stakeholders in these countries have not caught up with the new paradigm. This may be due to a lack of awareness of recent advances in the economics and technicalities of the field. Hence, the objective of this research to conduct a techno-economic analysis of competing DERs to gain knowledge of the financial and technical realities of deploying DERs in a developing country's healthcare setting.

The results of the minimum and maximum energy demand assessment for the entire healthcare facility is presented in Chapter 5. These form the basis for the hybrid optimisation modelling of various renewable and conventional power supply systems to investigate the most cost effective and reliable configuration. The reliability of the system is based on the ability of a facility to operate the system. This is determined by comparing the cost of failure (loss of life) for the most critical processes due to unreliable power in the facility and the cost of operating the most viable supply system. The Hybrid Optimisation of Multiple Energy Resources (HOMER) modelling software assists in determining the most viable energy system configuration by evaluating available renewable energy resources and conventional power sources.

2.14.1 Microgrids

A microgrid is a localised independent system of distributed energy resources operated in coordination with an energy storage system (ESS) and interconnected loads to achieve a specific function (Tam, 2016; Ton, 2015). It can operate in grid connected or island mode by connecting to or operating independently of the grid. Microgrids can operate while the main grid is down, hence, strengthening grid resilience and assisting in mitigating grid supply disturbances especially with respect to critical loads (Parhizi et al., 2015). Because they use local sources of energy to supply local electrical loads, microgrids help reduce energy losses attributable to transmission and distribution (see discussions in Section 2.3).

Due to their flexibility and support for an efficient electric grid, microgrids allow for the integration of increasing distributed energy resources such as wind, solar and energy storage system (ESS). This allows for hybridisation of various renewable

energy sources with the grid and fossil-fuel based alternatives to increase reliability and help reduce cost and environmental impacts of conventional power supply. Although microgrids are rapidly gaining recognition in developed economies possessing reliable grid infrastructures, the benefits of their deployment will probably be more significant in the underdeveloped world. The characteristics of microgrids make them ideal to address the supply-side issues faced in resource-constrained settings.

While affordable microgrids may not be able to provide all the energy requirements of a typical primary health facility, they can increase the resilience of unreliable power systems to support the functioning of critical equipment during disruptive events like power outages. A power system's ability to withstand disruptive events is known as its resiliency (Tam, 2016). For example, power systems in developed countries such as the United Kingdom are reliable but may not be resilient. There were instances of hours of power outages during heavy snow falls in March 2018 in London (Buck, 2018). Power systems in developing countries may not be as reliable but can be more resilient with the deployment of microgrids.

2.14.2 Distributed Energy Resources

Distributed energy resources are small-scale generation and storage units located at or near a load site (Mallikarjun and Lewis, 2014). They are organised and coordinated within a microgrid system that is either operated in connection with a central grid or in island mode to supply energy to users (Saviva Research, 2013). DER also include systems called combined heat and power (CHP) that designed to utilise waste heat from other localised power generators such as internal combustion generators, gas turbines or fuel cells (Hatzigiorgiou et al., 2007). These systems combined with solar photovoltaic (PV) units, small wind turbines, hydrokinetic turbines, inverters and converters, heat and electric storage systems and controllable loads are collectively referred to as distributed energy resources. A detailed review of DERs and current practices in microgrids including interaction issues from the combination of various DERs in a microgrid can be found in Parhizi et al. (2015).

DERs are emerging rapidly for reasons such as the rapid advancements in materials, design and engineering technologies to improve the reliability and

extend the limits of locations where DERs can be deployed. Erection of new transmission lines for traditional grids are expensive, wasteful and challenging to approve. Customer demand for a combination of reliable, sustainable and environment friendly power supply have also contributed to the acceleration of the emergence of DERs.

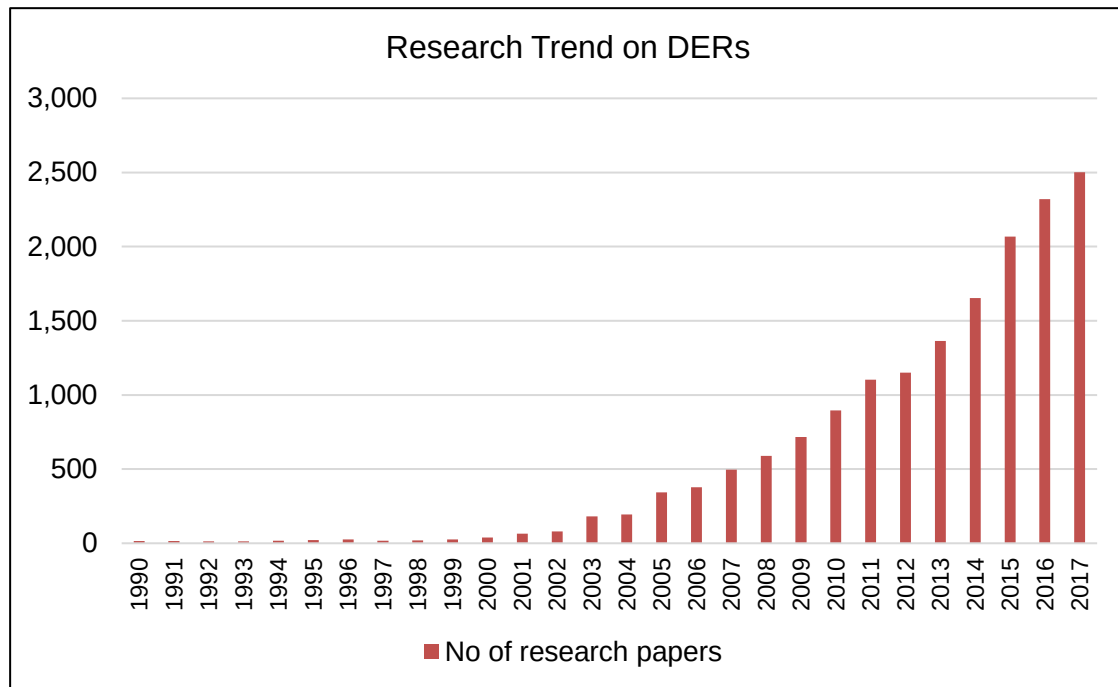


Figure 2-8: Rapid increase in DER research. Source: Researcher's review of DER literature on Scopus

The distributed energy resources selected in this study are discussed below in line with description in line with their HOMER definitions. Current costs, natural and technical factors influencing each resource are also described.

2.14.2.1 Solar Photovoltaics (PV)

Solar PV describes the process of direct conversion of solar radiation into electricity (Lo Piano and Mayumi, 2017). A PV system typically comprises of solar panels, each containing solar cells made of semiconducting material that generate electricity from sunlight. A comprehensive technical description of solar PV technology can be found in Jungbluth et al. (2012). System installations may be roof, wall or ground mounted. The mounting can either be fixed or employ a tracker to follow the sun as it moves across the sky.

As a DER, solar PV has many advantages including: no GHG emissions after installation; no operational moving parts resulting in low maintenance needs and zero noise pollution; easily scalable from wristwatches to hundreds of megawatts solar power plants; silicon, solar PV's base material, is non-toxic and the second most abundant element in the earth's crust (Jungbluth et al., 2012). However, the main drawback in PV systems is that power output is concentrated within a limited amount of hours that correspond with peak solar insolation (Lo Piano and Mayumi, 2017). Sometimes, these hours do not correspond with peak demands from human activities.

Furthermore, about 10% to 25% PV system's power output is lost if a tracking system is not incorporated (Lo Piano and Mayumi, 2017). This adds to the cost of the system. To generate the same amount of electricity with fossil-fuel based plants, a higher power capacity PV system is required due to low capacity utilisation factor of PV plants (Palmer, 2014). Obstructions in the atmosphere such as dust and clouds also affect power output (HOMER Energy, 2017). Although photovoltaics is emission free during use, critics point out that their production involves the use of energy from polluting sources. However, PVs recover the energy used to manufacture them in 1.5 and 2.5 years in southern and northern Europe respectively (Philipps and Warmuth, 2018)

Despite its disadvantages, advances in technology and increased scale of manufacture have increased the efficiency and reliability of solar PV installations while bringing down costs at the same time (Baziliana et al., 2013). In terms of installed global renewable energy capacity, solar PV is the third after wind and hydro powers with 300 GW, or 2% global electricity demand, installed at the end of 2016 (IEA, 2017).

2.14.2.1.1 Cost of PV

At the time modelling of power systems for this study began in 2016, the cost of solar PV from HOMER's inbuilt platform of PV dealers was \$3,000 per kW capacity installed. According to the UK's government official statistics, the mean cost of installation of solar PV in 2017/18 is 1.4% lower than in 2016/17 and 11.5% lower than in 2013/14.

2.14.2.1.2 Influencing Factors

Table 2-8 below highlights the factors that affect the power output of a solar photovoltaic system. The calculations of these factors are described in Chapter 5.

Table 2-8: Factors that affect solar PV power output (HOMER Energy, 2017)

Factor	Description
Ground reflectance	Fraction of solar radiation incident on the ground that is reflected, in %
Panel slope	Angle at which the panels are mounted relative to horizontal, in degrees
Panel azimuth	Direction the panels face, in degrees
Temperature coefficient of power	Number indicating how strongly the power output of a PV array depends on cell temperature, in %/°C
Nominal operating cell temperature	Cell temperature at 0.8 kW/m ² and 20°C ambient temperature, in °C
Efficiency at Standard Test Conditions (STC)	Maximum power point efficiency under standard test conditions, in %

2.14.2.2 Wind

Wind energy can be regarded as a form of solar energy. Wind is the effect of uneven heating of the earth's atmosphere by the sun, influenced by the earth's rotation and irregular surfaces (Paine, 2015). Wind power is abundant, widely distributed, renewable, clean, does not consume water, uses little land and produces zero GHG emission during operation (Fthenakis and Kim, 2009). The overall effects of wind power on the environment are less than those of traditional fossil-fuel based sources.

Energy from wind can be employed directly as mechanical power or indirectly as electrical power through the conversion of kinetic energy from wind (Kumar et al., 2016). There are two types of modern wind turbines: the vertical axis wind turbines or VAWTs; and the horizontal axis wind turbines or HAWTs. These convert the wind's kinetic energy into electricity. HAWTs are dominant in the wind industry due

to their greater efficiency and power output compared with VAWTs (Paine, 2015). HAWTs are considered in this study.

Wind power generation can be classified by location as onshore or offshore. Onshore wind turbines are installed on land and have 50 to 100 m tower heights with rotor diameters in ranging from 50 to 100 m (IPCC, 2012; Paine, 2015). On the other hand, offshore wind turbines are installed beyond the coast. The development of offshore wind farms has grown rapidly in recent years due to significant wind resources available at sea allowing for the establishment of larger wind farms utilising larger turbines than onshore farms (Kumar et al., 2016). However, only onshore wind turbines are considered in this study because they fit into the location-specific contexts employed in the research.

Key challenges with wind power include: high capital cost per MW installed; intermittency, as in other RETs, makes wind less reliable than conventional generation technologies; predictability is low for short-term operation; since wind speeds are not constant, capacity factor (ratio of actual annual production to name plate capacity) is low (15 – 50%); social and environmental challenges such as visual disturbance, noise pollution and telecommunication interference. It is important to note that recent technological improvements have gone a long way to ameliorate these issues. A comprehensive analysis of wind energy trends and technologies can be found in Kumar et al. (2016).

According to BWEA (2005), most wind turbines will start producing electricity at wind speed between 3 and 4 metres per second. They will produce their maximum rated power at about 15 m/s and generally shut down at wind speed above 25m/s to prevent damage. Nigeria has been shown to enjoy speeds of above 5 m/s in many cities especially in the northern regions (NERC, 2016; NPCN, 2010). On the other hand, RECP (2017a) claims that Nigeria's wind energy potential is modest. Nevertheless, the general trend in the design of wind turbines is to combine a higher tower with longer rotor blades in settings with lower wind potential than areas with better wind speeds (IEA, 2013).

2.14.2.2.1 Cost

A \$5,000/kW capacity installed was used at the beginning of the modelling process of this study in 2016. This was based on the combination of capital cost for a 10

kW Xzeres 442SR¹¹ small wind turbine, and transportation costs associated with the importation and moving heavy equipment across inland Nigeria. Milborrow (2018) presents the weighted average cost of installed wind power in 2017 as \$4,000/kW in the US.

2.14.2.2.2 Wind Factors

The factors that affect the level of power a wind system produces include wind speed, anemometer height and wind turbine hub height. These are discussed in detail in Chapter 4.

2.14.2.3 Micro Hydrokinetic

Hydrokinetic energy conversion systems employ electromechanical devices to convert kinetic energy of tidal currents, river streams, waves or man-made water channels into electricity without using an impoundment or special head (Yuce and Muratoglu, 2015). The two main methods of extracting energy from water are hydrostatic and hydrokinetic. The hydrostatic approach is the conventional method of creating a pressure head using reservoirs to accumulate water and employing suitable turbomachinery to convert the potential energy of released falling water to electricity (Khan, Iqbal and Quaicoe, 2008). On the other hand, the hydrokinetic method directly converts the kinetic energy in flowing water into electricity using relatively small scale turbines with little or no civil work (Kaygusuz and Guney, 2010; Riglin et al., 2016).

There are some advantages presented by hydrokinetic technologies over conventional hydroelectricity production and other RETs. Hydrokinetic systems require no additional cost of constructing a dam or reservoir to collect water. Electrical power is generated directly from the kinetic energy of moving water in form of current and waves. Furthermore, hydrokinetic turbines can be scaled as required through multi-unit array installations like solar PV arrays and wind farms.

Hydrokinetic power systems offer a good electrification choice for hydro sites with topographical, geological, technical or economic difficulties (Yuce and Muratoglu, 2015). They have minimal environmental impacts compared with dams.

¹¹ <http://www.xzeres.com/wind-turbine-products/xzeres-442sr-small-wind-turbine/>

Construction of large scale hydro dams usually require the relocation of people, methane gas emission, alteration of river features, and disruption of natural habitats and agricultural settlements. Deploying hydrokinetic turbines in remote and off-grid locations is regarded as potentially one of the cheapest and most suitable ways of supplying electricity (Kusakana and Vermaak, 2013). Hydrokinetic systems are also regarded as more reliable and predictable than wind and solar systems because river streams and tidal currents are highly predictable (Fraenkel, 2007).

Furthermore, larger amounts of energy can be harnessed using an in-river hydrokinetic turbine compared with a similarly sized wind turbine (Khan, Iqbal and Quaicoe, 2008). For example, a hydrokinetic turbine with a rated operational speed of 2-3 m/s can generate as much as four times the energy from an equally rated wind turbine (Yuce and Muratoglu, 2015). This is because the fluid densities of water and wind are approximately 1000 kg/m^3 and 1.223 kg/m^3 respectively. Hence, the power density of a hydrokinetic turbine operating under a waterflow velocity of 2 m/s is the same as that of a wind turbine under approximately 16 m/s wind speed (Twidell and Weir, 2015).

However, hydrokinetic technology has its own drawbacks when compared with other power generation technologies. The maximum efficiency that a run-of-the-river hydrokinetic turbine can attain is 59.3%, also known as the Betz limit for turbines in general. Nevertheless, high quality systems are required to achieve 50% efficiency (Yuce and Muratoglu, 2015). However, hydrokinetic turbines have relatively small scale power production. Furthermore, cavitation, the formation of water bubbles or voids when local pressure falls below vapour pressure, can cause significant damage to the turbine (Crowe et al., 2012). Harsh marine environments require strong hydrokinetic designs to withstand heavy and irregular water loads. Hydrokinetic system installations can also hinder navigation and fishing activities. Comprehensive investigation of negative environmental impacts of hydrokinetic turbines are ongoing (Yuce and Muratoglu, 2015).

The different classifications of hydrokinetic systems are presented in Figure 2-9. Most hydrokinetic turbines have a horizontal rotational axis parallel to the direction of water flow. The 20kW Guinard-P154 (Poseide 154) river and marine current

turbine used in this study's models is a horizontal axis turbine. Details of this hydrokinetic turbine are presented in Chapter 4. Further analysis of hydrokinetic technologies are presented in Kusakana and Vermaak (2013); Lago, Ponta and Chen, (2010); and Yuce and Muratoglu (2015). Experimental and numerical analysis of a run-of-the-river hydrokinetic turbine like the one used in this study are presented in Riglin et al. (2016)

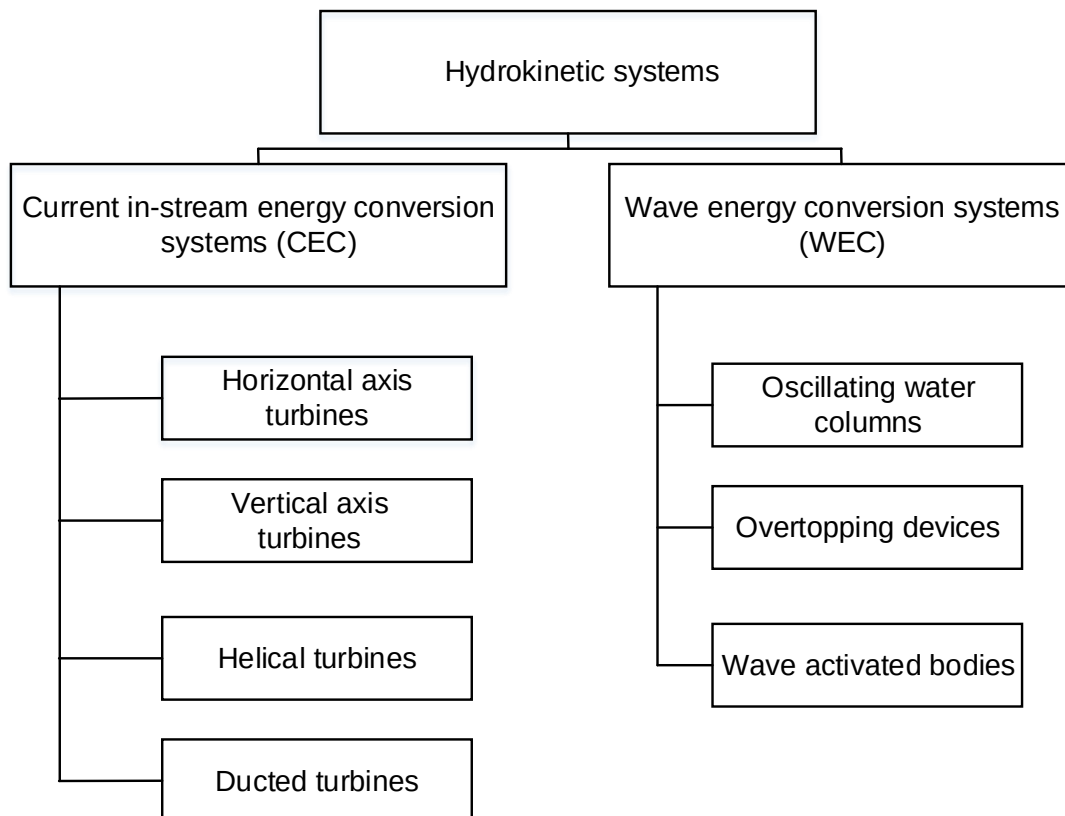


Figure 2-9: Classification of hydrokinetic systems (Yuce and Muratoglu, 2015)

2.14.2.3.1 Cost

Lako, Simbolotti and Tosato (2010) puts the cost of very small (≤ 1 MW) hydro power plants at \$2500/kW. However, based on the \$14,000 cost of the 20 kW hydrokinetic turbine used in this research, the installed cost of a micro hydrokinetic system can be as low as \$800/kW after installation costs. This shows how rapidly the cost of hydrokinetic systems have dropped in the last decade. When compared with other energy systems, hydropower usually presents the lowest cost of energy as shown in Figure 2-10. This is in addition to the technology's relatively low operation and maintenance cost (Laws and Epps, 2016).

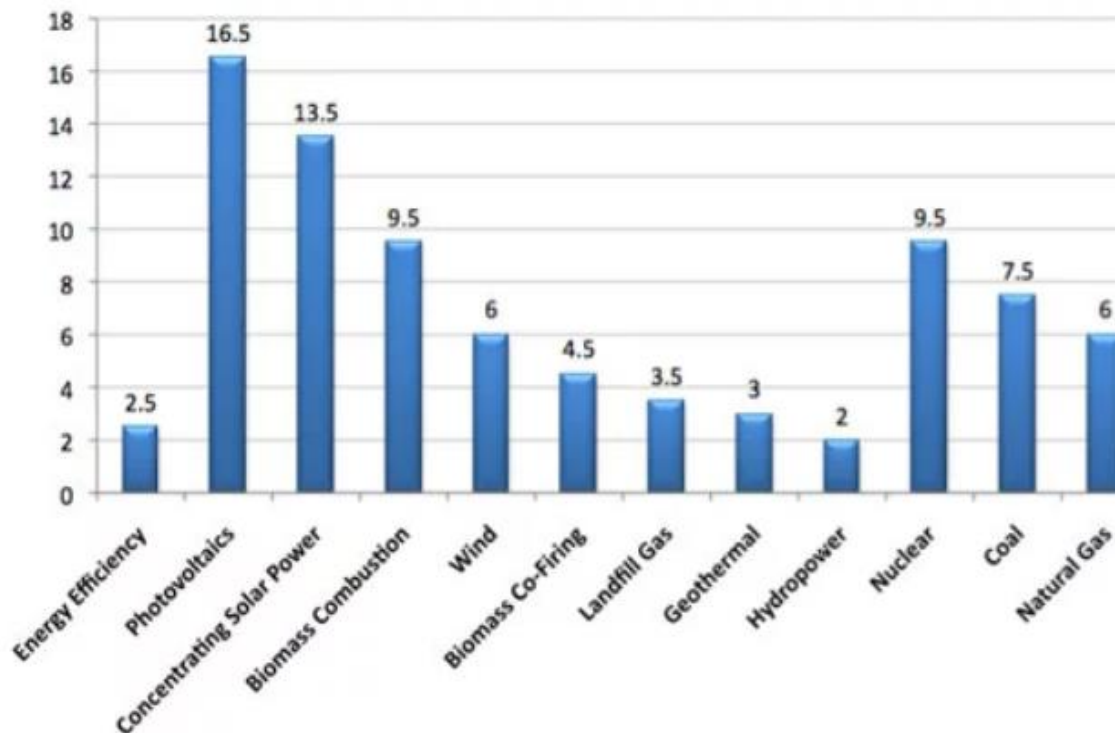


Figure 2-10: Levelised cost of electricity (¢/kWh) for different power and energy efficiency points (Meyers, 2016)

2.14.2.3.2 Influencing Factors

The key external factors that affect hydrokinetic turbine outputs are water flow speeds and water depth. For operational purposes, river flow speeds of between 0.75 m/s to 2.5 m/s and an average water depth of 2 to 3 m are suggested by Riglin et al. (2016). Nevertheless, hydrokinetic turbine manufacturers usually specify these operational parameters. The Poseide 154 requires a water depth of 3 m, minimum waterflow speed of 1 m/s to produce 0.7 kW power and 3.25 m/s to produce rated power output.

2.14.2.4 Battery Energy Storage System (ESS)

Renewable energy technologies such as solar PVs, wind turbine and hydropower are dependent on variable weather conditions leading to inherent intermittent and fluctuating features. To become more viable against conventional power systems, the variability of renewable energy needs to be smoothened out. Battery energy storage has been widely accepted as one of the viable solutions to intermittency in renewable energy supply, unreliable utility grids and fluctuating electricity

demand during the day (Guney and Tepe, 2017; Kim and Jung, 2018; Olabi, 2017; Yang et al., 2018; Zhang et al., 2018).

There is a plethora of literature on energy storage technologies. However, these technologies are at different levels of maturity with very few already proven for commercial scale deployment (Aneke and Wang, 2016). The main energy storage technologies are classified as shown in Table 2-9. The criteria for selection of energy storage technique has also been classified as: 1) available energy resources; 2) energy requirement and application; 3) energy storage efficiency; 4) energy storage cost; 5) energy storage infrastructure; and 6) other factors (Olabi, 2017).

Table 2-9: Classification of energy storage technologies (Olabi, 2017)

#	Energy storage system	Examples of devices
1	Magnetic	Superconducting magnetic energy storage
2	Electrochemical	Super-capacitors, batteries, fuel cells,
3	Hydro	Water pumps
4	Pneumatic	Air compressors
5	Mechanical	Flywheels
6	Thermal	Molten salt, water or oil heaters

The selection of battery energy storage in this study is based mainly cost and available infrastructure. Due to its application in the car and ICT industry, battery technology is far more mature than the others and is at the point where batteries can be deployed anywhere in the world with little or no maintenance requirement (Yang et al., 2018). This combination of benefits makes battery storage uniquely appropriate for applications in developing countries.

Currently, battery energy storage systems (BESS) present several advantages when compared with the other ESS. Batteries are modular in nature and can easily be sized or expanded according to changes in system loads. Other advantages include fast response capability, sustained power delivery, geographical independence and ease of integration with other energy technologies (Yang et al., 2018). Installation of battery systems are also flexible and have short construction cycles. With their increasing application across different sector apart from core

energy industry, battery ESS are experiencing rapid technical innovation (Zhang et al., 2018). The energy density, power density, efficiency and life-cycle of batteries have improved remarkably with the successful development of new batteries.

Some key disadvantages of battery ESS include: energy loss during conversion and reconversion processes; cost and complexity increases when scaling up due to addition of inverters and rectifiers or converters; there are challenges in the creation of support infrastructure and space requirements; batteries need to be replaced every few years; and environmental concerns from disposal issues in less regulated environments (Zhang et al., 2018). Furthermore, the raw materials used in making batteries are finite, although recycling techniques are proving effective in sustaining supplies (Guney and Tepe, 2017).

Table 2-10: Comparing different types of battery (Guney and Tepe, 2017)

	Lithium ion	Sodium sulphur	Lead acid	Nickel cadmium	Sodium nickel chloride
Specific energy (Wh/kg)	150–200	150–240	35–50	75	125
Cycle life	1000–10000	2500	500–1500	2500	90
Self-discharge	1%/month		2–5%/month	5–20%/month	
Charge/discharge energy efficiency	95	up to 90	80	70	90
Rated power (MW)*	< 36	< 50	< 36		
Specific power (W/kg)	200–315	90–230	75–300	150–300	130–160

*(Zhang et al., 2018)

Table 2-10 shows the comparison of different battery types. Currently, Lithium-ion batteries present the overall best attributes for the deployment of battery energy storage systems at a facility level. Lithium-ion battery storage systems also rank first in energy storage system installations around the world with 55% year-on-year

growth in installations (Guney and Tepe, 2017). Detailed analysis of battery storage techniques and their power condition can be found in (Zhang et al., 2018).

2.14.2.4.1 Cost

According to the Union of Concerned Scientists (2018), in 2010, Li-ion battery packs cost an estimated \$1000/kWh¹². They now cost approximately \$190/kWh in 2018. In Curry (2017), the cost of Li-ion is set to drop to \$74/kWh from the results of Bloomberg New Energy Finance models. In this study, the cost of battery energy storage unit used is based on HOMER's 2017 recommended figure of \$200/kWh and a replacement cost of \$160/kWh after 3 years.

2.14.2.4.2 Influencing Factors

The influencing factors of BESS are discussed in detail under Power Storage section in Chapter 5.

2.14.3 DER Modelling Software – HOMER

Hybrid Optimization of Multiple Electric Renewables (HOMER) is an energy system optimisation, sizing and modelling tool developed by the National Renewable Energy Laboratory (NREL). It simplifies the job of designing distributed energy generating systems, both off-grid and grid-connected, through sensitivity analysis, optimisation and simulation of economic, technical and natural resource variables. The modelling software includes optimisation and sensitivity analysis algorithms that allow users to evaluate the technical and economic feasibility of a large mix of technologies. It also accounts for cost of technology and energy resource availability (HOMER Energy, 2017). Comprehensive reviews of other energy modelling software can be found in Erdinc and Uzunoglu (2012) and Vaillancourt (2018).

As shown in Figure 2-11, the outer core of HOMER's capabilities is a simulation model that attempts to simulate a viable system for every possible mix of equipment a user wants to consider. Depending on how a user sets up the model and the number of equipment options, HOMER can generate thousands of

¹² Note that installed cost of batteries is in kWh compared with kW in the other microgrid components. This is because batteries do not generate electrical power, they save and dispense electrical energy.

systems. Optimisation follows the simulation of all possible systems. The systems are then filtered and arranged according to the criteria defined by the user. This allows the user to see the best solutions available. Fundamentally, HOMER is an economic optimisation tool, but a user can choose to limit pollutant emissions by minimising fuel usage. The sensitivity analysis is an optional step that allows users to simulate the impact of variables that are out of their control. For example, a user can vary the values of wind speed, interest rate and fuel cost to see how optimal systems change with the variations.

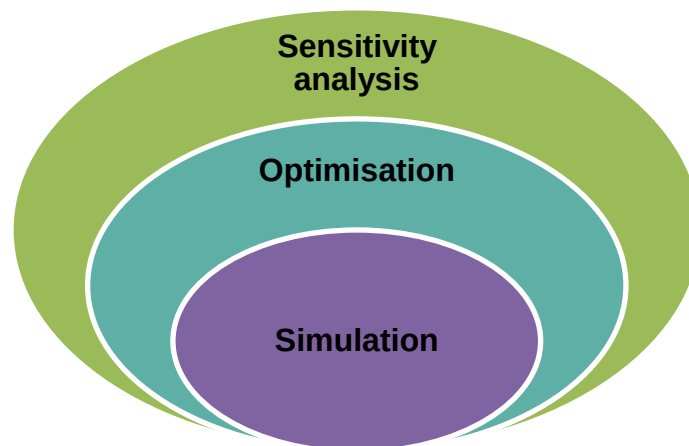


Figure 2-11: HOMER's core capabilities (HOMER Energy, 2017)

To use HOMER, the model is provided with inputs, which describe DER technology options, component costs, and resource availability. Outputs include optimal system sizing, capital costs, emission factors and cost of operation. Figure 2-12 shows the details of input and output parameters for HOMER.

The programme includes several energy component models, such as solar photovoltaics (PV), wind turbines, hydro, batteries, diesel and other fuel generators, electrolysis units, biomass power, electric utility grid, and fuel cells, and evaluates suitable options considering cost and availability of energy resources (Erdinc and Uzunoglu, 2012). Inputs such as energy resources are extrapolated from national and international databases such as NASA (solar radiation), wind speeds (national wind maps), and the US Environmental Protection Agency (emission coefficients).

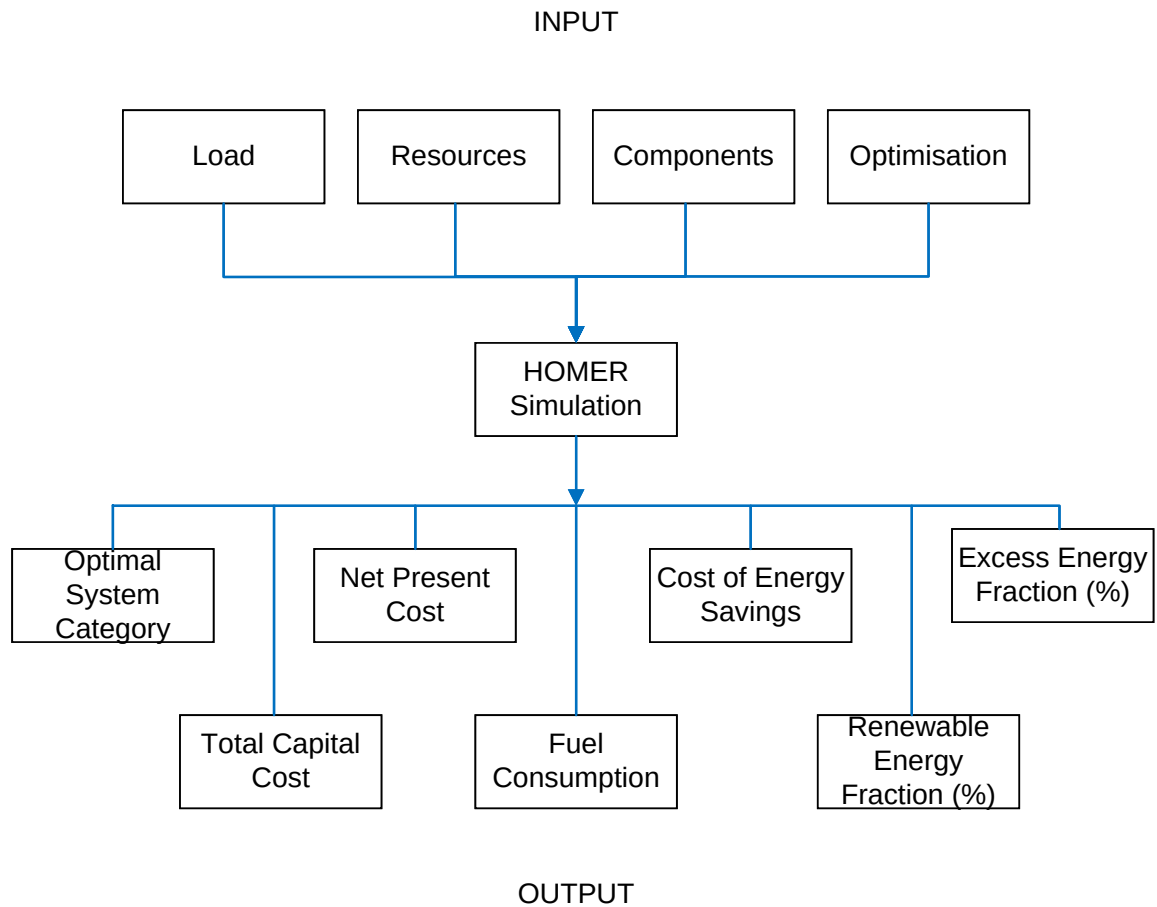


Figure 2-12: HOMER Architecture (Erdinc and Uzunoglu, 2012)

HOMER is used in this research because it presents a relatively high number and variations of renewable options alongside grid functions compared with other system planning models such as the Hybrid Power System Simulation Model (HYBRID2). Only grid-connected power systems are considered in this research since, according to Parhizi et al. (2015), power sharing in this mode results in lower energy prices and less intermittency than stand-alone operations. Furthermore, unlike other hybrid energy simulators, HOMER has two optimisation algorithms (Erdinc and Uzunoglu, 2012). The grid search algorithm simulates all the feasible system configurations defined by the Search Space (input and derived variables). The second algorithm uses a proprietary algorithm to search for the least cost system.

2.14.4 HOMER in Peer-reviewed Literature

The description of HOMER and detailed explanation of how it models various energy generation technologies are covered in Chapter 4. The Hybrid Optimisation of Multiple Energy Resources software is rapidly becoming the go-to modelling instrument for researchers and industry experts in the renewable and distributed energy resource industry. The HOMER software started off as an in-house National Renewable Energy Laboratory (NREL) tool from 2004 to 2008 before becoming mainstream in 2009. From its commercialisation in 2009, the modelling software has been used in 1,032 academic publications in Scopus, the world's largest database for peer-reviewed literature.

Some of the most prolific HOMER-friendly authors include Shaahid Syed M. (2004 – 2018) with 15 articles utilising HOMER processed models. Shaahid's articles focused mainly on techno-economic analysis of the potentials of hybrid wind, solar, diesel and battery based systems for commercial and residential loads in Saudi Arabia or hot regions in general. Kusakana Kanzumba (2008 – 2017) published 13 peer-reviewed articles employing HOMER as modelling tool. These papers explored the techno-economic feasibility of various two-component hybrid systems for off-grid rural applications mostly in South Africa and some in D. R. Congo.

Chowdhury Sunetra (2011 – 2017) conducted HOMER-based technical and economic assessments in 12 academic papers, mainly of biogas plants and PV systems in South African farms and rural communities. Saad Mehilef (2011 – 2018) co-authored 10 articles based on the performance, technical and economic assessment of PV, wind, diesel and battery hybrid power systems mainly in Malaysia and Nigeria. The HOMER models in these articles did not consider grid connected systems.

Eunil Park published 10 research articles between 2014 and 2018. These mainly explored the technical and economic implications of the installation and operation of independent and renewable electricity generation systems in different locations and special-use facilities such as stadiums and universities in South Korea. They identified with the South Korean government's green growth strategy which is encouraging increasing investments in renewable power generation. Chee Wei Tan co-authored 10 research papers from 2012 to 2018 focusing on the design

and techno-economic analysis of various combinations of PV, wind, fuel cell, tidal micro-hydro, diesel and battery systems. Tan authored publications went a step further than most of the other authors by investigating the effects of economic indicators and regulatory tariffs on the viability of the hybrid power systems.

160 other authors authored and co-authored from 7 to 1 peer-reviewed research papers using HOMER as simulation software. This highlights the significant role HOMER is playing in the current drive for a global shift from conventional grid-based power supply systems to more distributed and independent power supply systems.

However, none of these peer-reviewed papers explored a combination of wind, solar, microhydro, diesel and battery technologies in combination with grid power for varying levels of critical energy demand applications in the different regions of Nigeria. Olatomiwa et al. (2016) explored the hybridisation of PV-wind-diesel systems with battery configurations for rural health clinics in different regions of Nigeria. Their results showed that there is considerable solar potential throughout Nigeria, and wind in only a few areas. However, they did not include the national grid and hydrokinetic turbines in their systems. Furthermore, they did not explore different energy demand scenarios to provide less expensive alternatives to providing power for the entire health facility.

Few of the other studies investigated optimal systems for different regions of a country while exploring the effects of changes in economic and regulatory conditions. In addition, most of the studies focused on the general principle of reducing the carbon footprint of conventional power generation systems. Few addressed the possibility of using DERs as power supply solutions to unreliable grids for critical infrastructure.

2.15 Nigerian Case Study Cities

To simulate hybrid distributed energy systems, it is necessary to specify a context because different environments will usually present varied resource potentials. This research focuses on developing countries, and Nigeria, with six geopolitical regions, is selected as focus for investigation. Nigeria is known to have vast renewable energy resource potential, ranging from solar, wind, biomass to

hydropower (Olatomiwa et al., 2016; Ohunakina et al., 2014; Sambo, 2009a, 2009b). However, most of Nigeria's hydropower potential published relates to large hydro. Microhydro potential will be explored in this study.

Furthermore, the investigation of renewable energy's potential to provide quality and reliable electricity in Nigeria is largely for unconnected rural areas (Olatomiwa et al., 2016). This research aims to investigate solar, wind and microhydro potential in grid connected cities with unreliable supply. RE potential for health applications in Nigeria has received even less attention. Olatomiwa et al. (2016) investigated solar and wind power generation in PV-wind-diesel-battery systems for unconnected primary health facilities in rural Nigeria. They identified that southern Nigeria had poor to moderate wind speeds ranging from 2.12 to 4.13 m/s. Coastal areas of southern Nigeria and northern parts of Nigeria presented viable wind speeds of 4.0 to 8.60 m/s.

Review of six state capital cities from Nigeria's six geopolitical regions explored in this study are presented below. Each city is the capital city of a state from each region, containing some of the largest population densities experiencing unreliable power supply from Nigeria's grid. Table 2-11 shows the capital cities explored in this research, including their states and region of Nigeria. The map in Figure 2-13 illustrates the Nigerian states and their regions.

Table 2-11: States and capital cities in Nigeria's six geopolitical zones

City	State	Region
Ibadan	Oyo	South West
Port Harcourt	Rivers	South South
Awka	Anambra	South East
Abuja	Federal Capital Territory (FCT)	North Central
Kano	Kano	North West
Yola	Adamawa	North East

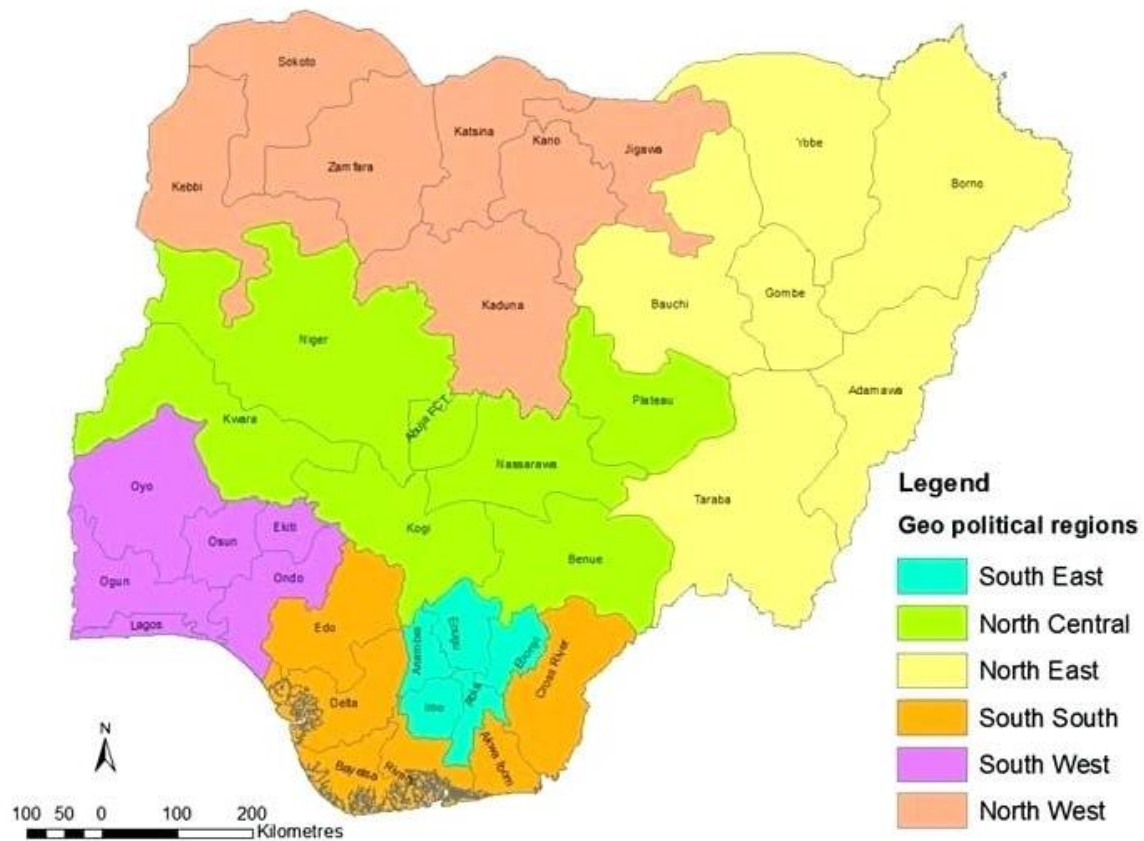


Figure 2-13: Map showing states in Nigeria's geopolitical zones (Ekong et al., 2011)

2.15.1 Ibadan, South West Nigeria

Ibadan is the third largest city by population of more than 3 million in Nigeria, behind Lagos and Kano (Citypopulation, 2017). It is the largest city in Nigeria by geographical area. The capital city of the south-western state of Oyo, it is located 128 km inland from the coastal city of Lagos (see map in Figure 2-14) making it an important commercial centre and trade route between coastal and landlocked areas of Nigeria (Tomori, 2010).

The city, like other cities in South West Nigeria, has a tropical wet and dry climate that is characterised by a lengthy wet season and temperatures higher than 18 °C throughout the year (Peel, Finlayson and McMahon, 2007). Most rainfall happens between March and October while dry periods occur between November and February. Usually, there is a lull in rainfall in August and picks up again in September, making September the month with the second highest average precipitation after June. The average maximum temperature is 26.41 °C and minimum is 23.89 °C, while maximum and minimum average precipitations are

244.73 mm in June and almost zero precipitation in December and January respectively.



Figure 2-14: Location of Ibadan in South West Nigeria. Source: HOMER's inbuilt maps

2.15.2 Port Harcourt, South South Nigeria

Port Harcourt is a port city located along the Bonny River, about 66 km upstream the Gulf of Guinea (Encyclopædia Britannica, 2013). With a 2011 population estimate of 1,750,000 Port Harcourt is the fifth largest city in Nigeria (Citypopulation, 2017). It is the largest and capital city of Rivers State in the South-South region of Nigeria (see map in Figure 2-15). Besides its political importance, it is regarded as one of the wealthiest cities in Nigeria due to its oil wealth. It was created in 1912 by the colonial government as a port city to export coal discovered in nearby Enugu city (Howard, 1974).

A coastal city, the city has a tropical wet climate featuring long and heavy rainy seasons followed by short spells of dry seasons during the months of December and January (WMO, 2017). The city experiences its heaviest precipitation between

July and September with an average precipitation of 521 mm in July and August. The driest period is between December and January with an average precipitation of 20 mm in January. Average maximum and minimum temperature in Port Harcourt are 26.16 °C in April and 24.29 °C in August respectively.

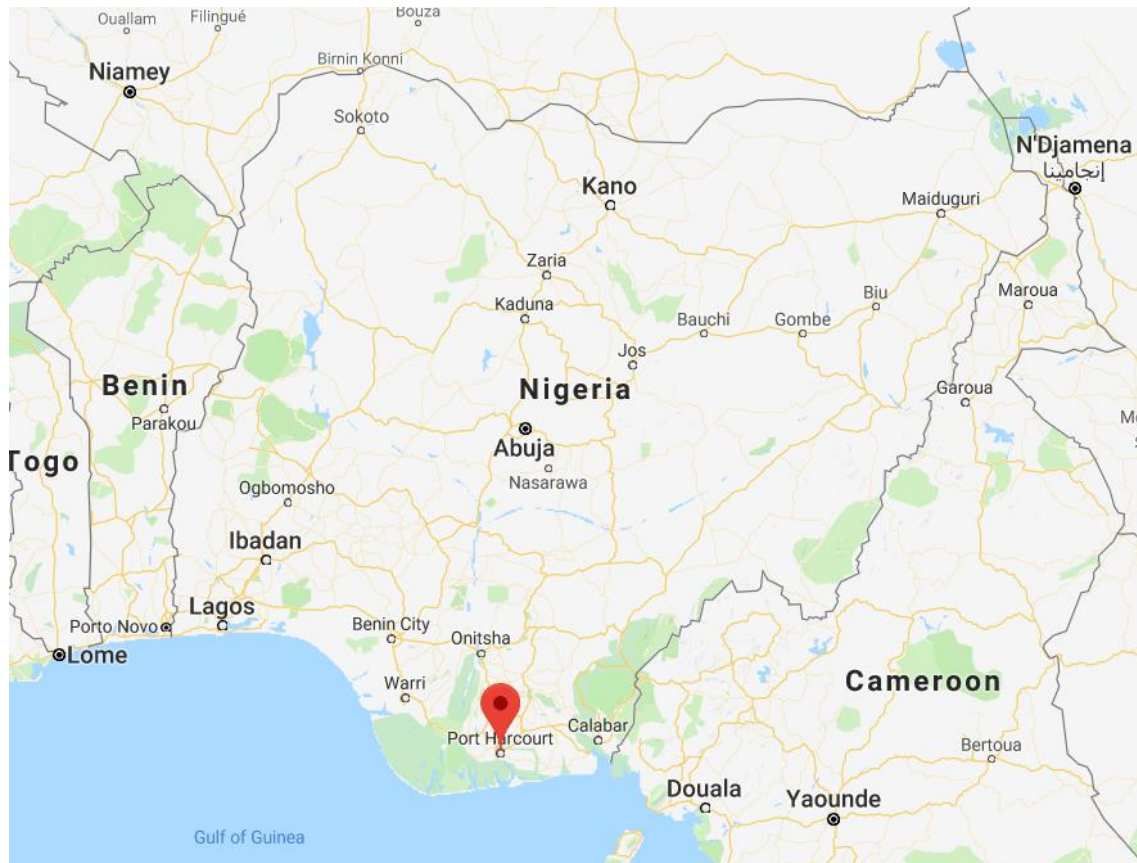


Figure 2-15: Location of Port Harcourt in South-South Nigeria

2.15.3 Awka, South East Nigeria

Awka is the capital city of Anambra State in South East Nigeria with a population of 301,657 according to Nigeria's 2006 census (Population Council, 2007). It is located directly North of Port Harcourt (see map in Figure 2-16) and is in the middle of the densely populated area occupied by tribal Igbo people of Nigeria. Its location between two important Igbo cities of Onitsha and Enugu made it a strategic choice as an administrative centre for colonial rulers and it still serves as the centre of government in Anambra State.

Awka is located within the tropical rainforest part of Nigeria characterised by two distinct wet and dry seasons. Two winds bring about these seasons. The south-westerly monsoon winds from the Atlantic Ocean bring six months of heavy

rainfalls between April and July. This period is punctuated by a brief period, two to three weeks, of dryness in August before rainfalls continue in September through October (World Weather Online, 2016). The north-easterly dry Harmattan winds from the Sahara Desert produce five months of dry weather between November and March characterised by a dusty haze which reduces clearness index in these months. Temperatures in Awka are at a minimum average of 24.19 °C in August and maximum average of 26.53 °C in February.



Figure 2-16: Location of Awka in South East Nigeria

2.15.4 Abuja, North Central Nigeria

Abuja, a landlocked city, has been the capital city of Nigeria since 1991 (Encyclopædia Britannica, 2013). It is located 300 miles northeast of the coastal former capital city of Lagos (see map in Figure 2-17). Abuja is located 360 m above sea level and has less humidity with a cooler climate than Lagos. Its terrain is dominated by high altitudes and undulating landscapes. As the political and administrative centre of Nigeria, Abuja has experienced unprecedented population growth in recent years. With a population of 776,298 in Nigeria's 2006 national

census, Abuja's 2011 population was estimated at 1,235,880 making it the fastest growing city in the world between 2000 and 2010 according to the United Nations.

Abuja's weather is characterised by a tropical wet and dry climate. The city experiences three weather conditions yearly including a warm and humid wet season and a scorching dry season interspersed with a brief period of harmattan. The dry harmattan is caused by the dust haze-carrying north-easterly trade winds (World Weather Online, 2016). Rainy seasons usually span between April and October with remaining months remaining largely dry.

During wet season, daytime temperature can reach as high as 30 °C with night time lows of around 22 °C. Daytime temperature in the dry season can be as high as 40 °C followed by night time temperature of 12 °C. Abuja's landlocked location, mountains and undulating terrain have moderating effects on its weather and are the causes of its larger diurnal temperature variation compared with coastal cities.



Figure 2-17: Location of Abuja in North Central Nigeria**2.15.5 Kano, North West Nigeria**

The city of Kano is the capital of the Nigerian south western state by the same name. Kano's population in 2006 Nigerian census stood at 2.8 million but 2016 official estimates put its population at 4.15 million ranking second behind Lagos as Nigeria's most populous city. The city used to serve as an important link to several northern Africa cities and was the most southern part of the renowned trans-Saharan trade routes. Kano is still a major trading hub in Nigeria has produced many wealthy Nigerians such as Aliko Dangote, the richest black man in the world.

Kano is 481 metres above sea level and located in the Sahelian region south of Sahara (see map in Figure 2-18) characterised by a semi-arid climate. The Sahel climate is characterised by dry, hot, sunny and windy weather all year. This climate typically receives relatively low amounts of precipitation annually. Despite its similarity to the desert climate of the Sahara, it is less extreme.

The city experiences approximately 980 mm of precipitation annually, mostly from June through September (WMO, 2017). Kano is usually hot throughout the year with maximum daytime temperatures above 40 °C recorded in April. However, the city is noticeably cooler from December to February with average daily temperatures of between 11 and 15 °C.



Figure 2-18: Location of Kano in North West Nigeria

2.15.6 Yola, North East Nigeria

The city of Yola is the administrative capital of Adamawa State in north east Nigeria (see map in Figure 2-19). The word *Yola* is derived from *yolde* a Fula word meaning a settlement on rising ground (Encyclopædia Britannica, 2013). The city's topography, and that of Adamawa State in general, is mountainous crossed in many places by the large river valleys of Benue, Yedsarem and Gongola rivers. It had a population of 392,914 as of the 2006 Nigerian census (Citypopulation, 2017)..

Yola experiences a tropical savanna climate with distinct wet and dry seasons over a relatively equal period. Typically, precipitation during the rainy season is less than in other tropical climes and the dry season is also more pronounced. Yola has a slightly longer dry than wet season. The area receives just enough rainfall during the shorter wet season to distinguish it from a semi-arid climate classification such as is found in Kano.

Wet season typically starts in May, slows down in June and experiences a heavy spell in August before giving way to a very dry weather in the middle of September. The hottest months are March and April with average maximum temperatures measuring 40 °C over the two months. The driest months are from November through to February with zero precipitation common throughout this period.



Figure 2-19: Location of Yola in North East Nigeria

2.16 Summary and Contribution to Knowledge

The identified power supply issues in developing countries and the significant gap in generation capacities compared with OECD and BRICS countries has been highlighted. The factors responsible for the incessant undersupply of power in parts of sub-Saharan Africa have been reviewed with a focus on impacts on different levels of healthcare facilities. A summary is provided below:

- A review of literature showed that factors responsible for unreliable power supply in developing regions of the world can be categorised into economic, technical and institutional/administrative factors. However, their impacts are

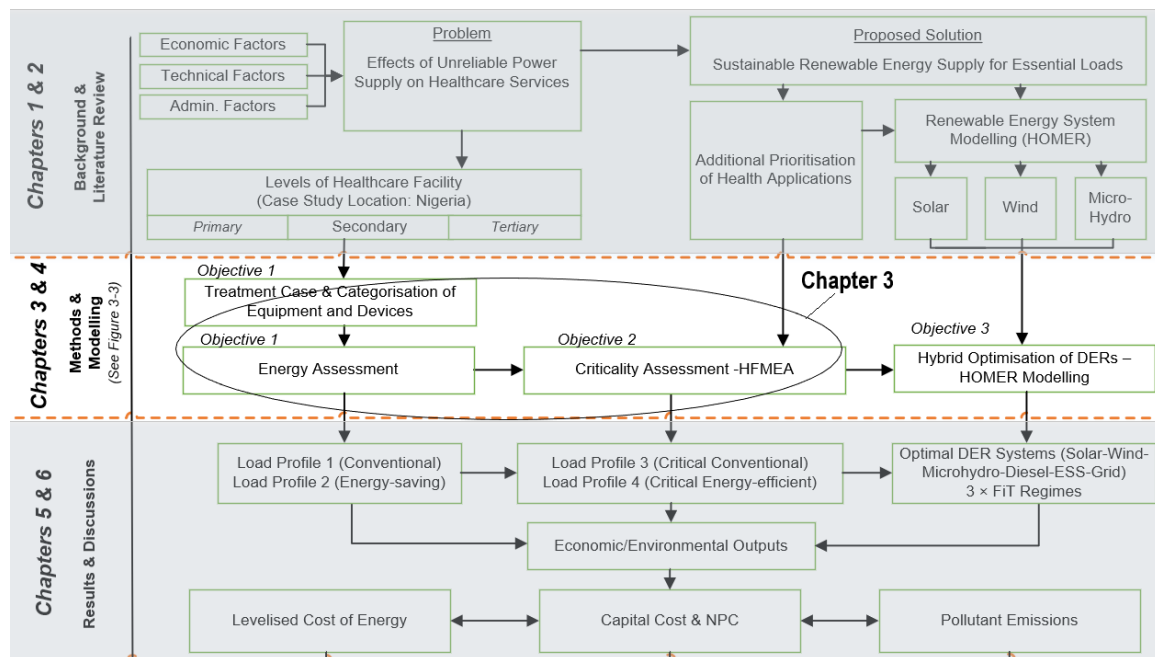
similar under each healthcare service level with increasing negative outcomes at lower levels.

- Technological advancements have made renewable energy sources viable alternatives to the central grid for critical applications.
- The underdeveloped state of power infrastructures in developing countries presents a unique opportunity for integration of microgrids into grid expansions.
- The addition of criticality analysis to traditional energy demand assessment process can help prioritise healthcare applications to create lower levels of energy demand requiring less expensive energy supply solutions.
- Review of available literature showed that while hydrokinetic turbines present higher efficiencies, reliability and flexibility than solar PV and wind turbines, little attention is given to this environment friendly renewable energy source.
- Background of one major city in each of Nigeria's six geopolitical zones are presented. Meteorological data indicating their renewable energy resource potentials are also reviewed.

Based on identified gaps in literature, the thesis is proposing the following contribution to knowledge:

- Establish focus group of local or regional health and facility management experts to determine representative emergency case requiring highest concentration of electrical medical services
- Determine pre-energy assessment criticalities using USAID load classification and identify devices with DC alternatives for additional prioritisation requirements.
- Apply a post-energy assessment criticality analysis using Health Failure Mode Effects and Analysis to create lower levels of energy demand and ensuring most critical treatment processes are available.
- Introduce event resilience index to identify minimum energy demand as percentage of total essential energy demand.

3 METHODS



3.1 Introduction

This chapter describes the methods employed in this research. The research is divided into three main phases: energy demand assessment, demand criticality assessment and energy supply simulation. The conceptual framework applied is introduced, highlighting the need to advance current models of health energy demand and supply assessment. Justification for including criticality analysis in existing health energy models is provided in Chapter 2. The proposed framework is not only an improvement on a well-established method, it is also a risk-limiting approach.

Figure 3-3 shows the relationships between the methods and data used in the different phases of this research. Phase 1 was achieved using a pre-determined treatment case to identify treatment steps and determine the energy demand of essential medical devices in the treatment.

Phase 2 is a criticality assessment that includes an initial load characterisation that guided the experts that conducted the HFMEA in determining the severity of power failure during the operation of different devices. Phase 3 involved the techno-economic analysis of hybrid renewable and conventional energy technologies in optimised systems in order to determine the most cost-effective,

environmentally sustainable and reliable configurations for the most critical equipment identified from Phase 2.

3.2 Conceptual Framework

Conceptual frameworks are regarded as organising tools in empirical research (Ravitch and Riggan, 2017). They are outcomes of qualitative processes of theorisation (Jabareen, 2009). Although the outcomes of this research are quantitative, the dearth of reliable healthcare data from Nigeria (Home Office, 2018) makes it necessary to build a bespoke treatment case for the empirical evaluation and modelling of energy demand and supply functions. A conceptual framework is typically used in qualitative research. However, it is used to organise the different concepts and models to arrive at a sustainable (economically and environmentally viable) power supply solution for a health facility.

The conceptual framework is a model or conception of what a researcher plans to investigate, and of what the current status of these things are and why. An in-depth guide to developing a conceptual framework and applying it throughout the research process is in Ravitch and Riggan (2017). The conceptual framework employed in this research is graphically presented in Figure 3-2. It represents an upgrade to earlier methodological frameworks employed in the determination of the best energy systems for a facility.

Miles and Huberman (1994, p. 440) stated that a conceptual framework “lays out the key factors, constructs or variables, and presumes relationships between them”. However, Jabareen (2009) suggested that conceptual frameworks be based on concepts alone and not on variables. Instead, the term *model* should be employed when variables or factors are involved.

This study is based upon a conceptual framework built on models of energy demand estimation, resource evaluation and energy system optimisation. The main aim of this study is to identify sustainable microgrid options for prioritised critical healthcare applications. Sustainability is a concept that has been addressed in multiple disciplines such as anthropology, architecture, design, economics, ethics, geography, sociology and urban planning. However, the definitions of sustainability

are “vague, devoid of operative definitions and fraught with contradictions” (Jabareen, 2009:55).

To remove any confusion, sustainability in this study is based on economic and environmental sustainability benchmarks (see section 2.9.3 and Table 2-3). The use of sustainable power supply as a concept in this study hinges on the ability of a health facility to utilise its financial and natural energy resources to provide the most reliable and cleanest energy for its most critical processes. The HOMER modelling software is then used to evaluate competing microgrid components without the bias associated with qualitative research. The model will help identify economically and environmentally viable power supply solutions for the selected health facility.

In Maxwell (2013, p. 39), a conceptual framework is defined as a visual or written work that “explains, either graphically or in narrative form, the main things to be studied – key factors, concepts or variables – and the presumed relationships among them”. The relationship between demand-side and supply-side factors in a health facility based in a developing country are studied and analysed in this research. These are investigated using the simulation technique.

Olatomiwa et al. (2016) employed the traditional framework illustrated in Figure 3-1(a). They used a generic energy demand profile in assessing wind and solar power potentials for a rural health clinic. They presented no metric for determining environmental impact costs other than a direct comparison between the settings considered. A similar approach was prescribed by the World Health Organisation (WHO, 2015a). Furthermore, this approach relies heavily on supply-side solutions to electricity access issues. While this might be convenient for settings with no previous access to electricity, the cost of setting up such renewable power generation might discourage facilities that are already connected to an unreliable grid.

Apichonnabutr and Tiwary (2018) advanced this traditional approach by employing a stakeholder survey to determine a more precise current and future energy demand instead of using a prescribed energy demand profile. Furthermore, they employed an external costing model to determine the environmental impact, in financial cost, of potential energy systems for their facility. This approach improves

on the previous framework by providing a more accurate assessment of a facility's energy demand, both current and near future. It also provides a financial cost-based approach to measuring the impact of pollutant emissions. However, these do not address the problem of high capital cost of renewable power generation. If anything, the outcome of this approach presents a higher capital outlay compared to the previous framework due to allowances made for future loads.

The conceptual framework employed in this research extends both frameworks as follows:

- A focus group of experienced medical practitioners are employed to create a typical emergency treatment case upon which the energy demand profile is created for the tier 3 health facility. Only medical equipment and devices, and essential support devices like lighting and ventilation equipment, that are required for positive health outcome in common emergency cases are considered;
- Using another focus group, a criticality assessment is conducted after the energy demand of the facility has been determined. This produced a lower level of energy demand than in the step above and is used to determine event resilience index of power generating system required;
- Modelling and comparative analysis of pollutant emissions from optimised systems generated across different levels of electrical loading and feed-in-tariffs is conducted and CO₂ emissions are benchmarked against WHO prescribed limit of $\leq 1000 \text{ gCO}_2\text{-eq /kWh}$ for the level of health facility considered (see Table 2-3).

The modelling aspect of this study involves the simulation and optimisation of economic (capital cost, NPC, and operating cost) and environmental (wind speed, water flow velocity, and solar insolation) factors of inherently intermittent renewable energy technologies to determine if they can reliably compensate for unreliable grid power supply. Part of the process of deriving this answer involved some qualitative assessments. The treatment case on which the health facility's energy demand assessment is based was determined through a qualitative assessment of common critical emergencies by a focus group of clinicians and health facility managers.

Since the researcher has no experience as a health expert or a health facility manager, the expert judgement of the focus group was requested within clearly defined objectives and criteria. The same approach was used during the criticality assessment used in prioritising critical treatment process steps. However, there was more engagement with the participants in providing training on the application of the Health Failure Modes and Effects Analysis (HFMEA).

It is important to note that, while the other studies reviewed focussed on addressing all the energy needs of the facility, this research started by addressing the most critical electrical loads. As highlighted in Chapter 2, economic factors are major impediments in the uptake of modern energy technologies in developing countries. This has led to many decision makers becoming unreceptive to the potential that RETs have in solving many quality issues in power supply. Presenting a progressive or staggered approach to renewable power generation can help reduce the financial burden of deploying these technologies locally.

The conceptual framework is a theory that is key in designing a research. It incorporates elements that exist elsewhere, “but the structure and overall coherence” is unique to a research work not “something that exists ready-made” (Maxwell, 2013). Hence the conceptual framework deployed in this study includes the layout of existing health energy frameworks with the inclusion of the elements described above and illustrated in the graphical representation of the framework in Figure 3-2.

The research design is based on the extended framework, which, taken together, are associated with the research objectives. The three phases of the research have been mapped to the steps of the framework as shown in Figure 3-2. Research Objectives 1, 2 and 3 are respectively expressed in Phases 1, 2 and 3 of the research design.

There are two major limitations in any conceptual framework. First, the framework can be affected by the researcher’s knowledge and experience of the subject(s) under study. This is also known as the “initial bias”. Second, some concepts within the framework may be given prominence and others ignored. This is referred to as “ongoing bias” (Taheri, 2016). These limitations were eliminated through several reviews of the conceptual framework over the course of this research.

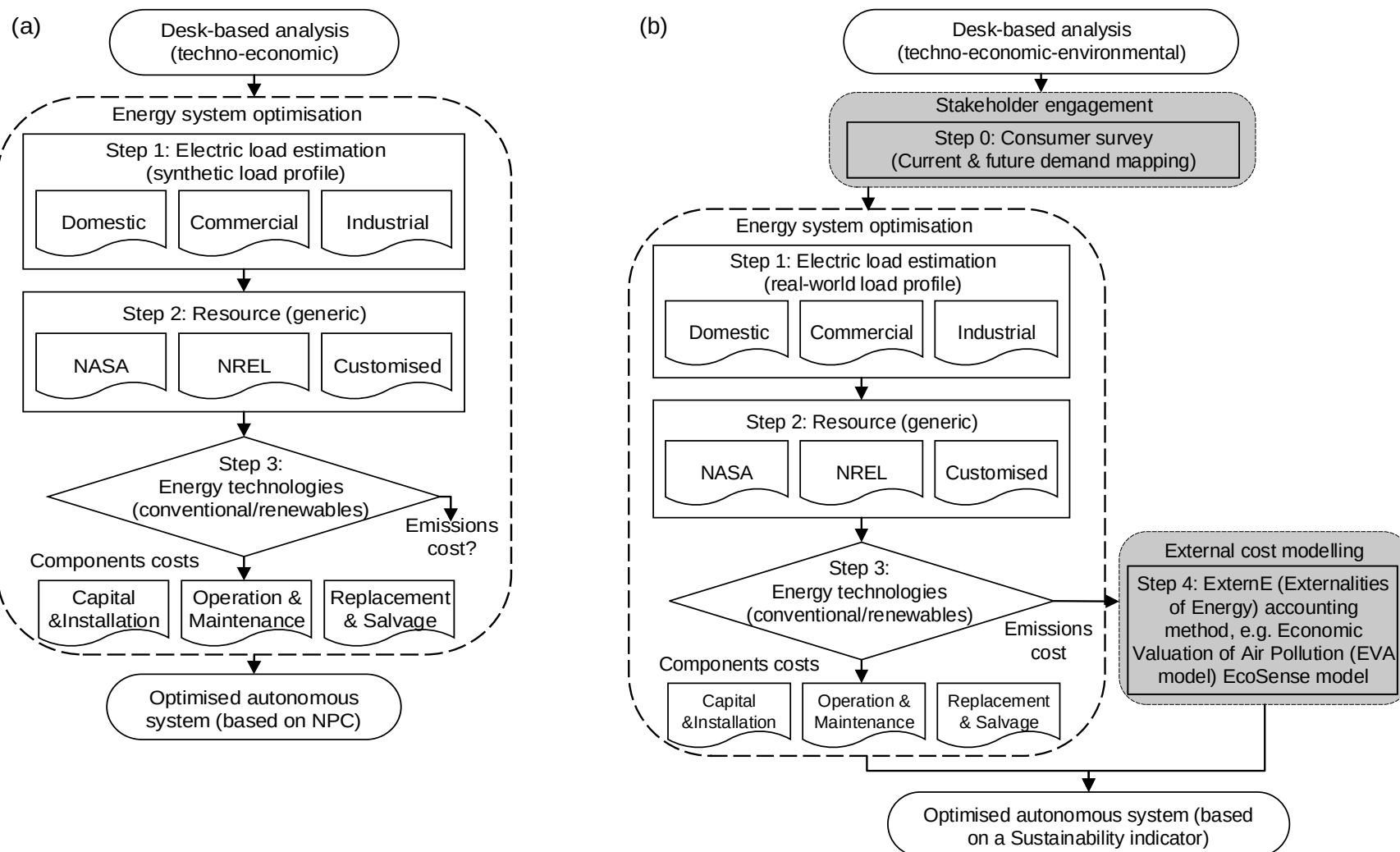


Figure 3-1: Frameworks for selecting optimised autonomous energy system (a) Current practice employed in Olatomiwa et al. (2016); WHO (2015a)
(b) Recent advancement in Apichonnabutr and Tiwary (2018)

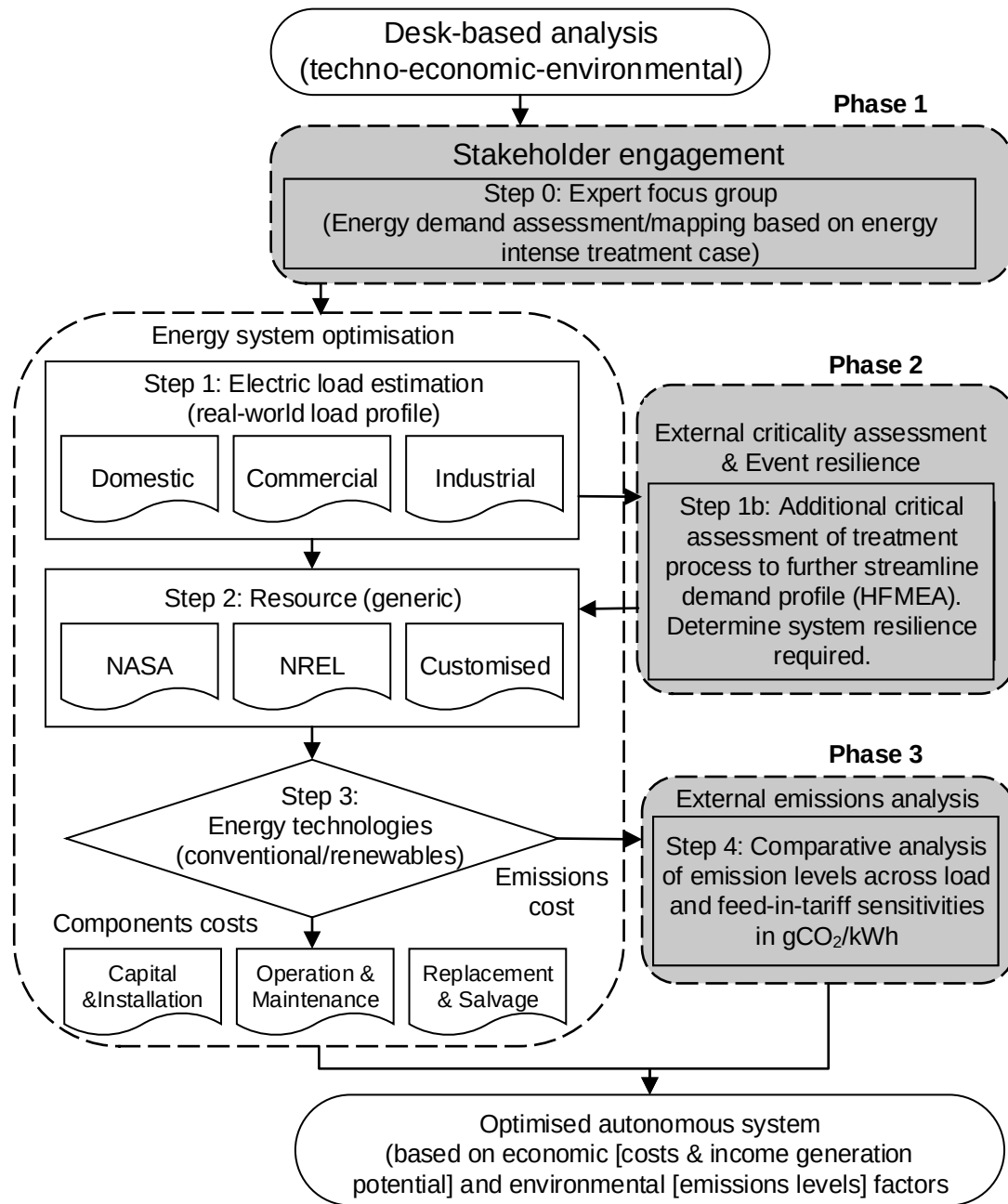


Figure 3-2: Proposed conceptual framework – update to recent advancement

3.3 Research Design

Figure 3-3 illustrates the design of this research, which followed a mixed methods approach. The energy demand assessment in Phase 1 is based on an emergency treatment case study determined through a focus group of doctors and health facility managers. The criticality assessment in Phase 2 is based on a qualitative risk assessment tool (HFMEA) employed by another focus group on the result of the energy demand assessment.

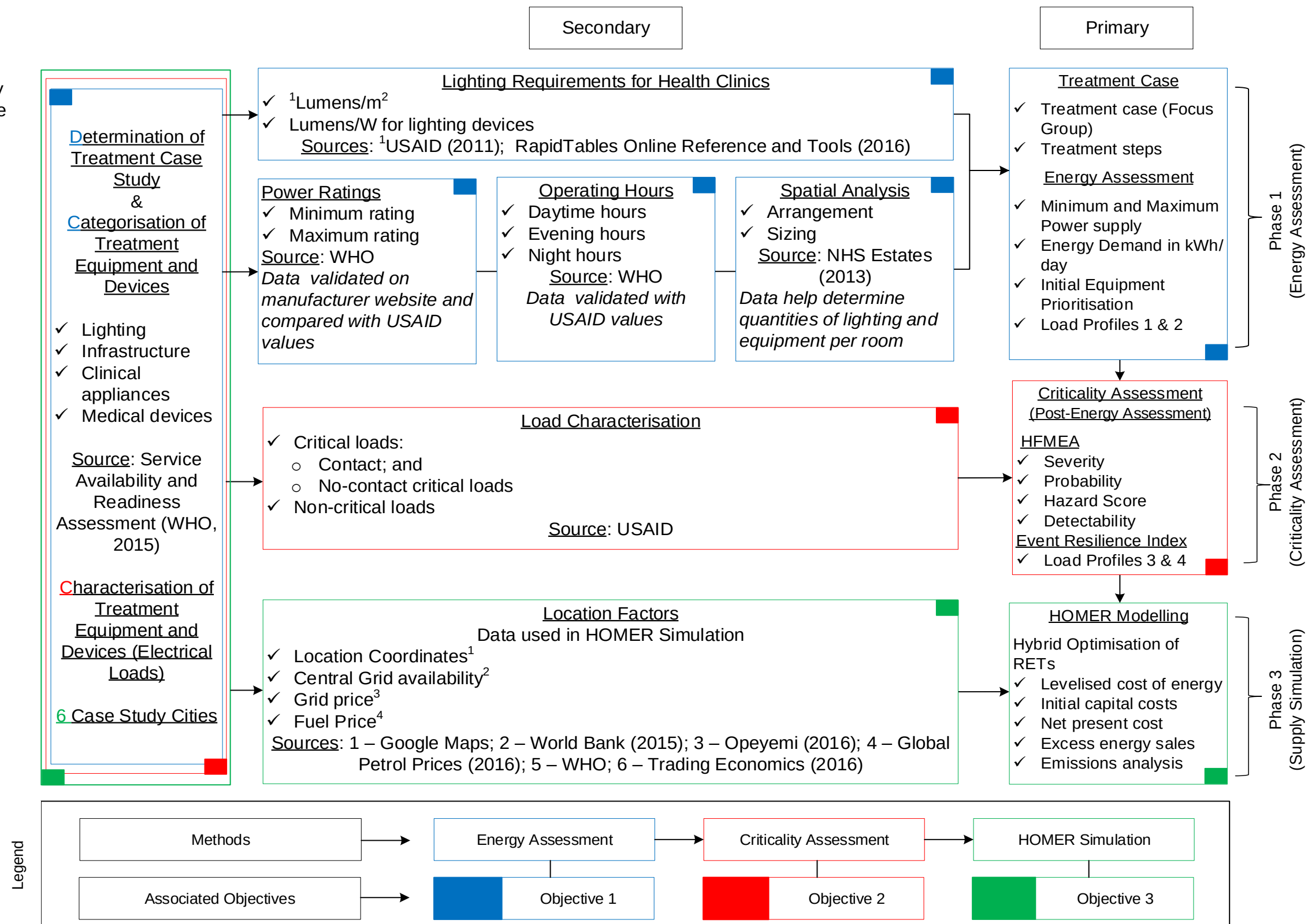


Figure 3-3: Research design - Methods, Data and Associated Research Objectives

Phase three involved the case study analysis of the energy resource potentials of 6 cities in Nigeria's six geopolitical zones. These formed the basis for the simulation of optimised hybrid power supply systems for the same tier 3 health facility in each city. Detailed explanation of each phase of the research design is present below.

3.4 Phase 1 Methods and Data – Treatment Case and Energy Demand Assessment

Phase 1 covers the pre-energy assessment activities and the energy assessment in the study. The pre-assessment activities include the determination of a typical treatment case for a critically ill patient and spatial analysis of the patient's movement through the health facility as they are being treated.

Carrying out the assessment of energy demands of a healthcare facility is crucial in the process of selecting the most suitable energy system. For example, a hospital that provides a wide range of services such as specialist treatments, medical diagnostics and surgical operations can be considered a high energy demand facility. On the other hand, a basic medical clinic providing medical services such as the treatment of minor injuries and illnesses, child deliveries, and the provision of basic immunisation can be regarded as relatively low energy demand facility (Olatomiwa, Mekhilef and Ohunakin, 2016).

As discussed in Chapter 2, the energy demand assessment in this research will employ a Nigerian secondary health facility which is comparable to WHO's Tier 3 or USAID's Category II facility. The use of a secondary facility is appropriate for this level of study because the energy demand profile of such facilities is appropriate both for the depth of assessment and the resources available to the researcher. Whereas, the energy demand profile of a primary facility is too low for this level of investigation and the demand profile for a tertiary health institution will require substantial resources beyond the limits of a doctoral research. A detailed WHO multi-tier evaluation of electricity supply in health facilities is presented in Table 2-3 and section 2.6.

Using generic WHO-prescribed energy demand profiles for specific tiers of health facilities is academically pertinent, as demonstrated in Olatomiwa, Mekhilef and

Ohunakin (2016) and WHO (2015a), and is not uncommon. However, the expert judgement of a focus group of clinicians and health facility managers in a Nigerian secondary health facility is used in this research to determine the facility's energy demand profile to provide more practical and current view of energy use.

Both qualitative and quantitative data were collected through the focus group for the selection of the treatment case used for the energy demand (objective 1) and criticality assessments (objective 2). Qualitative data collects information that seeks to describe a subject more than measure it. It is used to gain deeper knowledge of people's motivations, attitudes and thinking (Maxwell, 2013; Survey Monkey, 2018). In the absence of statistical figures of emergency incidences, the focus group provides expert judgement on the occurrence of emergency treatment cases in a health facility. The quantitative data collected through the focus group include the number and specifications of medical equipment and devices in the facility.

The dearth of reliable data on occurrence and frequency of localised clinical emergencies in Nigeria's healthcare has made it necessary to create a medical treatment profile that will underpin this research. Although there are nationally available health-related statistics such as maternal and child mortality rates from international health organisation like WHO, these do not come with facility level specific information that can be used to create localised energy demand profiles. However, this situation is unsurprising given that Nigeria has no health technology national policy (WHO, 2016) which is one of the prerequisites to the collection, processing and dissemination or application of such data.

A focus group is an organised discussion with an expert group of specialists or consumers aimed at learning about the ideas, perceptions, attitudes and feelings of the group (Kahan, 2001; Moultrie, 2018). A focus group was employed in this research to establish a critical emergency case that requires urgent medical attention and the use of a relatively high number of electrical devices. This treatment case will form the foundation for energy demand assessment and criticality analysis of treatment process steps for prioritisation of the most critical devices.

Selection of focus group participants are based on the judgement sampling technique. Judgement sampling is a non-probability sampling technique where a sample is selected on the basis of knowledge of a subject matter expert with knowledge of the process under investigation (Perla and Provost, 2012). It involves the identification and selection of an individual or a group of individuals that is proficient and knowledgeable about a subject of interest (Etikan, Musa and Alkassim, 2016). This type of convenience sampling is affordable and easy to deploy and is typically used in qualitative research to identify and select the information-rich cases for the most proper utilisation of available resources (Patton, 2002). This approach is suitable for this research which is aimed at identifying sustainable energy resources for reliable power supply in health facilities.

Four focus group participants comprising of two medical doctors and two health facility managers from a hospital in Ibadan Nigeria is recruited. The participants are selected through the judgement of the facility's medical director based on availability, qualification and experience. Each of the participants will have at least a graduate degree and minimum of ten years' experience as clinician or facility management personnel. They will meet face-to-face three times, once for each focus group objective. The main method of contact with the focus group is via email and telephone. The focus group objectives will be achieved through the expert judgment of the selected focus group participants.

The objectives of the focus group include to:

- i. identify the three most common emergency cases in the hospital using expert judgement.
- ii. determine the most critical of these cases using the triaging and GCS methodologies.
- iii. determine the critical energy use profile of health facility using the provided WHO health facility energy demand profile template.

Using the expert judgement relating to hours of use and combining this with the power ratings of the devices, the load profile of the facility is created. Expert judgement is a technique in which judgement is made based on a specified set of criteria or expertise that has been acquired in a given knowledge area, discipline,

industry or product area (PMI, 2017). This knowledge base can be provided by a member or members of a group or project team. Typically, expert judgement requires an expertise that is not available within the group. As such, it is common to find an external person or group with the relevant skill or experience to be invited for consultation. The full discussion of the focus group design including the justification for sampling technique, data analysis and limitations are described in Appendix O.

3.4.1 Determination of Typical Emergency Treatment Case

The treatment case selected is based on a local hospital's emergencies and not on a nationally observed emergency treatment statistic. These figures are not available centrally in Nigeria, and even where health statistics are stated, they are usually described as inaccurate (Home Office, 2018).

Table 3-1: Traige sieve/classification (Rull, 2014)

Classification	Interpretation	Description	Colour code
Priority 1 (P1)/ Triage 1 (T1)	Immediate care needed	Requires immediate life-saving intervention	Red
P2 or T2	Intermediate or urgent care needed	Requires significant intervention within 2 - 4 hours	Yellow
P3 or T3	Delayed care	Needs medical treatment, but this can safely be delayed	Green
Dead	Beyond help	Important to prevent the expenditure of limited resources	Black

Two emergency patient assessment tools commonly employed in the Nigerian health sector were used to select an eventual emergency case, namely, patient triaging and Glasgow Coma Scale (GCS). These are used in selecting one out of

the three the emergency treatment cases considered by the energy demand focus group.

Triaging is the assessment and sorting of injured people for prioritising for treatment (or transport) according to their severity of injury (Rull, 2014; Smith et al., 2017). This is especially useful in situations where limited medical resources must be allocated. Table 3-1 shows a triage sieve or classification.

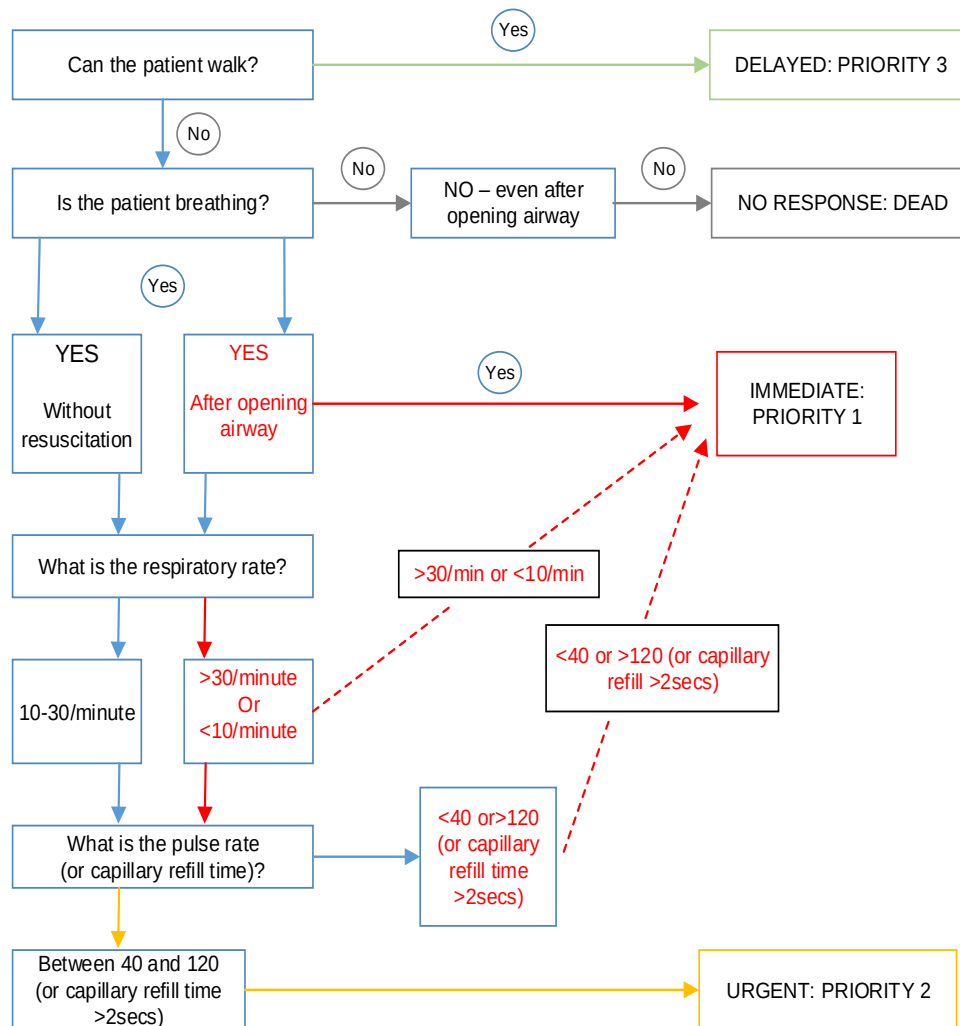


Figure 3-4: Additional patient triage (Rull, 2014)

Triaging is required to be dynamic and carried out frequently on patients. Following an initial triage, a more detailed triaging of trauma patients is usually necessary. Figure 3-4 shows the framework for an additional triage of patients using the same colour coding presented in Table 3-1 for the classification of patient status.

The GCS is an adopted metric for assessing the mental status of acutely ill trauma and non-trauma patients (Teasdale et al., 2014). The Glasgow Coma Scale is

developed for application in ongoing assessments of patients with coma either from surgical or medical causes. It is frequently used in pre-hospital and acute care settings to assess a patient's mental status, both in traumatic and non-traumatic cases. Table 3-2 shows GCS criteria, their indicators and scores allocated to them. The lower the score value, the worse the status of the patient.

Table 3-2: Glasgow Coma Scale/Score (Runde, 2017; Teasdale et al., 2014)

Criteria	Response	Value
Eye	Eyes open spontaneously	+4
	Eye opening to verbal command	+3
	Eye opening to pain	+2
	No eye opening	+1
	Not assessable (trauma, edema, etc)	C
Verbal	Oriented	+5
	Confused	+4
	Inappropriate words	+3
	Incomprehensible sounds	+2
	No verbal response	+1
	Intubated	T
Motor	Obeys commands	+6
	Localizes pain	+5
	Withdrawal from pain	+4
	Flexion to pain	+3
	Extension to pain	+2
	No motor response	+1

3.4.2 Spatial Analysis

Figure 3-5 shows the flow of emergency admissions for patients arriving by ambulance at an accident and emergency (A&E) department. Functional space consideration for emergency treatments in a UK A&E department is 464 m² (NHS Estates, 2013). The A&E deals with real life-threatening emergencies such as loss of consciousness, severe non-stop bleeding, breathing difficulties and severe allergic reactions. These cases are required to be processed rapidly through the

emergency unit, which is designed to facilitate the patients engagement with essential health services and applications (NHS Estates, 2013). Highly trained staffs in A&E departments provide emergency medical services 24 hours 365 days of the year. The layout of an emergency ward at an acute hospital in the UK is used to mirror that of a secondary hospital in Nigeria. This is because the layout of spaces in the emergency ward is similar to those of a Nigerian secondary hospital. Primary and secondary health facilities, especially in developing countries, often serve as first point of treatment for emergencies (WHO, 2015a).

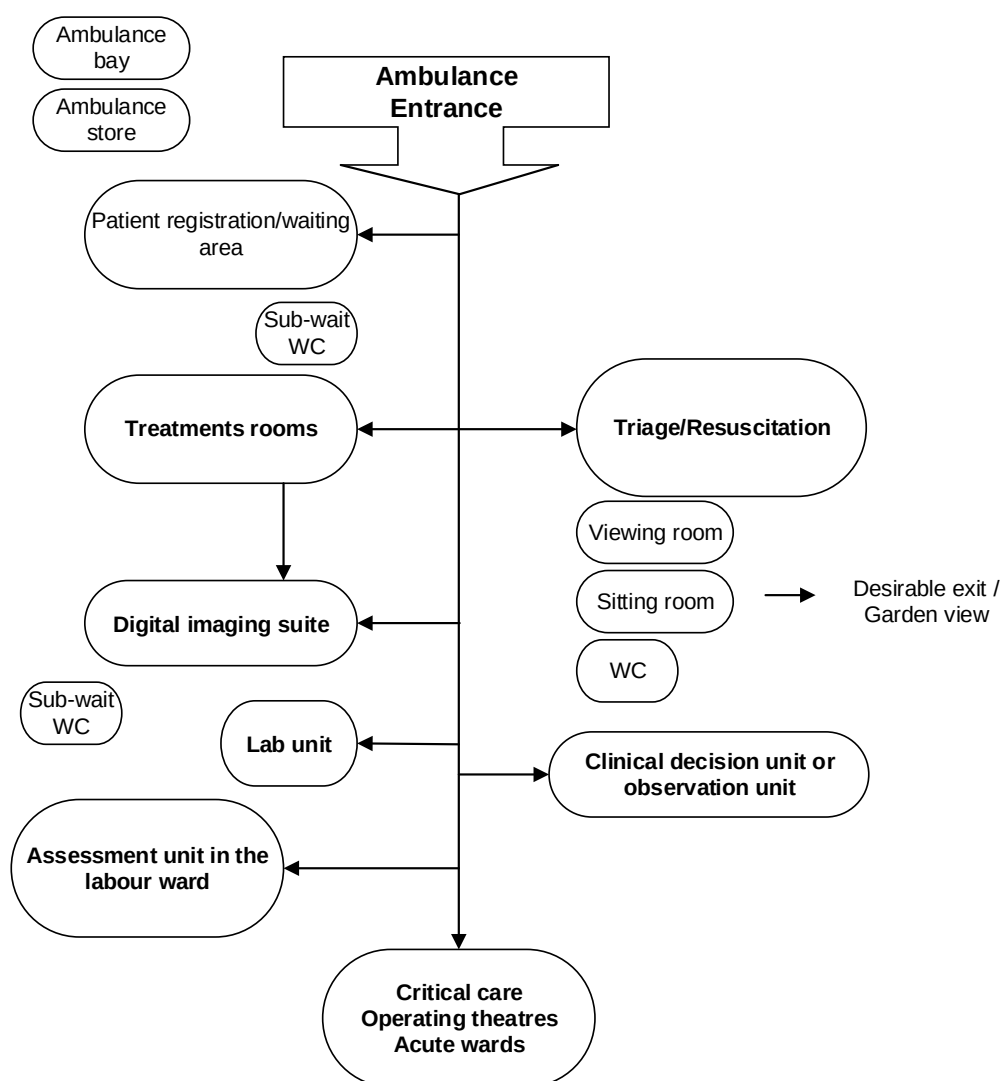


Figure 3-5: Spaces in emergency facilities (NHS Estates, 2013)

3.4.3 Classification of Treatment Equipment and Devices – SARA and USAID

Due to the ability of healthcare facilities to offer a wide variety of services, ranging from catering to emergency treatments, a systematic approach to defining energy

needs in terms of equipment required is yet to be achieved universally. Nevertheless, health infrastructure surveys such as WHO's SARA contain detailed inventories of available equipment in healthcare facilities (see Appendix J, Appendix K and Appendix L).

Therefore, the assessment of essential electric power supply needs in a healthcare setting can be based on the SARA health service classifications (WHO, 2015a). The SARA classification was used by the energy demand focus group to classify the loads in the health facility for the energy assessment in Chapter 4. The classifications include: (i) infrastructure, such as lighting, water supply, sterilisation and communication; (ii) medical devices such as ultrasound scanner, anaesthesia machine and electrocardiograph (ECG); and (iii) support appliances for specific services such as surgical services, blood transfusion and vaccination. These classifications are summarised in Table 1-1, Table 1-2 and Figure 1-3.

3.4.4 Load Characterisation

It is imperative to characterise identified electrical loads by their ability to survive disruption in power supply in readiness for the HFMEA criticality assessment in Chapter 4. This allows for the exclusion, from criticality assessment, of some equipment that require prioritisation in the treatment process but are more able to withstand power failures. Load characterisation is a qualitative method of categorising loads by resilience (Powering Health, 2014). Characterisation of loads was done during energy assessment.

Health energy loads are characterised in one of three ways: non-critical loads, contact critical loads and no-contact critical loads. The second to the last column of Table 5-1 in Chapter 5 shows the characterisation of loads required in the treatment of Patient A. Critical devices with the least resilience to power disruptions are given more priority than more resilient ones.

Non-critical loads are those that, if not supplied with power, will not put patients at immediate risk or substantially disrupt facility operations (Powering Health, 2014). Automatic doors, fans and air conditioners, in most cases, are examples of non-critical loads. On the other hand, a critical load is normally defined as equipment that is crucial to the operation of a facility or, for this study, crucial to the successful

completion of a treatment process. Critical loads require that power supply must be maintained under any circumstance for the successful outcome of an operation or process. successful. Examples include emergency and operating room equipment, laboratory equipment, computers and lighting. Critical loads are further categorised by their need for high quality, uninterrupted power.

- Contact critical loads are those that can endure minor fluctuations in voltage and brief loss of power. This type of critical load can include lighting or vaccination refrigeration and battery powered alternatives. However, a laboratory refrigerator may not fall under this category because the risk of damage from minor fluctuations and the consequence may be too high.
- No-contact critical loads are loads for which any interruption in power will result in damage to the equipment or loss of data. Sensitive laboratory instruments, medical equipment such as x-rays, and data acquisition systems are all no-contact critical loads. However, some equipment with readily available DC or battery-powered alternatives such as pulse oximeter can be regarded as contact critical loads if available in the facility.

The characterisation of a facility's equipment is an important precursor to the classification of the most critical devices per the potential severity of their failure. In addition, proper identification of the different aspects of a facility's total load that represents contact or no-contact load is essential to estimating backup or alternative power systems. Designing backup supply for non-critical loads inevitably leads to a larger and more expensive system than necessary. Likewise, uninterruptible power supplies (UPS) must be sized to accommodate all no-contact loads, providing a UPS for contact loads will lead to a higher system cost, with little added benefit.

It is important to note that every device assessed in this study are essential load according to WHO's definition. Essential electrical loads are devices that define the level and nature of service delivered by a service. A secondary hospital is normally expected to provide maternity services and therefore, a fetal heart

monitor will be regarded as an essential device. Essential loads can be critical or non-critical.

3.4.5 Treatment Energy Demand Assessment

The energy assessment model employed in WHO (2015a) was extended in its application in this research. The proposed model adds considerations for spatial and characterisation of loads. Furthermore, an additional load profile was created in the proposed energy assessment model after a criticality assessment of the loads. Table 3-3 compares WHO's current health energy assessment model with the one proposed in this study. The proposed model aims to create a lower level of energy demand for conventional and energy-efficient devices.

Typically, health facilities in developing countries present low energy demand profiles when compared to more advanced settings. A primary health facility was used in an energy assessment in WHO (2015a). The facility was presumed to require 8.61 kWh/day to provide its health services using conventional devices. The peak conventional load occurring at any time was 1.24 kW and the least load was 0.03 kW. Whereas, under the scenario where energy-efficient devices are in use, the primary health facility was presumed to require 5.95 kWh/day to run. The peak load at any time under this scenario was 1.07 kW and the least load was 0.02 kW (WHO, 2015a).

The result of the energy assessment in this study showed an energy use intensity (EUI) of 58.51 kWh/m².year compared with an average of 108 kWh/m².year for a small hospital in Sweden (Lycke, 2012). In terms of real energy use, the amount of electricity consumed in functional spaces by primary and secondary hospitals in developing countries pale in comparison with their counterparts in developed countries.

To give some perspective, the secondary hospital used in this research requires 21.53 kWh/day to power essential devices. However, the small emergency hospital in Sweden has a total electrical energy demand of 8,219 kWh/day. This is mainly due to the comparatively large sizes of small hospitals in industrialised settings compared with those in developing countries (Lycke, 2012). Furthermore, there is much less energy demand for HVAC systems in primary and secondary

hospitals in developing countries with tropical climate. Meanwhile, energy is measured in real terms (kWh) in this study instead of relative terms (kWh/m² or kWh/patient) commonly used in industrialised settings. This is due to unavailable floor area and patient data from developing countries.

Table 3-3: Current energy assessment model vs. proposed model

Steps	WHO (2015a)-prescribed	Proposed energy assessment approach	Steps
1	Determine daily and hourly noise in demand (10% daily, 15% hourly variance)	Determine daily and hourly noise in demand (10% daily, 20% hourly variance proposed by energy demand focus group)	1
2	Create load profile (quantity and power rating) for two scenarios, conventional and energy-efficient medical devices	Create initial load profile (quantity and power rating) for two scenarios, conventional and energy-efficient medical devices	2
3	Determine daily distribution of hours of operation of medical devices across day, evening and night-time	Create load profile (quantity and power rating) for conventional and energy-efficient medical devices	3
4	Estimate total daily energy required based on analysis of load profile and presumed distribution of daily load demands for both scenarios in step 2	Determine daily distribution of hours of operation of medical devices across day, evening and night-time	4
		Estimate total daily energy required based on focus group's analysis of load profile and distribution of daily load demands for both scenarios in step 2 and characterise the loads	5
		Pause to determine most critical loads and then create a reduced second load profile for the two scenarios in step 2	6

3.5 Phase 2

Phase 2 of this research process includes a criticality assessment leading to the prioritisation of electrical applications in the selected treatment case. It also includes the calculation of the level of system resilience required to ensure that the DER system continues to supply reliable power in an unplanned event of grid outage. The Health Failure Mode and Effects Analysis, described in Chapter 2, was employed in prioritising health applications while the Event Resilience Index was used to calculate the required power system that secures the resilience of the facility to unreliable power supply.

3.5.1 Criticality Analysis – Health Failure Modes and Effects Analysis (HFMEA)

The UK Department of Health identified electricity as “the most vital of all infrastructure services” (Department of Health, 2014: p. 29). Most of the other services depend on it to function. Therefore, HFMEA is applied only to electrical medical devices in this study. All failure modes are assigned to failures caused by power quality attribute of electricity supply.

A HFMEA team was organised to use process flow diagrams, a hazard scoring matrix and the HFMEA decision tree to identify and assess potential vulnerabilities in the treatment process from Phase 1. The HFMEA technique was used to identify and rank the most critical functions within the life-saving treatment process. This is achieved by giving highest priority to devices used in completing process with the highest severity score. For ease of comprehension, the HFMEA process was synthesised into a graphic flow diagram in Figure 3-6 for the team.

An HFMEA study of five processes in the emergency ward of Qaem Hospital in Iran took 6 months to complete (Taleghani et al., 2016). Due to time constraints and the fact that this assessment is required to identify priority applications, the full HFMEA process was conducted partially up to Step 4 illustrated in Figure 3-6. Step 5 activities are required for management decisions which are not included in this study.

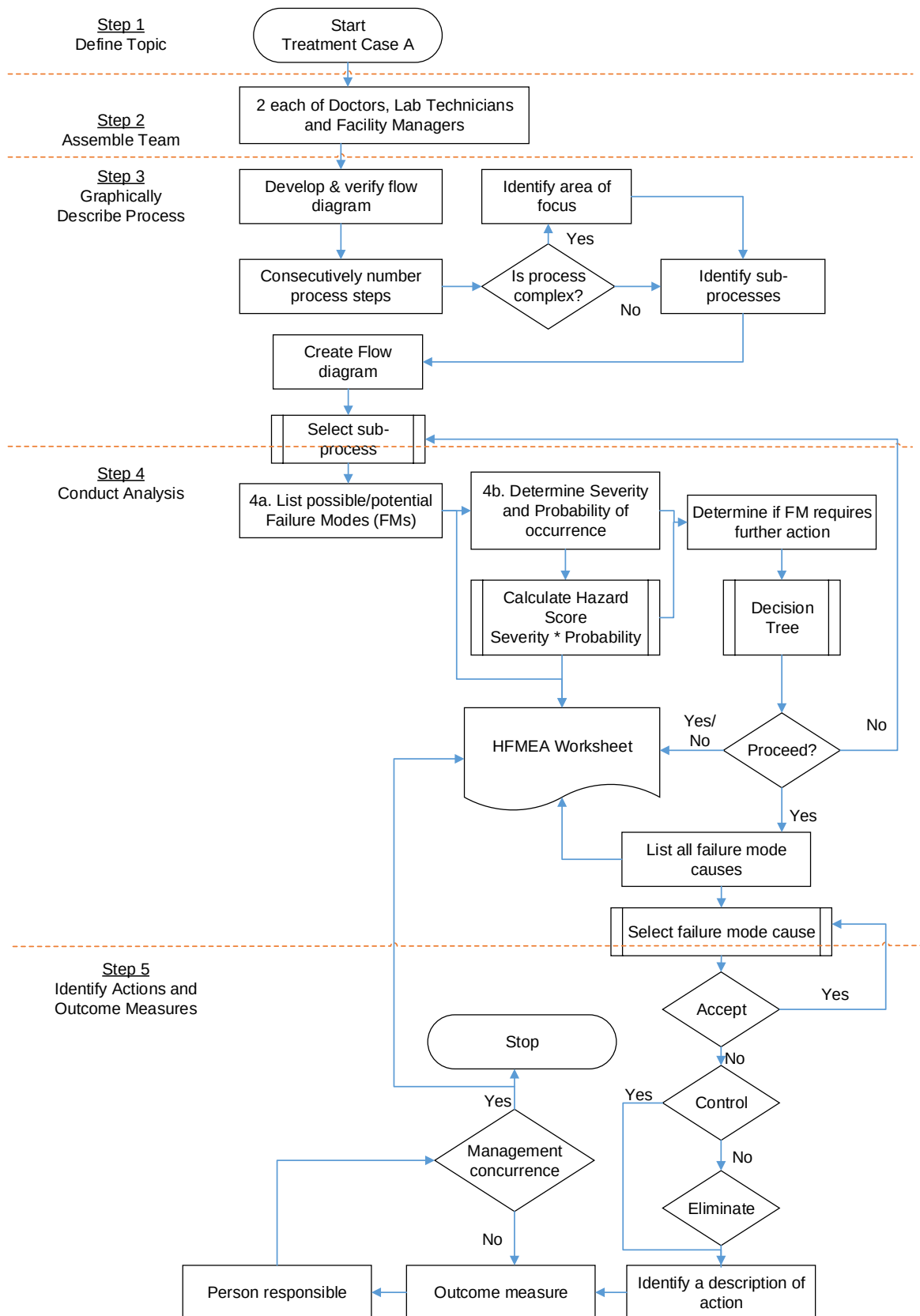


Figure 3-6: The HFMEA process flowchart (Source: Researcher's elaboration of the HFMEA process)

A multidisciplinary HFMEA team of two medical doctors, two laboratory technicians and two hospital facility managers were drafted to participate in the HFMEA process through brainstorming. They are all from the same health facility and have between 5 to 20 years' experience of working in healthcare. Due to availability constraints and the need for uniformity in the sources of contribution, judgement sampling was used to select equal numbers of experts from three departments. This non-probabilistic sampling method involves selection of sample participants based on the judgement that members from the medical, laboratory and facilities management department are in the best position to create treatment process steps and identify failure mode in the steps.

A review of HFMEA-based case studies (DeRosier et al., 2002; Giardina et al., 2016; van Tilburg, 2006) reveal that judgement sampling is commonly employed in the selection of HFMEA participants. It was also decided that participants have no less than 5 year's work experience in their area of expertise. This equates to approximately 10,000 hours of work which, according to Gladwell (2008) is key to achieving world-class expertise in any skill.

Brainstorming is an activity where a group of people converge to generate innovative ideas and solutions in a particular area of interest by removing inhibitions such as criticism (Osborn, 1963). Some researches refute the potential of brainstorming to generate more ideas than individuals working alone (Diehl and Stroebe, 1987). Nevertheless, Isaksen (1998)'s review of 50 brainstorming studies showed that a lack of understanding and poor application of brainstorming methods was responsible for weakened the results and validity of their conclusions.

A common weakness in brainstorming is blocking. Blocking is the situation where one participant gives an idea and the other participants in a team brainstorming session forget an idea they were going to share or decide not to share it because they think it is inferior or no longer relevant (Haddou et al., 2014). This can limit the number of ideas generated in group brainstorming and their novelty compared with individuals working separately.

To prevent blocking, an initial HFMEA training session was conducted with the participants and the team idea mapping method of brainstorming was carefully

explained. Team idea mapping starts with a well-defined topic, which aligns with the HFMEA methodology. Each member of the team brainstorms individually before all the ideas are merged together. During the ideas merging process, participants discover commonalities in their interpretation of the failure modes in the treatment process as they share their experiences. At the same time, new understandings and ideas are built through association and added to the existing ones.

Using an Excel spreadsheet, participants were requested to anticipate where things might go wrong within the treatment process for Patient A due to unreliable power. As discussed in Chapter 2 (Section 2.9.1), unreliable power in this context is defined under the following power quality parameters: transient disturbances, power interruptions, under-voltage, over-voltage, waveform distortion, voltage fluctuations and frequency variations (IEEE, 2009; Seymour and Horsley, 2011) (see Appendix N for definitions). These parameters were carefully defined and described to each participant. The causes of unreliable power supply in the health facility were restricted to four mutually agreed origins as most common events namely: insufficient power due to other users and power outage, low voltage from grid, grid voltage fluctuations and back-up generator problems.

3.5.2 Event Resilience Index Calculation

As discussed in Chapter 2, ERI is the ratio between electric loads served after an event and before the event. In settings where grid reliability is indeterminable, a power system can be designed to make a facility resilient to unplanned power outages by calculating its event resilience index using its minimum and maximum operational power requirements.

For this research, the electric power demand for essential loads - both conventional and energy efficient devices - represent the maximum operational load. On the other hand, the reduced energy demand derived from the HFMEA assessment represents the minimum operational load for the selected treatment process. Therefore, the DER system required for the health facility to become resilient to unexpected power outages while providing critical services is calculated as follows:

$$\text{Event Resilience Index (ERI)} = \frac{\text{Loads served during event (min)}}{\text{Loads served before the event(max)}} \quad (3-1)$$

The ERI calculation is a product of the dual-level energy demand assessment approach employed in this study. The ERI can be used to compare ERI figures for health facilities in other settings.

3.6 Phase 3

Phase 3 of the research design includes the case study analysis of the energy resource potential of six cities from Nigeria's six geopolitical regions. Each location presents different climatic conditions. Therefore, detailed study of long term wind speeds, solar insolation and river flow speed data in these cities is necessary to predict energy output potential and design systems to convert these into electricity. Furthermore, the Hybrid Optimisation Hybrid Optimization of Multiple Energy Resources (HOMER) modelling software is used in simulating optimal DER systems to supply electricity to the selected health facility assuming it is located in each city.

3.6.1 Case Study Cities

The six cities investigated were selected from each of Nigeria's six geopolitical zones as discussed and illustrated in Section 2.15. Each city is the capital of a state in each of Nigeria's regions. Capital cities in Nigeria typically have the largest populations out of every city in each state because the government is the biggest employer of labour (Akeju, 2016). This study is aimed at grid-connected settings with unreliable power supply. These cities represent locations where the effects of unreliable power supply are most felt because of their large populations.

The potential for solar power at each site was analysed based on solar parameters including monthly direct nominal irradiance (DNI), diffuse irradiance, ground reflected radiation and clearness index. Radiation and clearness index data spanning a 22-year period (1983 – 2005) were obtained from National Solar Radiation database of NREL.

Wind power potential was evaluated based on monthly wind speed data measured at a hub height of 24 m. The wind speed data collected over a period of 10 years from 1983 to 1993 were obtained from NASA surface meteorology and solar energy database of worldwide energy resources (NASA, 2017). Other wind power parameters used in the analysis include Weibull k values, 1-hour autocorrelation factor, diurnal pattern strength and hour of peak wind speed.

Microhydro potential was determined using Nigeria's highest national river flow velocity in m/s to estimate the flow rate for all the cities. River flow speeds are directly proportional to level of precipitation (FAO, 2017). Port Harcourt, known to have one of the highest precipitation levels in Nigeria (AQUASTAT, 2016) was assumed to have the highest flow speed of 6 m/s.

3.6.2 Hybrid Optimisation of Multiple Energy Resources – HOMER

As described in Chapter 2, HOMER is the modelling software employed in assessing the techno-economic and environmental feasibility of utilising hybrid solar, wind, microhydro, ESS, and diesel generator systems in combination with the grid. HOMER uses energy resource and economic data including system constraint inputs to generate optimal power supply systems for selected energy demand profiles.

Chapter 4 is used to describe the modelling of hybrid power supply and storage technologies. Solar, wind and hydro resource data used in analysing renewable energy potential for the selected sites are presented in the next chapter. The equations and modelling techniques employed by the HOMER software to calculate the resource potentials are also described including the energy conversion technologies employed.

Besides direct comparisons between systems generated, the cost of energy of each optimal system's affordability is benchmarked against a figure of \$0.14 /kWh, which is twice Nigeria's 2016 grid tariff for health facilities. For environmental viability, the CO₂ emissions of generated systems were benchmarked against WHO prescribed figure of $\leq 1000 \text{ gCO}_2\text{-eq /kWh}$ for level 3 health facilities.

3.7 Summary and Contribution to Knowledge

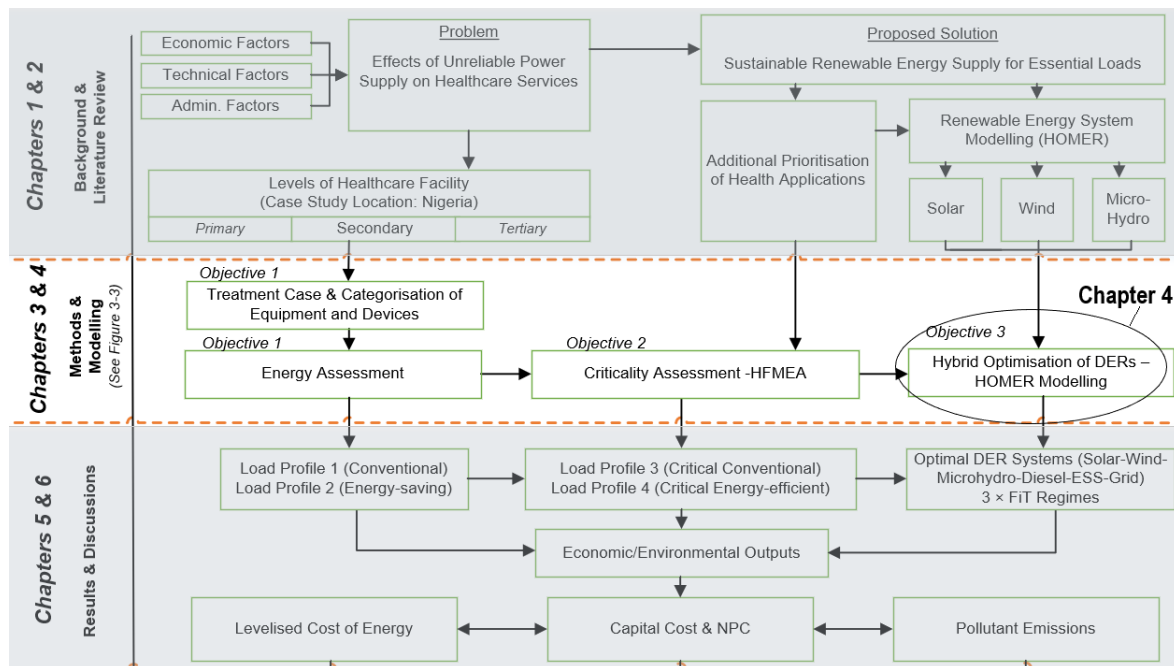
Gaps in existing health energy assessment frameworks were identified and discussed. Existing frameworks are over-reliant on supply-side management approaches for provision of reliable and environment-friendly energy in resource constrained settings. The conceptual framework employed in conducting this research was described with respect to current developments in health energy provision frameworks. The development of lower level energy demand as a demand-side strategy to provide reliable, low cost and environment-friendly health

energy was highlighted. The research design including the three phases of the research process have been described. Phase 1 covered pre-energy assessment activities including their methods, and the energy assessment technique employed. Phase 2 includes the procedure for criticality assessment of treatment steps using the HFMEA technique to produce a lower energy demand level. Phase 3 introduced the six case study cities and the modelling method used in simulating optimal energy systems.

The key contributions to knowledge highlighted in this chapter include:

- Gaps in existing health energy frameworks were highlighted. Current frameworks are over reliant on supply-side interventions. An advancement using a demand-side intervention has been proposed to create lower energy demand levels.
- Advancement of current health energy provision frameworks to also include: a focus group of experts to determine essential electric loads; a HFMEA criticality assessment to prioritise essential loads; and evaluating pollutant emissions in $\text{gCO}_2\text{-eq /kWh}$ to determine CO_2 emissions per unit energy generated.
- The introduction of spatial analysis into the assessment of energy demand for facilities in developing countries to have a basis for comparing energy use in different settings.
- Deployment of the Health Failure Modes and Effects Analysis as a tool for identifying and prioritising critical electrical applications in the treatment of an identified life-threatening incident.
- Application of event resilience index to measure the required resilience of stand-alone power systems using demand-side parameters.

4 HYBRID OPTIMISATION OF MULTIPLE ENERGY RESOURCES AND ENERGY STORAGE SYSTEMS



4.1 Introduction

This chapter presents the description of input variables modelled in HOMER and how HOMER calculates its outputs. Variables required in HOMER include electric load profile, energy resources, power generation components and energy system economic and environmental constraints (see Figure 2-12). Sensitivity analysis were conducted based on three feed-in-tariffs and four load profiles. The modelling outputs include economic results such as cost of energy, net present cost and capital cost. System results include system configurations, energy input and power output of each component, and total annual power generated by the system. Environmental or pollutant emissions results include all the emissions associated with the power generation technologies modelled.

HOMER is a simulation model that allows users to simulate viable systems for all possible power generating equipment they intend to consider. As discussed in Chapter 2, HOMER evaluates every feasible combinations of system types in each run and sorts the systems by the selected optimisation variable. In this research, the cost of energy has been selected to determine the least-cost options for distributed generation of electricity. By using the sensitivity analysis capabilities in HOMER,

these least-cost options are further evaluated for least capital cost, lowest pollutant emissions and best reliability considerations. The sensitivity analysis allows the observation of the impact of variables beyond the user's control on the optimal systems. Detailed description of the methods and algorithms used in the HOMER software can be found through this [link](#)¹³.

4.2 Variables Modelled in HOMER

There are 231 input variables in HOMER (HOMER Energy, 2017). These allow the software to determine if the user-specified configurations and conditions can meet load demand and to estimate the cost of installation and operation over the lifetime of the system. As illustrated in Chapter 2 (Figure 2-12), the categories of input variables are loads, resources, components and optimisation.

The modelling of multiple values for variables used is employed as the means of validating the results of the optimisation of DERs in the selected regions of Nigeria. Chapter 6 entirely focuses on determining the importance of selected natural, technical and economic variables by specifying a range of value and observing how the changes affect the optimised solutions.

Nevertheless, energy demand and energy resource sensitivity analyses are conducted in this chapter to see how the outputs from the model change in response to changes in input variables. For example, different energy demand values and different location conditions are modelled to determine the optimal and least expensive supply configurations for different loads and locations.

4.2.1 Load

The input loads used in the simulations are based on four loading scenarios based on energy demand assessment for standard and energy-efficient loads for essential loads and most critical loads in the health facility as described in Chapter 3. The values determined from the energy assessment are used as primary loads in the simulations. The first load profile represents all essential loads in the facility assuming all the devices are conventional. Representing the essential loads of energy-efficient devices is the second load profile.

¹³ https://www.homerenergy.com/products/pro/docs/3.11/homers_calculations.html

The third and fourth load profiles are determined after the treatment process has been risk-assessed to determine the most critical electrical applications to be prioritised. These profiles represent prioritised conventional and energy-efficient devices respectively to present lower energy demand profiles, which will potentially require less expensive power supply systems.

4.2.1.1 Daily and hourly noise

Day-to-day (daily) and time-step-to-time-step (hourly) noise refer to variations in actual power demand and operations in the hospital. As it is common in many power systems, load variations are likely to occur on an hourly or daily basis. If the total energy demand calculated is modelled without noise, the software will repeat the load profile precisely every day. Whereas, in real life, the size and duration of power usage will vary. Therefore, a daily and hourly noise is added to the models to make the demand data more realistic.

Due to the absence of daily measured data for an entire year, for all the simulations conducted, the assumption was that there is a 10% daily noise and 20% variance for a time step size of 60 minutes. These figures are presented in Table 3-3 of Chapter 3. With these, HOMER randomly perturbs the daily load profile from a normal distribution with a mean of 0 and standard deviation equivalent to 10%, once daily. Furthermore, the hourly load profile is randomly perturbed every 60-minutes from a normal distribution with a zero mean and 20% standard deviation.

If the noise inputs are left as described above, the load profile will retain the same shape throughout the day, every day. However, by selecting a community facility load profile during the design stage, HOMER scales the load profiles upwards and downwards for different periods of the day (Figure 4-1) and months (Figure 4-2) and based on available statistics of operational patterns for community facilities. shows the load profile for a whole year used in HOMER for every model conducted in this research. See Chapter 5 for electric load figures.

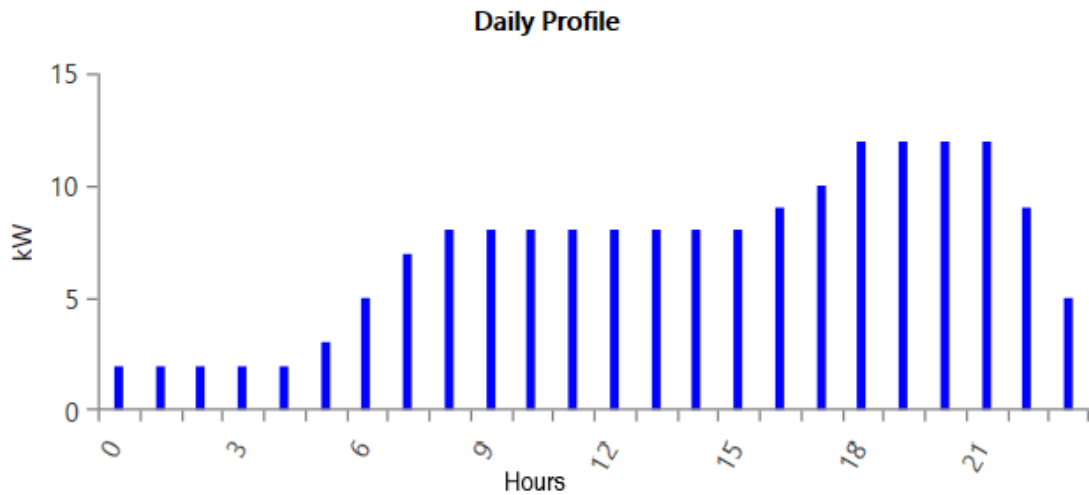


Figure 4-1: Daily load profile for January using conventional equipment. Source: sample HOMER model load profile

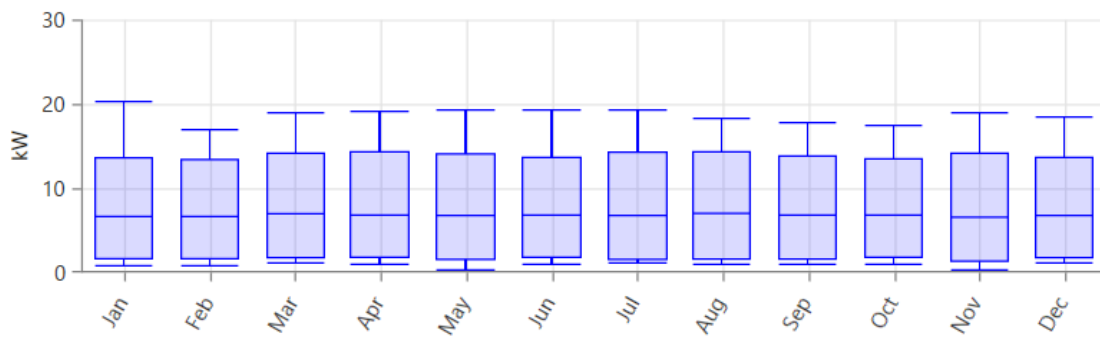


Figure 4-2: Seasonal load profile

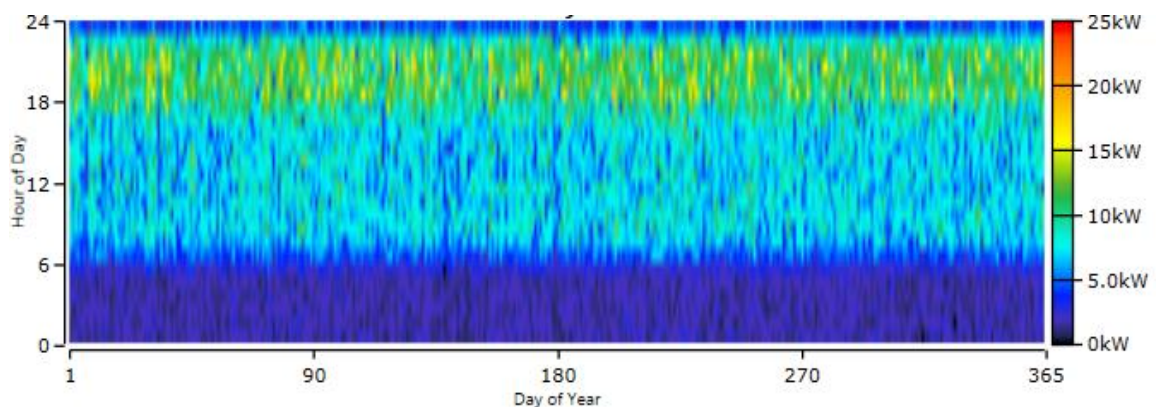


Figure 4-3: Yearly load profile

4.2.1.2 Variable Power Requirements and Energy Demand

For all the simulations conducted, four load profiles were deployed. Total energy demand for profiles are 21.53, 14.29, 7.31 and 4.82 all in kWh/day. The determination of these figures is presented in the energy assessment in the next

chapter. The first scenario includes the power requirements for all medical devices and appliances at the higher end range for conventional equipment. The second also considers all electrical equipment however, at the lower end range for energy-efficient devices.

The third and fourth load profiles include power requirements for standard and energy-saving critical equipment only respectively. These critical devices and appliances are also determined in Chapter 5.

While patterns of operations vary significantly in actual health facilities, the assumption for the case facility used was that the clinic operates mostly during daytime hours and essential equipment like refrigerators draw power intermittently throughout the night. Energy demand are presumed minimal during the early hours of the day while combined processes, such as multiple non-emergency blood testing, are usually deferred to night hours.

4.2.2 Resources

In HOMER, anything that is external to the power system is regarded as a resource. Evaluating the resource potential of each city is a means of validating the results of the hybrid optimisation of multiple energy resources. Cities with relatively high solar, wind or hydro resources should produce systems that seek to prioritise solar, wind and hydro conversion technologies. Table 4-1 shows the resources that are used for the associated renewable energy component in the HOMER models employed in this study.

The distributed energy resources modelled include solar GHI (Global Horizontal Irradiance), monthly average temperature, wind speed, fuel (diesel) and hydrokinetic resource (water speed). These were used to model hybrid microgrids composed of multiple combinations of solar PV, wind turbine, standalone electric generator and hydrokinetic turbine components.

The choice of these technologies is based on the evidence, from literature (NNPC, 2011; Obideyi, 2017; UNDP and ECN, 2006), of the abundance of these resources and access to the technologies to convert them to electricity in Nigeria. Furthermore, the estimation of the availability of wind, solar and hydro resources in Nigeria are fairly uniform in literature.

Table 4-1: Resources and associated components in HOMER (HOMER Energy, 2017)

Resource	Components	Relevance
Solar GHI Resource	PV (Flat Panel)	✓
Solar DNI Resource	PV (Concentrating PV)	x
Temperature Resource	PV, Wind Turbine	✓
Wind Resource	Wind Turbine	✓
Fuel Resource	Generator, Boiler, Reformer	✓
Hydrokinetic Resource	Hydrokinetic	✓
Hydro Resource	Hydro Component	x
Biomass Resource	Biogas Generator	x
Custom Resource	Custom Component	x

These resources, including biomass, form the basis for the country's renewable energy masterplan from 2015 to 2025 (UNDP and ECN, 2006). However, biomass is excluded due to a significant disparity the estimation of available biomass resource available in Nigeria in research publications. Using any of these estimates will render the results of simulations conducted unreliable.

4.2.2.1 Calculation of the Radiation Incident on the Solar PV Array

HOMER employs the methods in the first two chapters of Duffie and Beckman, (1991) to calculate the radiation incident on the surface of the PV array. The methods involve calculating various factors that determine the amount of radiation incident of the surface of the PV array.

The Solar GHI Resource page in HOMER allows for the specification of the Global Horizontal Irradiation (GHI) for each time step (monthly in this study) in the simulations. Solar GHI is the total amount of solar radiation striking the horizontal surface on the earth (Duffie and Beckman, 1991; HOMER Energy, 2017). However, the power output of a PV array is dependent on the quantity of radiation that strikes the surface of the PV array, which is typically not horizontal. Therefore, in each time

step, HOMER calculates the global solar radiation incident on the surface of the PV array.

As shown in Figure 4-4, Solar GHI is the combination of beam radiation (also known as direct nominal irradiance, DNI), diffuse irradiance and ground reflected radiation. HOMER uses the average global horizontal radiation to calculate the clearness index, then the diffuse radiation for every time step. It then calculates the beam radiation by subtracting the diffuse radiation from the global horizontal radiation. Appendix C gives detailed step-by-step description of how ground reflected radiation and all the factors are calculated.

Solar GHI is used to calculate flat panel PV array output (Boland, Scott and Luther, 2001; Erbs, Klein and Duffie, 1982; Graham and Hollands, 1990), which is the case in this research. Whereas, concentrating PV uses the Solar DNI resource. Concentrating PV only captures DNI, the beam radiation component of GHI.

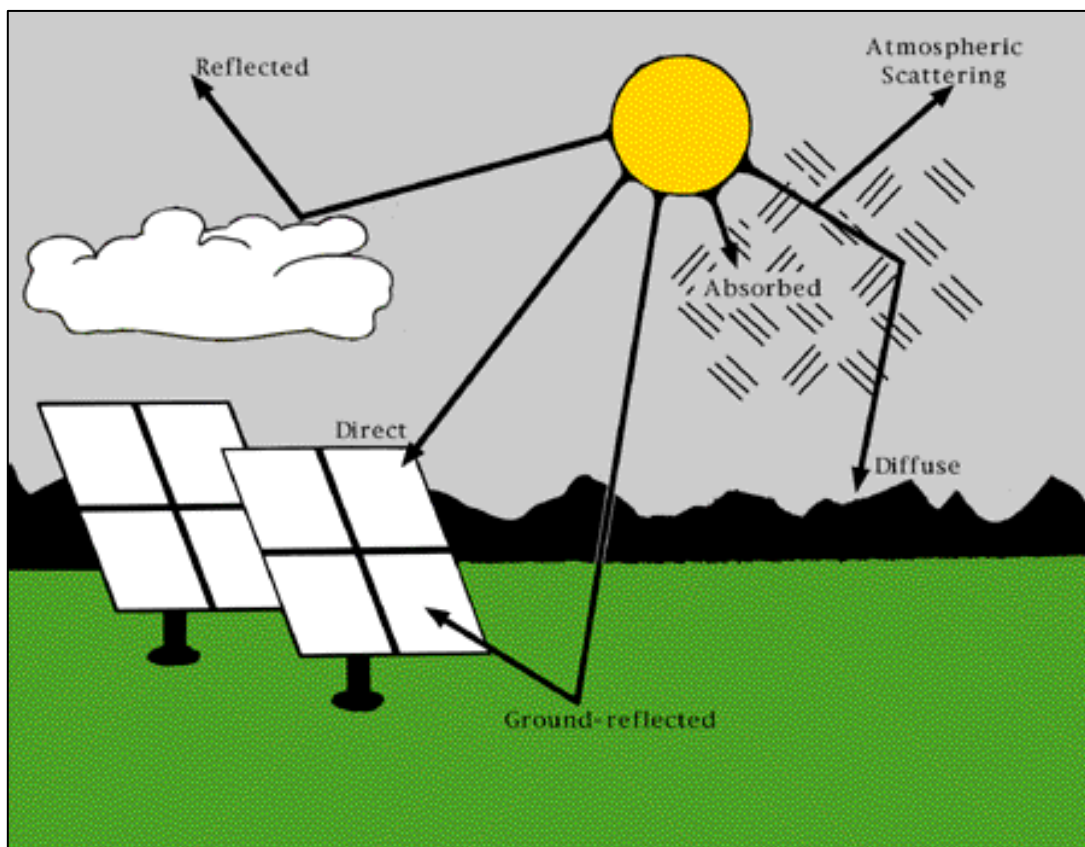


Figure 4-4: Global Horizontal Irradiance (GHI) (HOMER Energy, 2017)

The clearness index is a measure of the atmosphere's clearness. It is the portion of the solar radiation that is transmitted through the atmosphere to strike the surface

of the Earth. Clearness index is a dimensionless number between 0 and 1, calculated as the surface radiation divided by the extra-terrestrial radiation (Boland et al., 2001; HOMER Energy, 2017; Sorensen, 2011). The clearness index is low value under cloudy conditions, and high under clear, sunny conditions.

The clearness index can be derived instantaneously, hourly, or monthly. Its values in HOMER's Solar Resource inputs page are monthly average values. The symbol for average monthly clearness index is k_T and is calculated using equation (4-1) below.

$$k_T = \frac{\bar{G}}{\bar{G}_o} \quad (4-1)$$

Where:

- $\bar{G}$ = the global horizontal radiation (solar radiation striking a horizontal surface at the bottom of the atmosphere) on the earth's surface averaged over a time step [kW/m²]
- $\bar{G}_o$ = the extra-terrestrial horizontal radiation (solar radiation striking a horizontal surface at the top of the atmosphere) averaged over a time step [kW/m²]

Typical values of k_T range from 0.25 (a really cloudy month, such as an average December in London) to 0.75 (a really sunny month, such as an average June in Phoenix) (HOMER Energy, 2017).

Some of the solar radiation incident on the earth's surface is beam radiation. This is the solar radiation that travels directly from the sun to the earth's surface without getting dispersed by the atmosphere (HOMER Energy, 2017). Beam radiation, also known as direct radiation, casts a shadow. The rest of the solar radiation is called diffuse radiation. This is the solar radiation whose direction has been altered by the earth's atmosphere. Diffuse radiation does not cast a shadow and comes from all parts of the sky. The addition of beam and diffuse radiation is called global solar radiation. Global solar radiation is expressed as:

$$\bar{G} = \bar{G}_b + \bar{G}_d \quad (4-2)$$

Where:

$\bar{G}_b$ = the beam radiation [kW/m²]

$\bar{G}_d$ = the diffuse radiation [kW/m²]

Distinguishing between beam and diffuse radiation is important when evaluating the quantity of radiation that is incident on a tilted surface. The effect of the positioning of the surface is stronger on beam radiation, which originates from only one part of the sky, than it does on the diffuse radiation, which emanates from every part of the sky (HOMER Energy, 2017).

However, only the global horizontal radiation, not its beam and diffuse fractions, are measured in most calculations. Consequently, HOMER expects the user to insert global horizontal radiation in its Solar Resource inputs page. This implies that, HOMER must resolve the global horizontal radiation into its components, in each time step, to find the incident radiation on a PV array. HOMER employs the correlation in Erbs et al. (1982), which calculates the diffuse fraction of the radiation as a function of clearness index, using the following equation:

$$\frac{\bar{G}_d}{\bar{G}} = \begin{cases} 1.0 - 0.09 \cdot k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604 \cdot k_T + 4.388 \cdot k_T^2 - 16.638 \cdot k_T^3 + 12.336 \cdot k_T^4 & \text{for } 0.22 < k_T \leq 0.8 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \quad (4-3)$$

In HOMER Energy (2017), the HDKR (Hay, Davies, Klucher, Reindl) model is used to compute the global radiation striking the inclined surface of a PV array. The model proposes three elements of diffuse solar radiation, namely: an isotropic element that emanates from all parts of the sky evenly; a circumsolar element that comes from the direction of the sun; and a horizon brightening element that comes from the horizon. However, the three factors governing these components must first be defined before applying this model.

The first factor refers to the ratio of beam radiation (R_b) on the tilted surface to beam radiation on the horizontal surface, given as

$$R_b = \frac{\cos \theta}{\cos \theta_z} \quad (4-4)$$

Where:

θ = the angle of incidence [°]

θ_z = the zenith angle [°]

The second factor is the anisotropy index (A_i). It is the measure of the atmospheric transmittance of beam radiation. A_i helps in estimating the quantity of circumsolar diffuse radiation, also known as forward scattered radiation. This factor is depicted as:

$$A_i = \frac{\bar{G}_b}{\bar{G}_o} \quad (4-5)$$

The last factor accounts for horizon brightening and explains why more diffuse radiation comes from the horizon than from the rest of the sky (HOMER Energy, 2017). It is associated with cloudiness and is presented as:

$$f = \sqrt{\frac{\bar{G}_b}{\bar{G}}} \quad (4-6)$$

Using the HDKR model, HOMER computes the global radiation incident on a PV array using the following equation:

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i) R_b + \bar{G}_d (1 - A_i) \left(\frac{1 + \cos \beta}{2} \right) \left[1 + f \sin^3 \frac{\beta}{2} \right] + \bar{G}_g \left(\frac{1 - \cos \beta}{2} \right) \quad (4-7)$$

Where:

$\bar{G}_T$ = global radiation incident on PV array

$\bar{G}_b$ = the beam radiation [kW/m²]

$\bar{G}_d$ = the diffuse radiation [kW/m²]

A_i = anisotropy index

R_b = the ratio of beam radiation on slanted surface to beam radiation on horizontal surface

β = the slope of surface [°]

f = factor accounting for horizon brightening

ρ_g = the ground reflectance, also known as the albedo [%]

4.2.2.1.1 Solar Radiation Data

The baseline solar data required in HOMER is a one-year time series that represents mean global solar radiation on a horizontal surface for each time step of the year, expressed in kWh/m². HOMER presents the average monthly radiation and clearness index of the baseline data in a graph and table on the Solar Resource window.

There are two methods of creating baseline data, a modeller can employ HOMER in synthesising hourly data from monthly averages or present time series radiation data from an external file. HOMER accepts solar radiation data as a time series or monthly averages. This study utilised monthly average solar radiation data from the TMY2 and TMY3 data sets (NREL, 2015, 2016) freely provided by the US National Renewable Energy Laboratory (NREL).

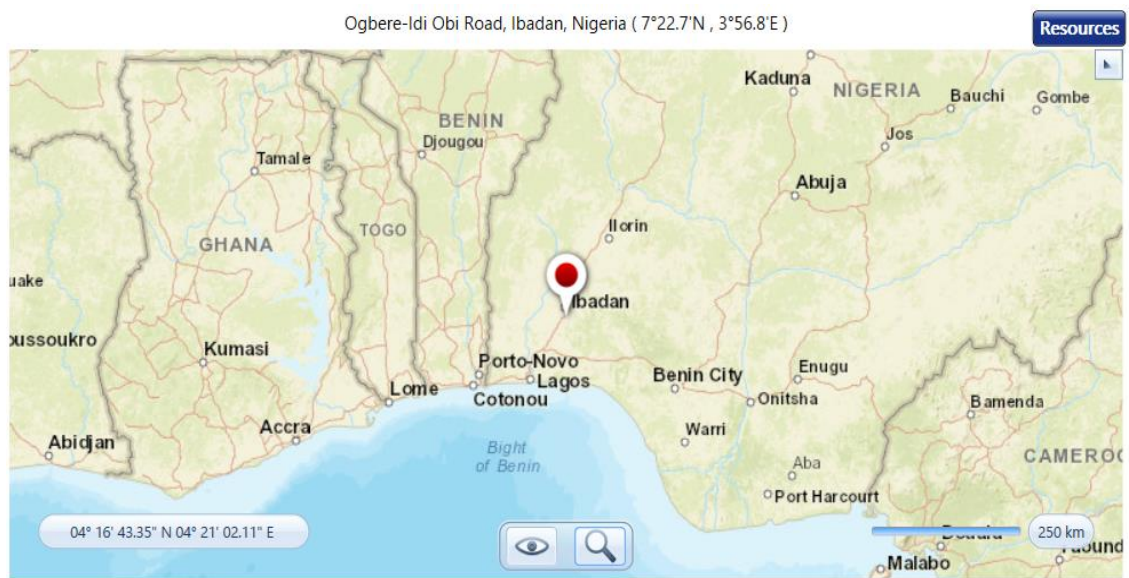
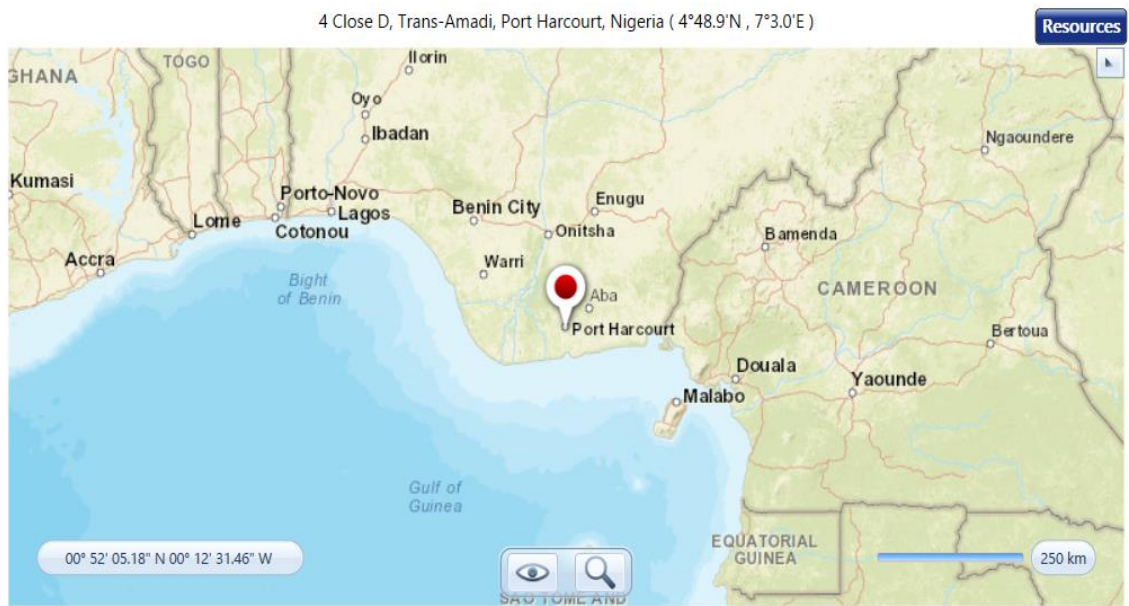
For the simulations in this chapter and the next, TMY2 and TMY3 files were imported directly into HOMER's Solar Resource Inputs window. Many peer-reviewed literatures (Baldwin et al., 2012; Helm and Kauai-Burman, 2010; Lee et al., 2012; Lopez et al., 2012; Myers, 2005; Upton and Snyder, 2017) have cited these data sets and their values strongly correlates with US National Aeronautics and Space Administration's Surface Energy Data Set (NASA, 2017). Appendix D provides details of the sources of resource data used in the simulations.

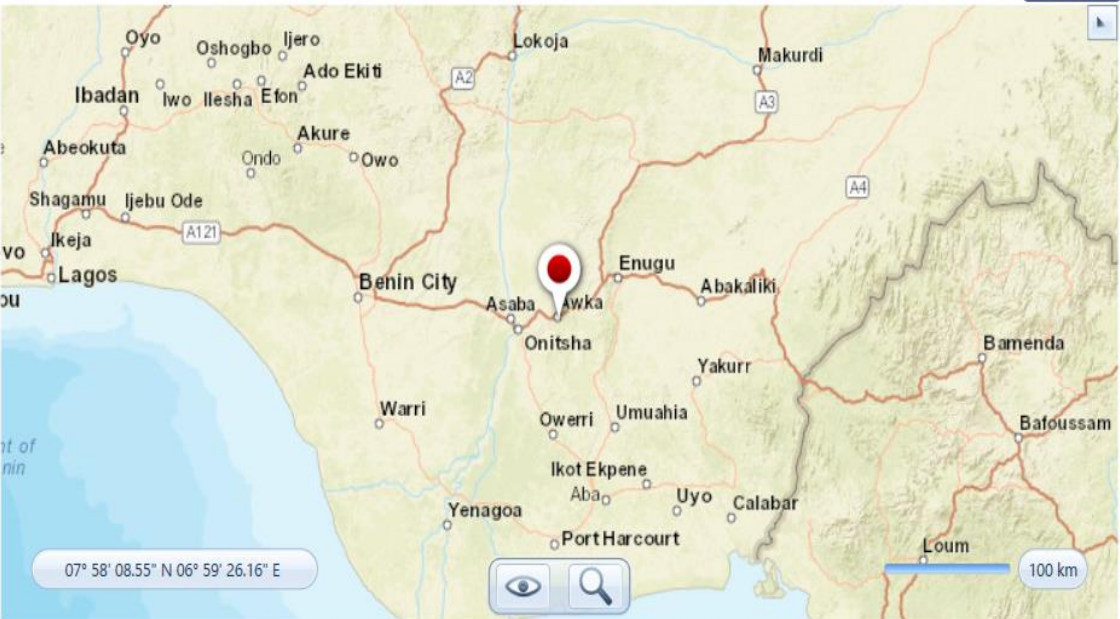
4.2.2.1.2 Locations

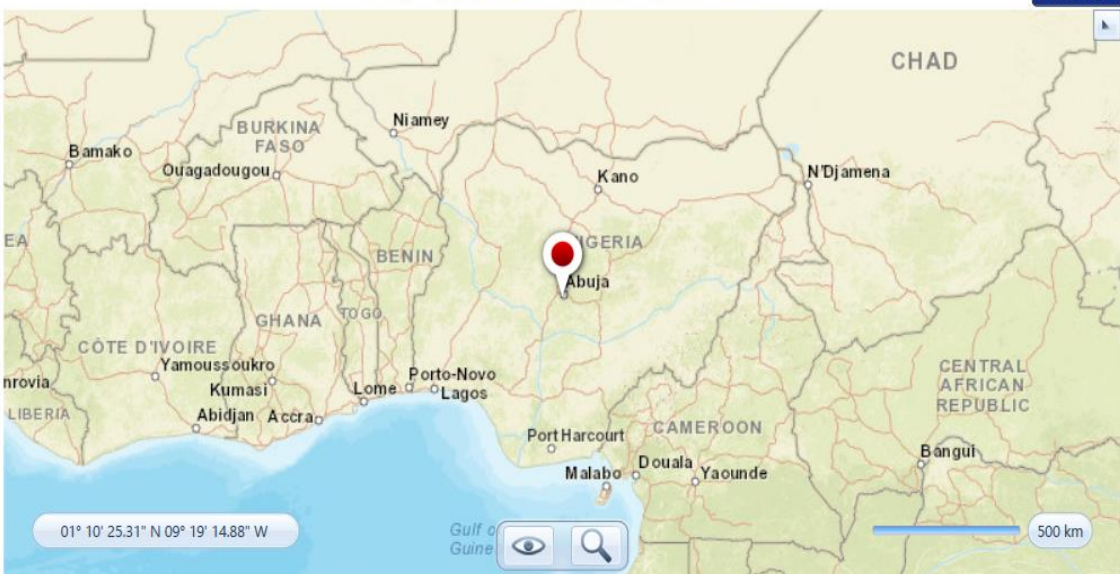
For the main simulations, six major cities, one in each of Nigeria's geopolitical zones, are selected to determine the optimal microgrid configurations for the selected hospital and treatment case. In HOMER, a city can be searched directly from the map function in the home page and the longitude and latitude will appear directly here. The user can also manually input the longitude and latitude of a location for better precision.

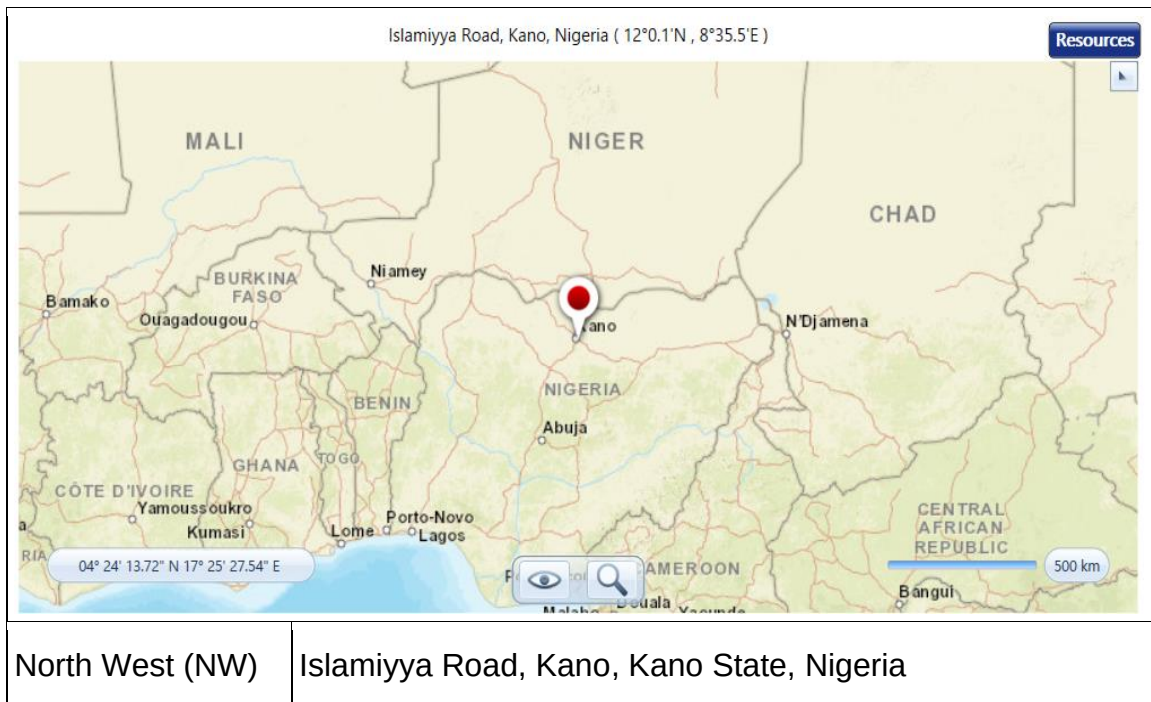
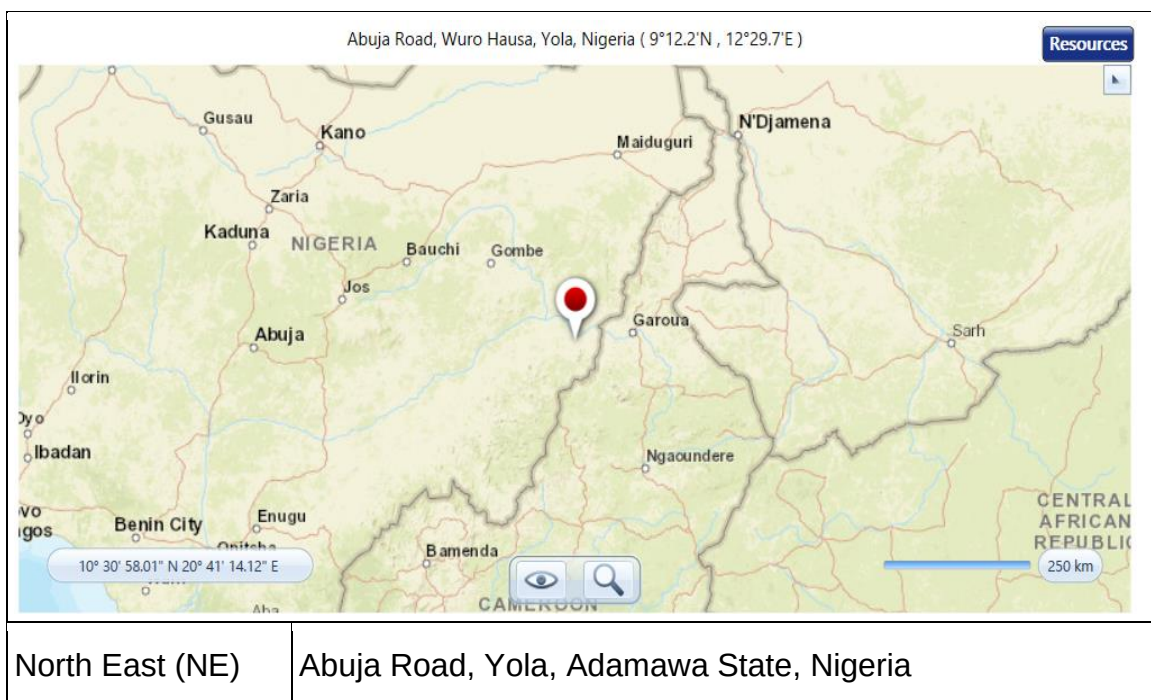
Table 4-2 shows the details of the locations selected for all the simulations in Nigeria with the corresponding states and regions of Nigeria shown on maps. The longitude and latitude values were obtained from HOMER and validated using Google Maps.

Table 4-2: Locations modelled in HOMER. Source: Researcher's elaboration using HOMER internal maps

Location Map	
Region of Nigeria	Location Address
	
South West (SW)	Ogbere-Idi Obi Road, Ibadan, Oyo State, Nigeria
	
South South (SS)	4 Close D, Trans-Amadi, Port Harcourt, Rivers State, Nigeria

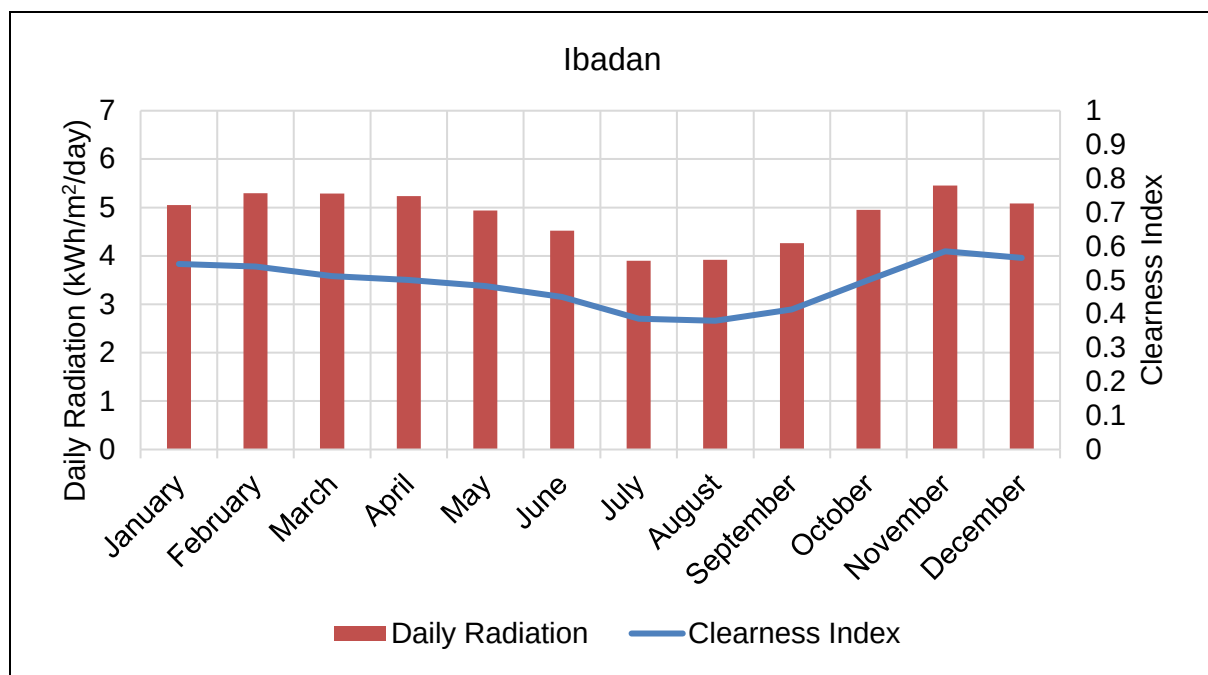
<p>G I Nwigbo Street, Awka, Nigeria (6°13.3'N , 7°4.9'E)</p> 	
South East (SE)	G I Nwigbo Street, Awka, Anambra State, Nigeria

<p>Gordian Oranika Cl, Abuja, Nigeria (9°4.6'N , 7°23.9'E)</p> 	
North Central (NC)	Gordian Oranika Close, Abuja, FCT, Nigeria



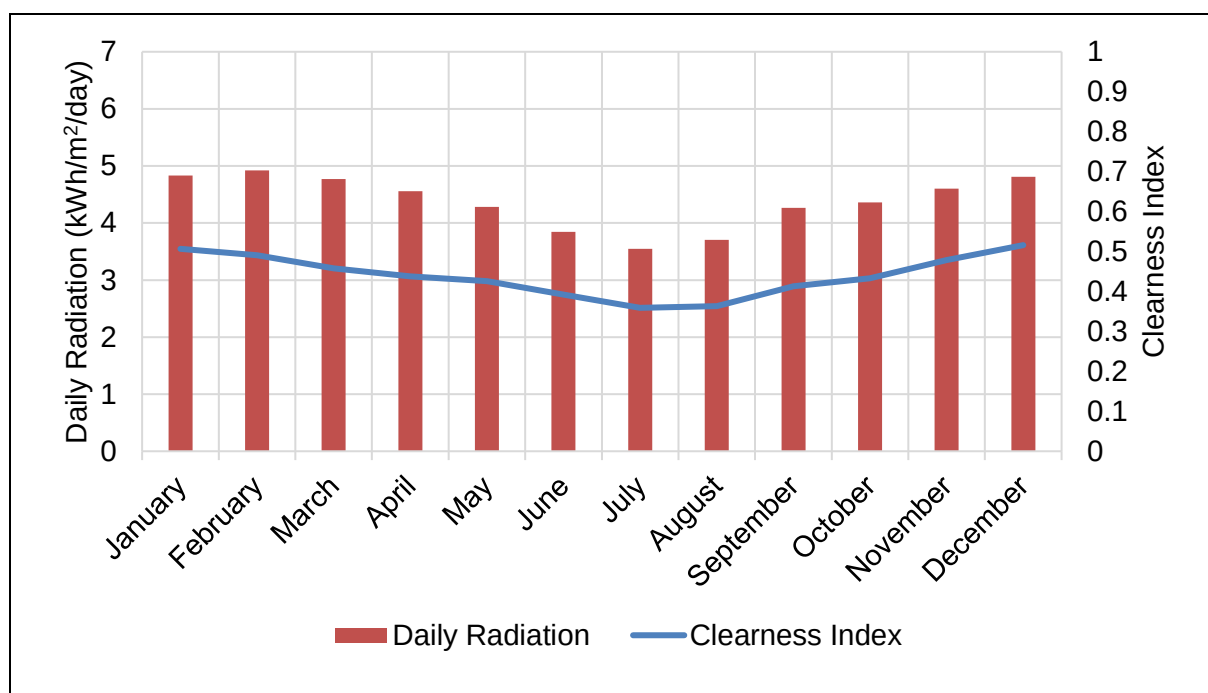
4.2.2.1.3 Input Data for Solar Resource

The charts in Figure 4-5 show solar radiation data used in the simulations run in HOMER and the Clearness Index results produced by HOMER for each location. The values represent average monthly solar irradiance in each location measured over a period of 22 years downloaded from the National Renewable Energy Lab (NREL) through HOMER.



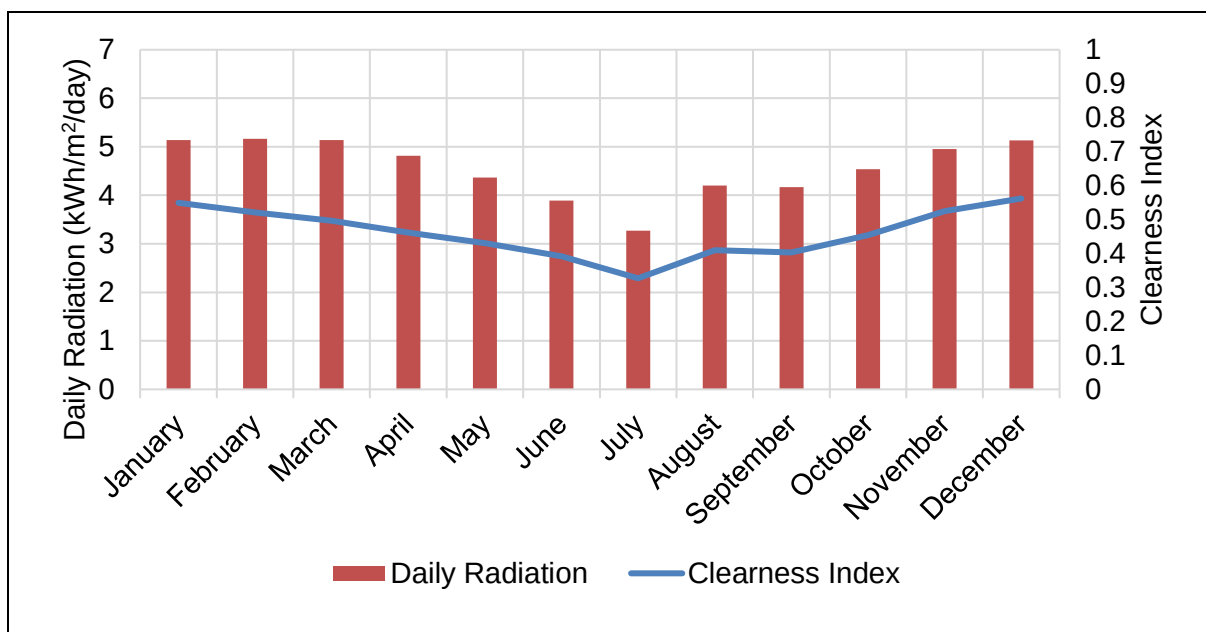
Solar GHI and daily radiation at Ibadan, South West Nigeria.

Data downloaded on 31/05/2017 13:07:49



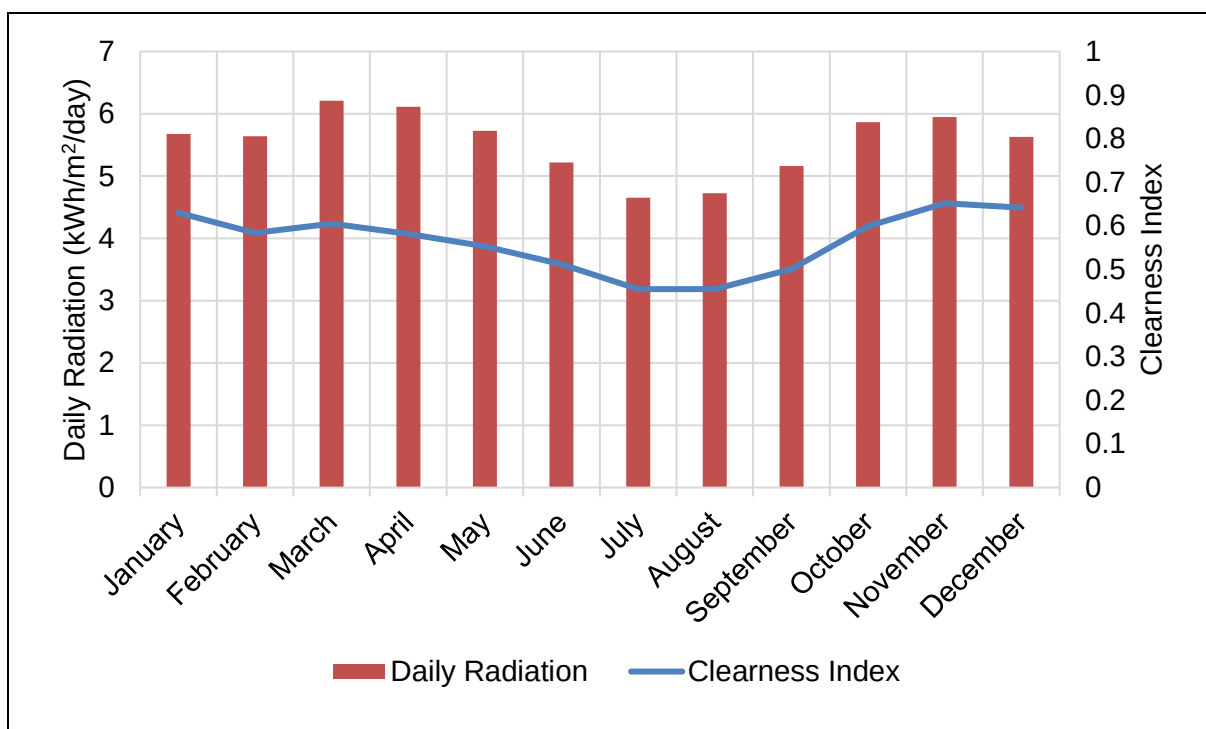
Solar GHI and daily radiation at Port-Harcourt, South-South Nigeria.

Data downloaded on 05/06/2017 22:56:47



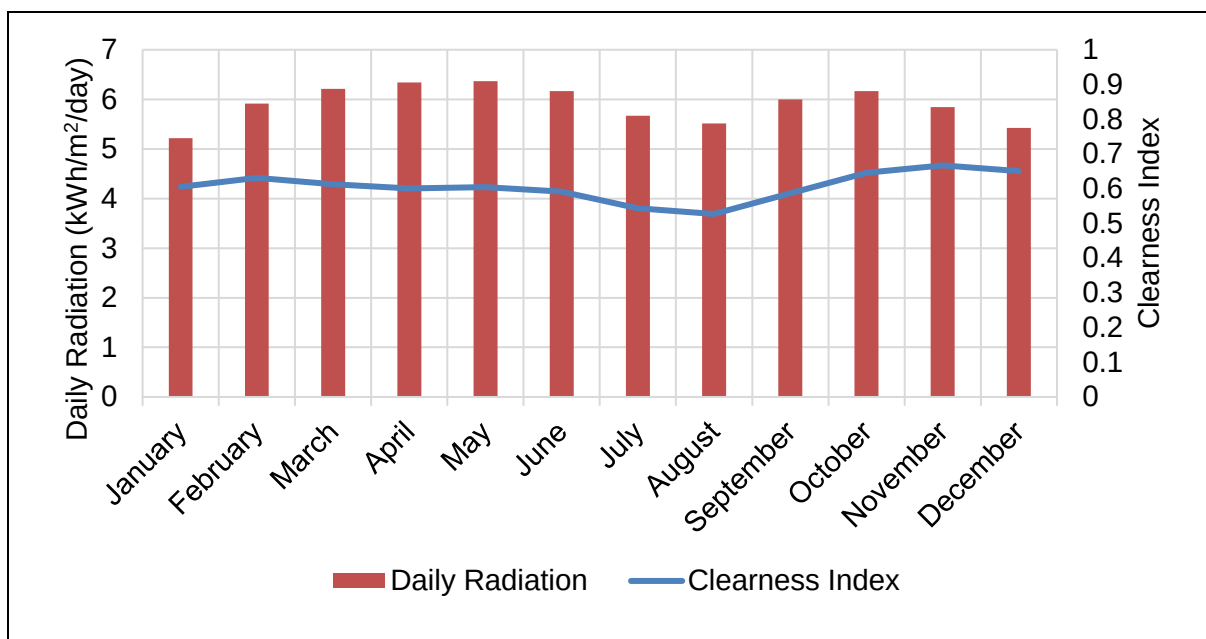
Solar GHI and daily radiation at Awka, South East Nigeria

Data Downloaded on 06/06/2017 00:11:26



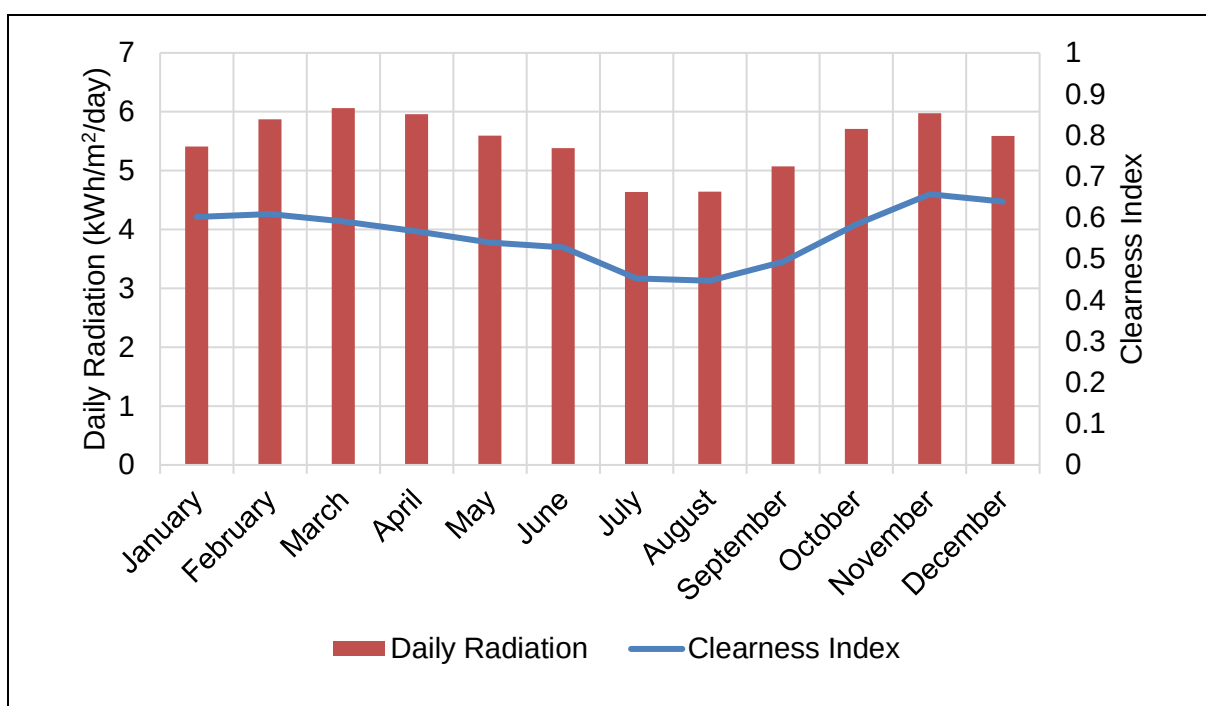
Solar GHI and daily radiation at Abuja, North Central Nigeria

Downloaded on 30/05/2017 11:59:22



Solar GHI and daily radiation at Kano, North West Nigeria

Downloaded on 06/06/2017 00:57:21



Solar GHI and daily radiation on Yola, North East Nigeria

Downloaded at 06/06/2017 00:25:42

Figure 4-5: Solar GHI vs daily radiation for case study cities. Data source: NREL National Solar Radiation Database. Monthly averaged values 1983 – 2005

4.2.2.1.4 Clearness Index Comparison between Nigeria's Geographical Regions

Analysis of the clearness index of the different regions in Nigeria shows that northern regions have clearer skies throughout the year compared with southern regions. The results plotted in Figure 4-6 align with those elaborated in Falayi and Rabi (2008). The authors used a correlation and regression analysis of meteorological and temperature data obtained from the Nigeria Meteorological Agency.

The results generally tally with the effects of northern Nigeria's Sahel climate which only sees rainfall in three to four months between June and September. The rest of the year is normally hot, dry and characterised by clear skies (Adedoyin, 1989). Whereas, the southern part of Nigeria experiences 6 months of dry and rainy weather each. The dry months come with fairly clear skies while the rainy period is dominated by heavy clouds.

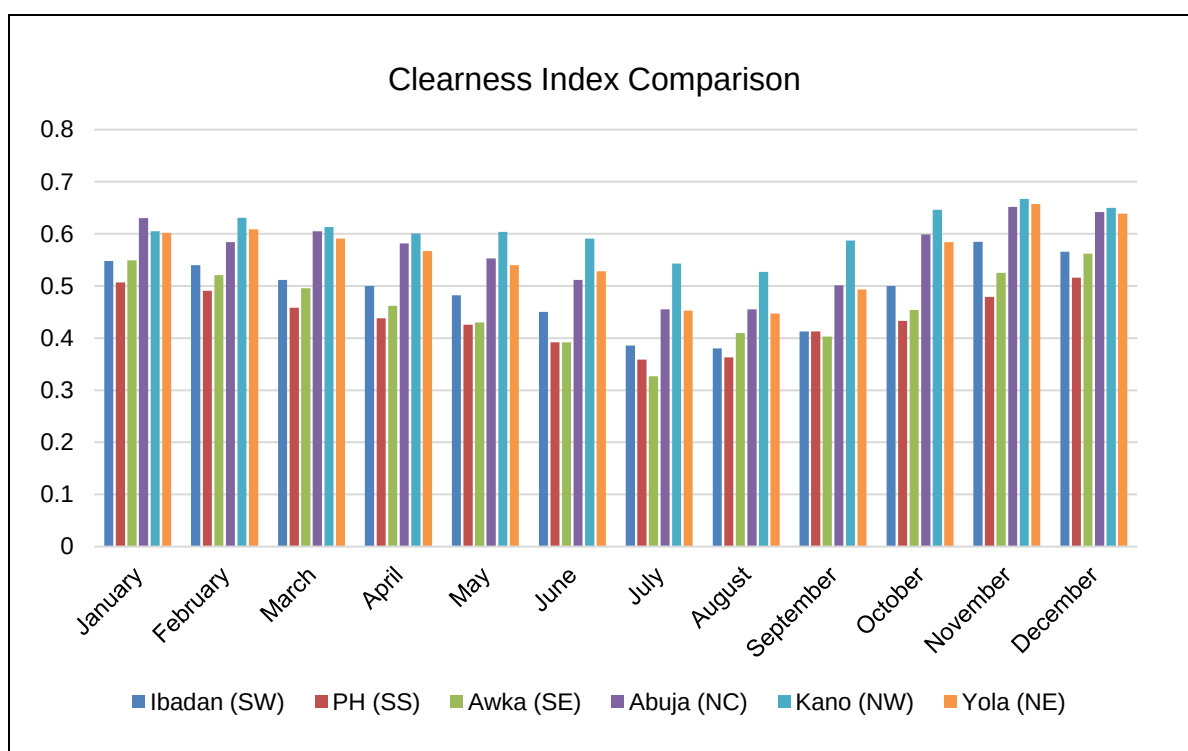


Figure 4-6: Nigeria's Regional Clearness Index – Annual (NREL, 2016)

The proximity of southern Nigeria to the Atlantic Ocean exposes its climate to the monsoons of the south Atlantic driven inland by the maritime airmass. The warmth and high humidity of this sea-to-land seasonal wind gives it a propensity to rise rapidly forming clouds of condensing water vapour and subsequent abundance of

rainfall (Krishnamurti, 2009). This cloud tends to keep the clearness index of southern Nigeria low during the rainy season between March and September.

4.2.2.1.5 Daily Radiation

The same climatic factors that influence the relatively higher clearness index in northern Nigeria are responsible for the higher daily solar radiation in northern Nigeria. Although clearness index is highly correlated with solar radiation, other factors can allow for lower solar radiation measurements in some cities despite higher measures of clearness index. For example, although Kano in Northwest Nigeria usually experiences higher clearness index than other northern cities for most of the year, its solar radiation dips below measurements in Abuja and Yola between November and January (see Figure 4-7). This is possibly attributable to higher amounts of dust in the lower atmosphere.

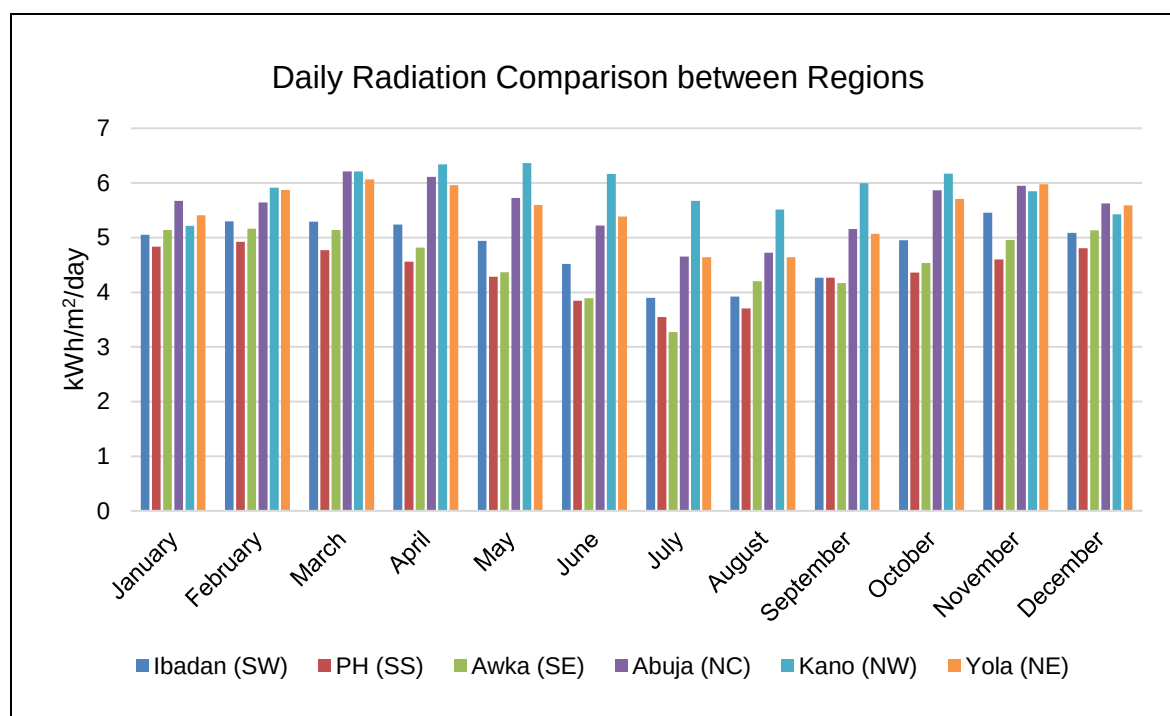


Figure 4-7: Daily Solar Radiation in Nigeria's Regions (NREL, 2016)

The above analyses suggest that the higher amounts of solar radiation in northern Nigeria makes solar power generation more viable in that region. Nevertheless, the effect of dust on incident radiation may require more frequent cleaning of PV arrays. These figures correlate with analyses provided by the Africa-EU Renewable Energy Cooperation Programme (RECP, 2017a, 2017b).

4.2.2.2 Wind Speed Data

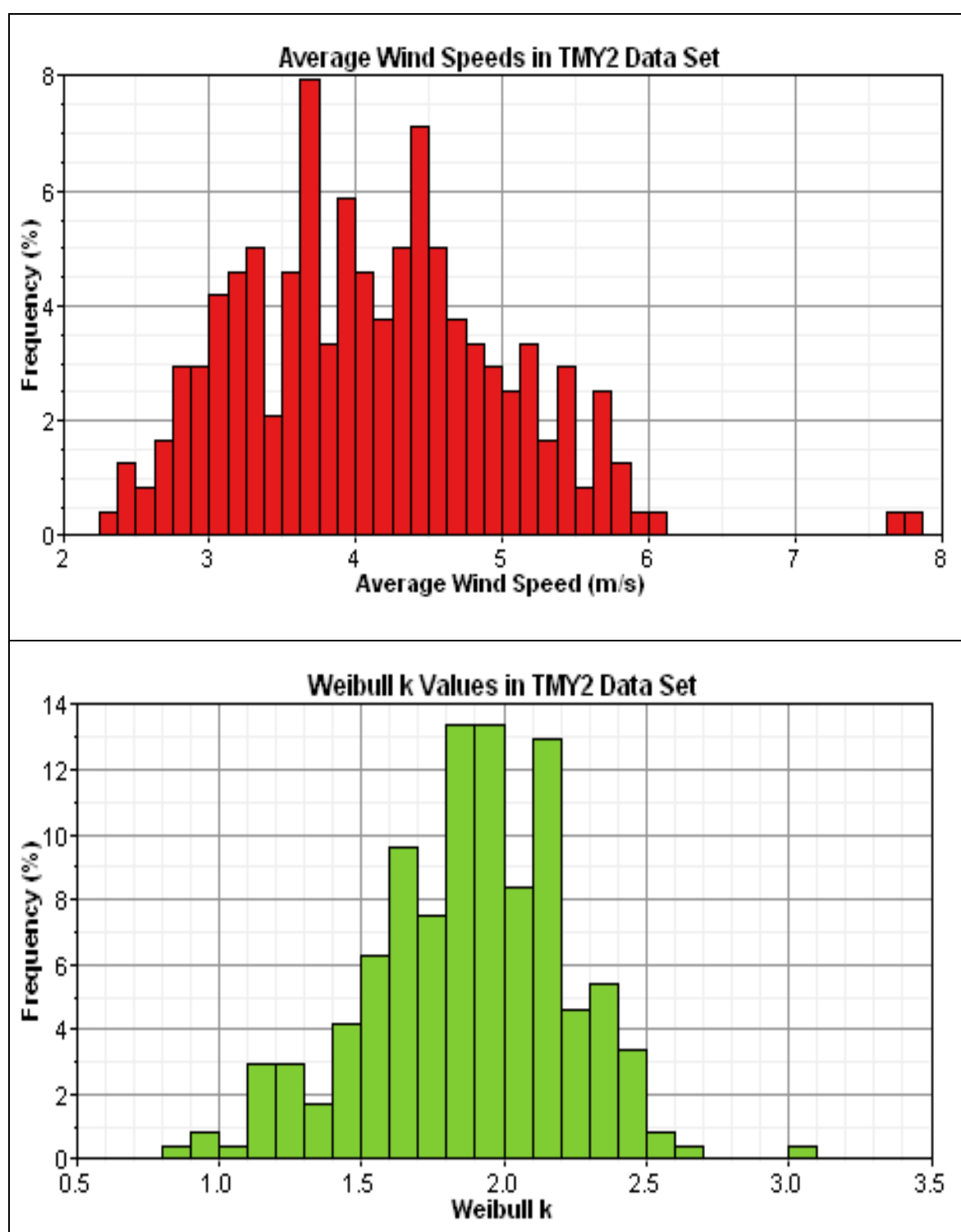
Obtaining measured wind speed data can be expensive and time consuming. Furthermore, average wind speeds typically vary significantly over short distances due to the effect of terrain changes. Therefore, the synthesis of wind speeds from estimated average monthly wind data is usually necessary (HOMER Energy, 2017).

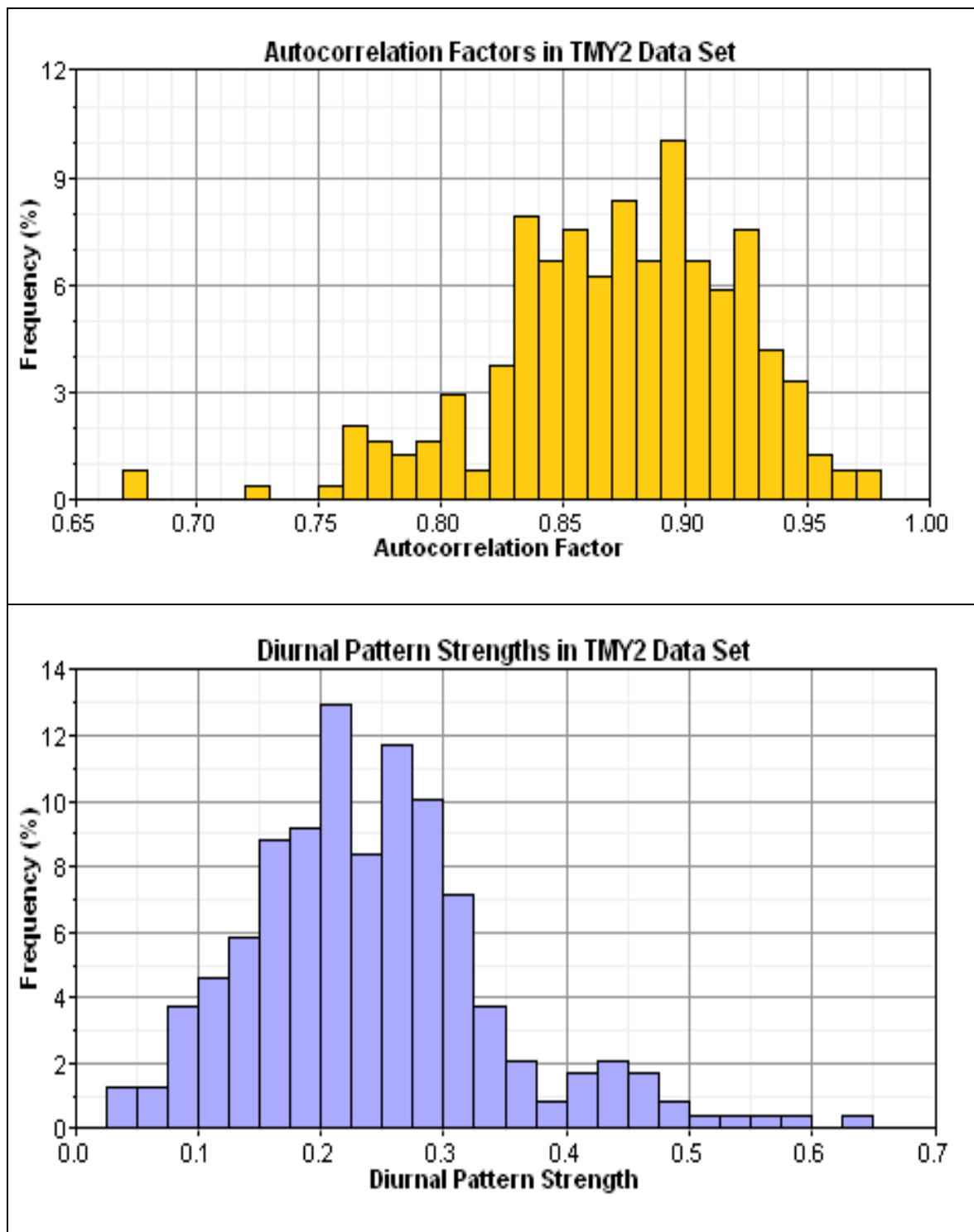
The average monthly wind speeds used in this research are obtained from the NASA Surface meteorology and Solar Energy database through HOMER. HOMER uses the monthly average wind speeds in addition to the four parameters shown in Table 4-3 to synthesise wind data for modelling.

Table 4-3: Parameters HOMER uses to Synthesise Wind Speed Data (HOMER Energy, 2017)

Parameter	Description	Default
Weibull k	Indicates the extent of the distribution of wind speeds over the year	2.0
1-hour autocorrelation factor	Indicates how strongly the wind speed in one-time step depends on the wind speed in the previous time step	0.85
Diurnal pattern strength	Indicates how strongly the wind speed depends on time of the day	0.25
Hour of peak wind speed	On average, the hour of day that tends to be the windiest	15

HOMER's resource database contains data for these parameters for some specific regions in the United States. However, HOMER's default values for these parameters are used in this study. By using measured wind data from known regions, the Wind Data Histograms Figure 4-8 are created in HOMER to describe the typical values and distributions of these parameters. The data for the 239 locations used to calculate the distributions can be found in Appendix G. This makes it possible to synthesise wind data for any location provided average wind speeds are available.





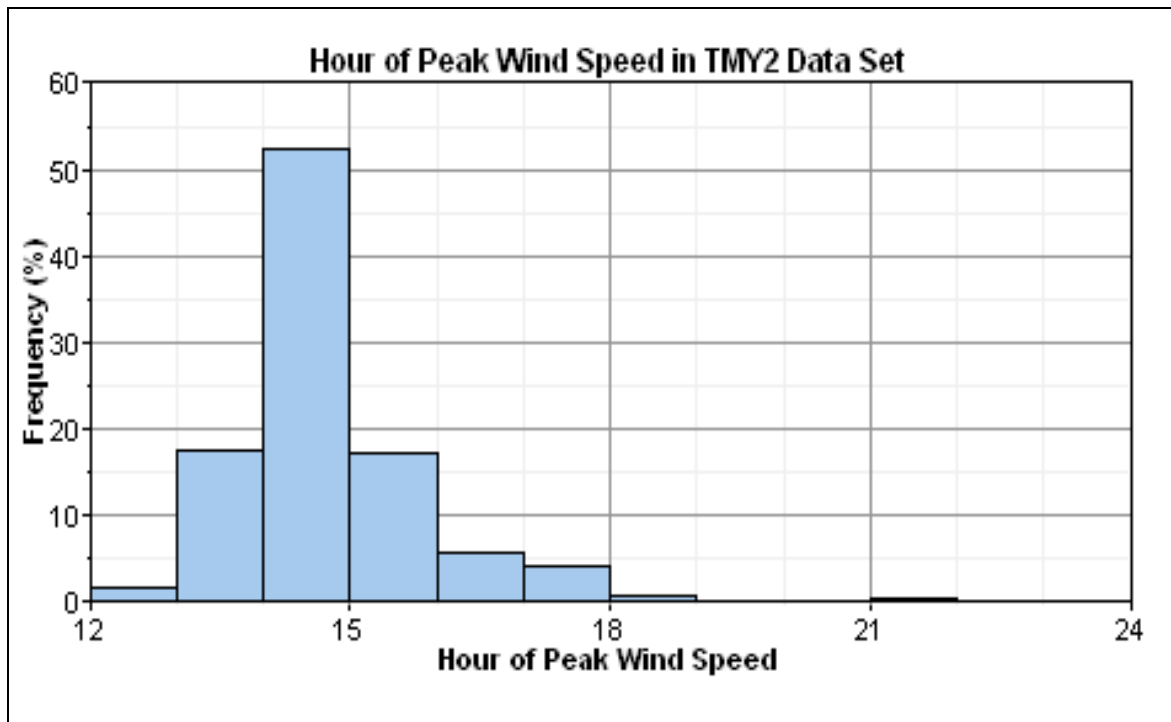


Figure 4-8: Distribution of wind power parameters in 239 locations used in HOMER (HOMER Energy, 2017)

To synthesise wind data in HOMER, it is necessary to enter or download twelve average wind speed values: one for each month of the year. To download the monthly averages for synthesised wind data, a location must be selected on HOMER's Home Page. Then the averages are downloaded from the HOMER website which utilises the NASA Surface Meteorology and Solar Energy database (see Figure F-1 in 7.5Appendix F). The NASA database is a commonly used source of validated data within contemporary renewable energy research domain. Peer reviewed journals and conference papers such as Gökçek and Kale (2018); Mahmood and Mahmood (2017); Middel (2016); and Narottama et al. (2018) used the database extensively in their studies.

4.2.2.2.1 Anemometer Height

This is the height at which wind speed is quantified. Generally, wind speeds tend to increase with height. Therefore, if wind turbine hub height is not the same as that of the anemometer, HOMER will adjust the wind speed data accordingly (see Section 4.2.3.2.1 for details of HOMER's calculation of wind turbine power output at anemometer and hub heights). 10m above ground is a commonly used anemometer height for meteorological measurements (HOMER Energy, 2017). To calculate wind power potential, anemometers are normally placed higher than 10m, because wind

turbine tower heights are typically between 25 and 100m. The closer the anemometer height is to the eventual hub height of a wind turbine, the more precisely it measures the wind resource to which the wind turbine will be exposed.

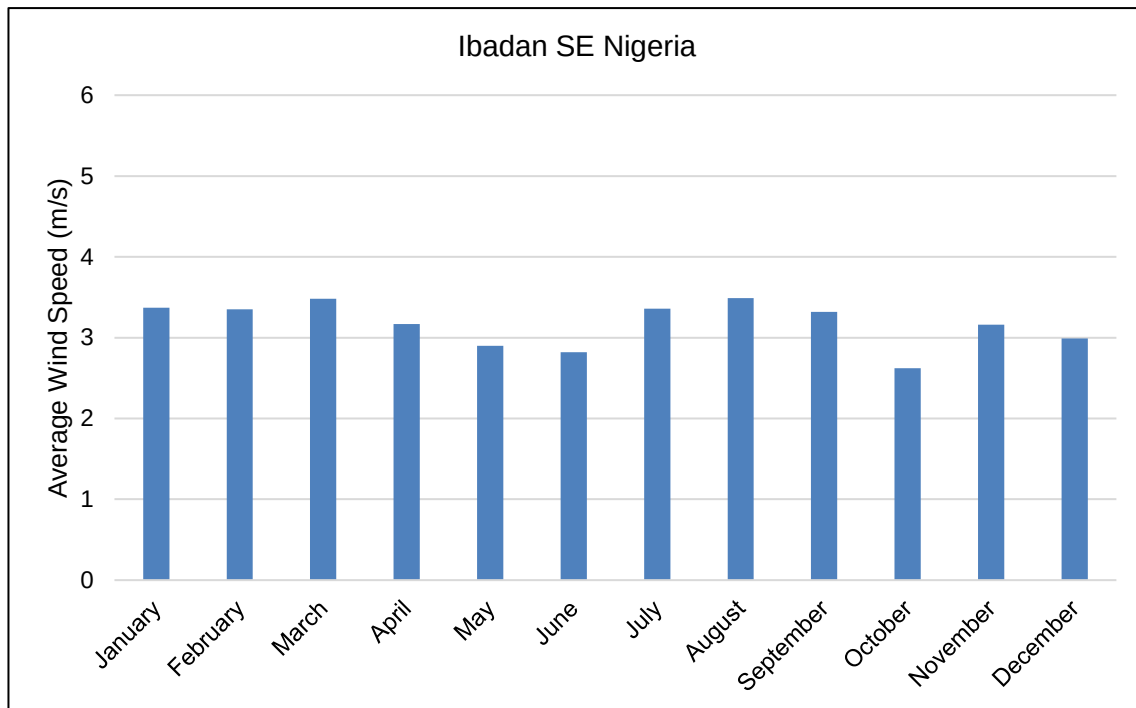
Wind resource data in HOMER is accompanied by the anemometer height where the wind speed was determined. Downloading a wind resource data in the software automatically sets this input to the correct value. The anemometer height used for the data available through HOMER is 50m above the surface of the earth for terrains similar to airports. The wind resource data available for some regions include values for the four parameters described in Table 4-3 above. For selected regions, the four parameters are automatically set when the average wind speeds are downloaded.

4.2.2.2.2 Wind Turbine Hub Height

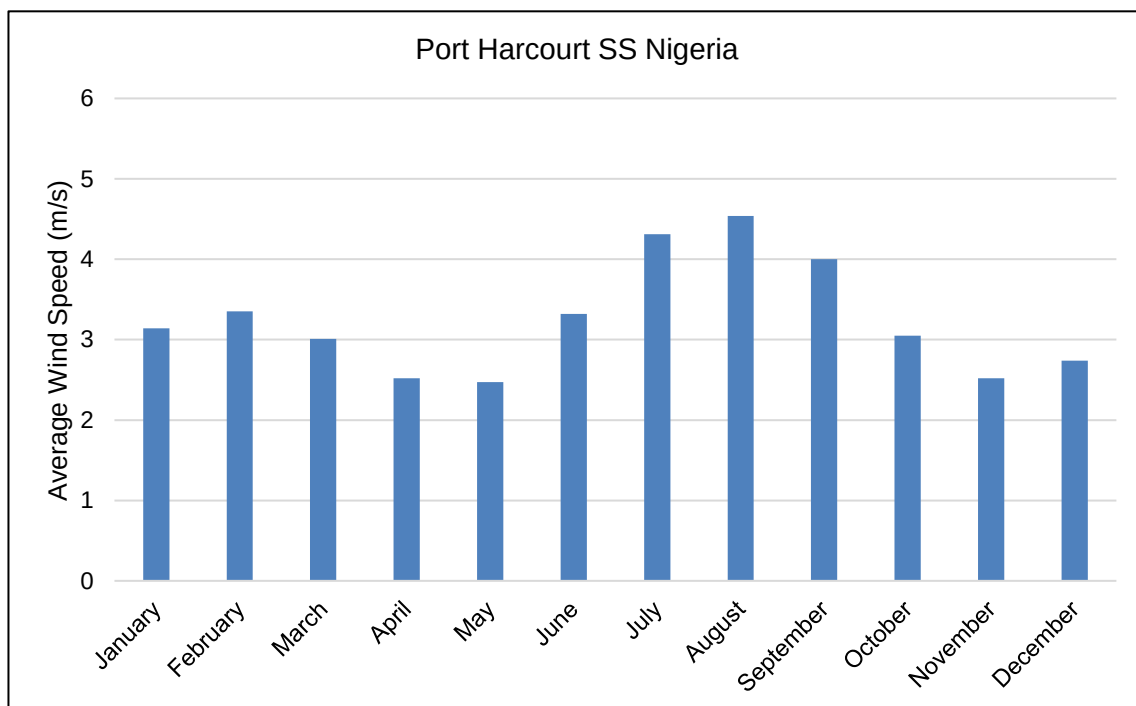
A wind turbine's hub height is the its rotor height above the ground. Hub heights are normally between 25m for smaller wind turbines of ≤ 50 kW rating and 100m for large, multi-megawatt wind turbines. Ground obstacles such as buildings, vegetation, and topographic elements tend to curtail wind speeds near the surface. Wind speeds tend to increase with height above ground because the effect of these obstacles reduces with height above ground. A hub height of 24m was selected for this study according to the manufacturer's specification for the 10kW wind turbine used.

4.2.2.2.3 Synthesising Wind Speed Data in HOMER

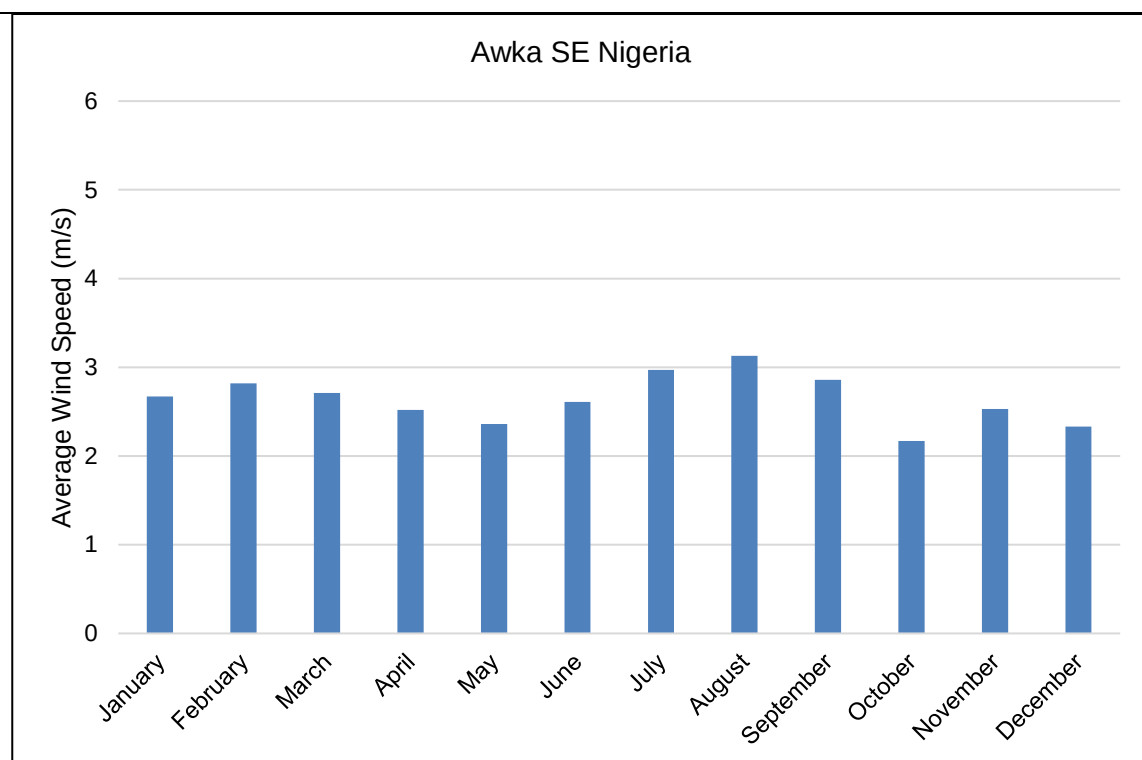
Collecting actual wind speeds in the 6 regions of Nigeria is a resource-intense endeavour. Wind speeds also vary markedly in the same months of different years. Therefore, HOMER utilises an algorithm to synthesise one year of time series wind speed data using the four wind parameters described above and NASA and NREL historical wind speed databases. The sources of known wind speed data for some regions and step by step description of the wind speed algorithm are shown in Appendix R. The charts in Figure 4-9 show the synthesised wind speed data used in the simulations. The bars represent monthly average wind speeds in each city over a period of 10 years between 1983 and 1993. Comparing measured wind speeds in these cities with HOMER's synthesised wind data is a potential area for further studies.



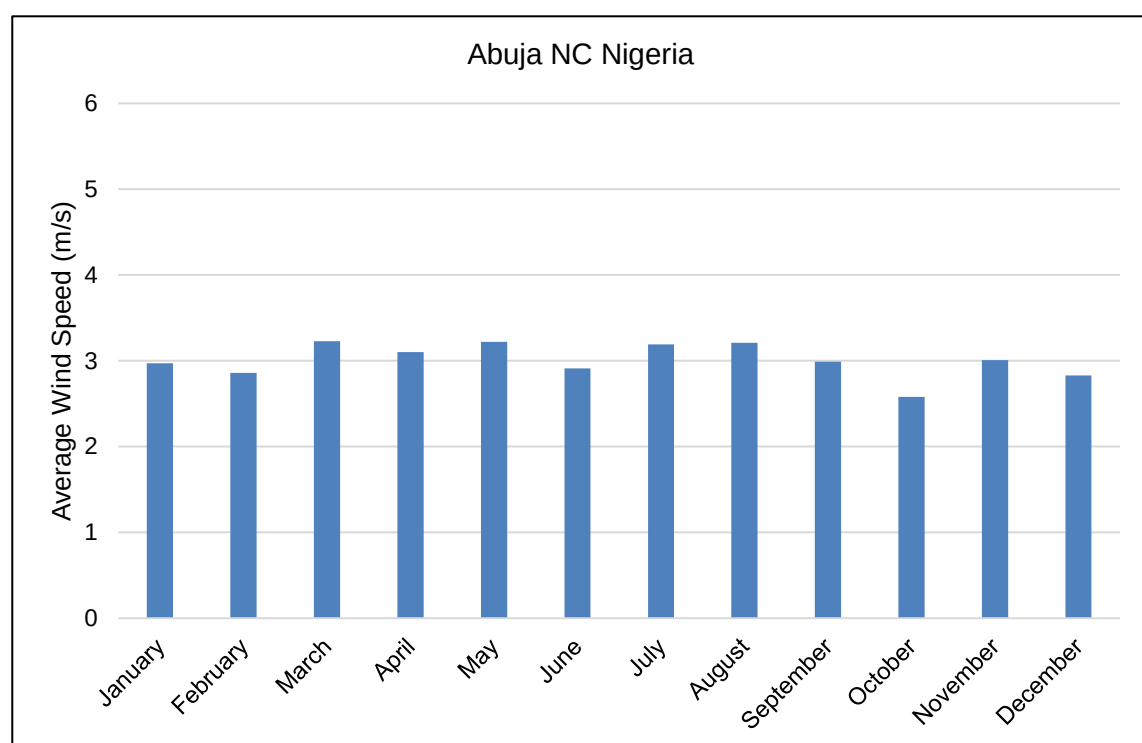
Data downloaded at 31/05/2017 13:12:14



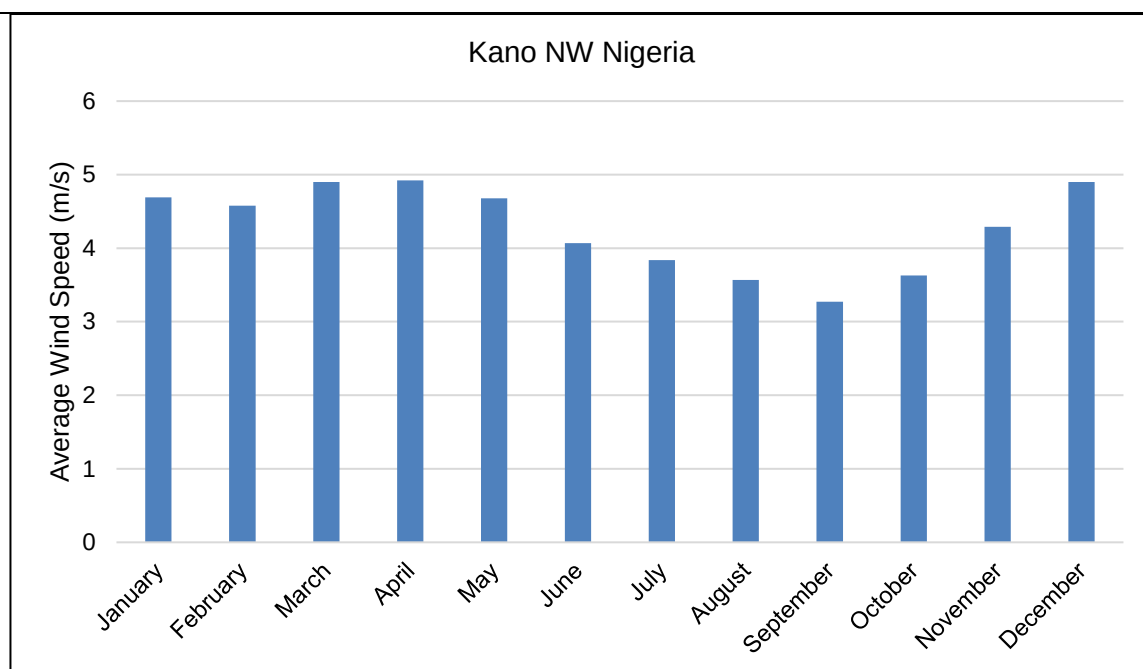
Data downloaded at 05/06/2017 22:57:29



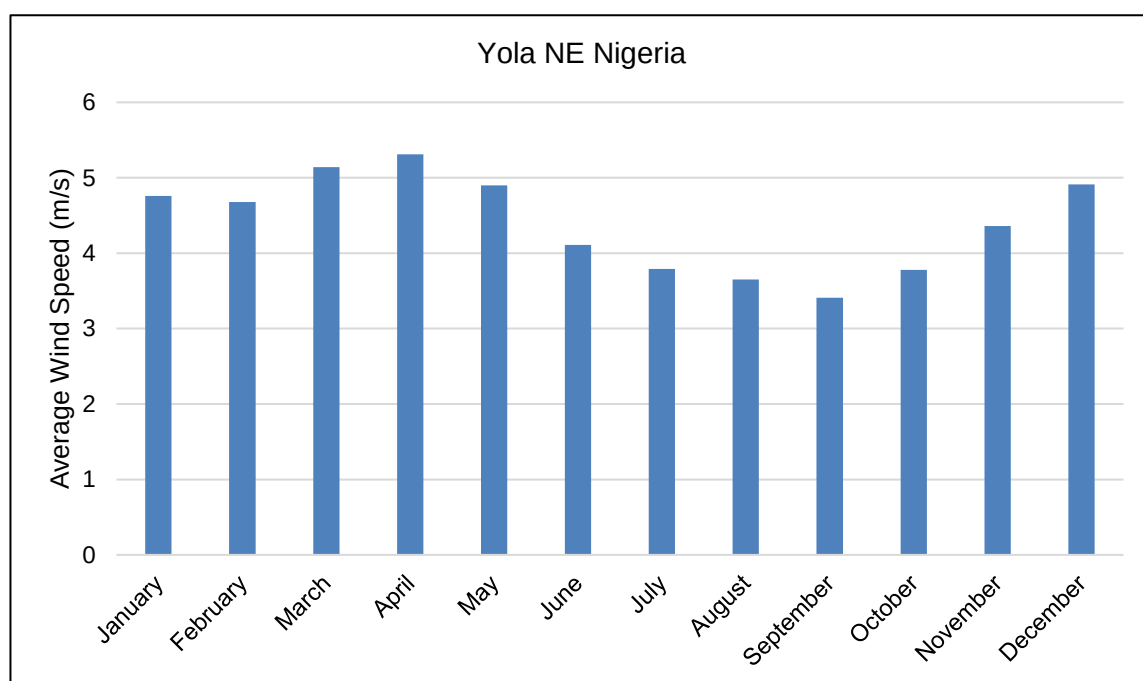
Data downloaded at 06/06/2017 00:11:56



Data downloaded at 30/05/2017 11:59:39



Data downloaded at 06/06/2017 00:59:43



Data downloaded at 06/06/2017 00:26:58

Figure 4-9: Wind speeds in Nigeria's major cities¹⁵

¹⁵ Data source: NASA Surface meteorology and Solar Energy database. Wind speeds at 50m above earth surface for terrain similar to airports. Monthly averaged values 1983-1993

4.2.2.2.4 Comparative Analysis of Nigeria's Regional Wind Speeds

Analysis of the regional average wind speeds shown in Figure 4-9 reveals that, regions in northern Nigeria enjoy comparatively higher wind speeds than in the south. The 4 m/s speed ceiling, illustrated in Figure 4-10, was hardly breached in the southern cities except for Port-Harcourt between July and September. This exception is likely due to Port-Harcourt being a coastal city.

Abuja in Central Nigeria and Awka in the South-East have the least average speeds throughout the year. Whereas, the northern cities of Kano and Yola consistently experience wind speeds of above 4 m/s. These results also correlate with Nigeria's wind map (RECP, 2017a) as shown in Figure 4-11.

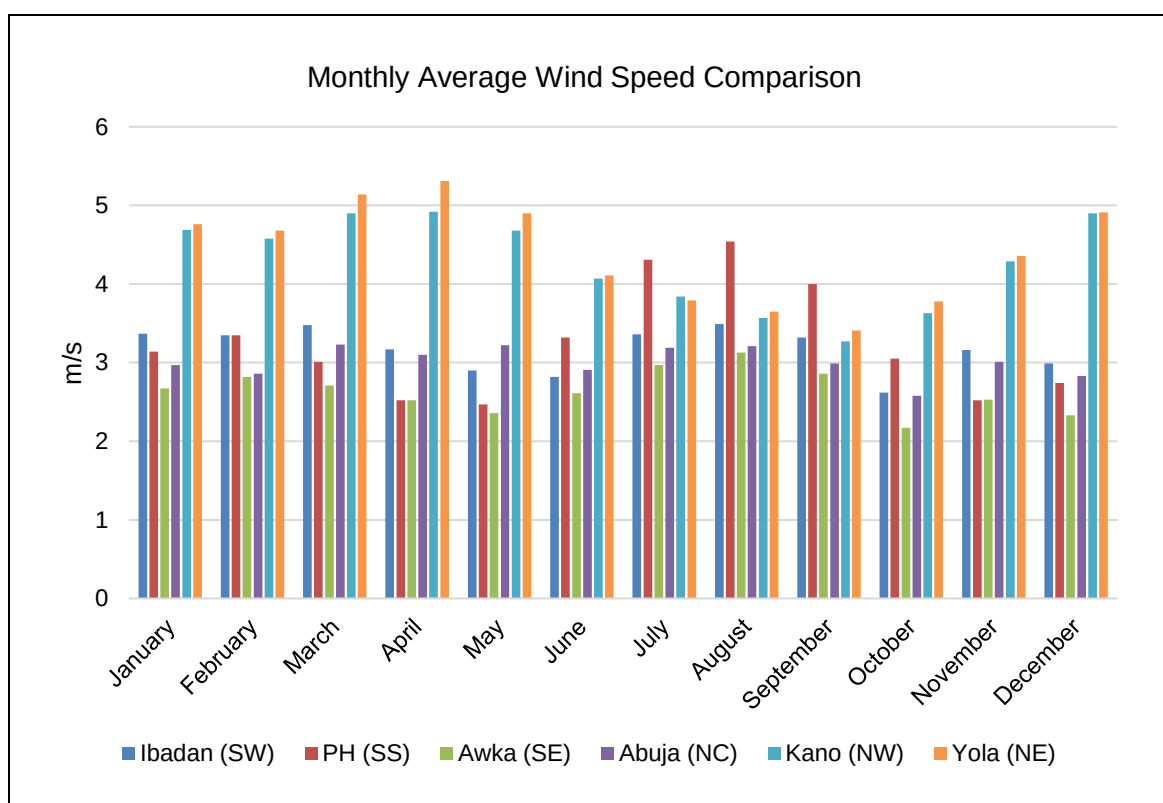


Figure 4-10: Monthly average wind speeds in Nigeria's regions¹⁶

The implication is that northern Nigeria has higher potentials for wind power generation with average wind speeds consistently above 4.4 m/s. It is however notable that Port-Harcourt, a coastal city, enjoys higher wind speeds between July

¹⁶ **Source:** Researcher's elaboration using HOMER-synthesised wind speed data

and September peak rainy season. This agrees with precipitation data from Port-Harcourt in Section 4.2.2.4 showing the highest figures in any Nigerian city within those months.

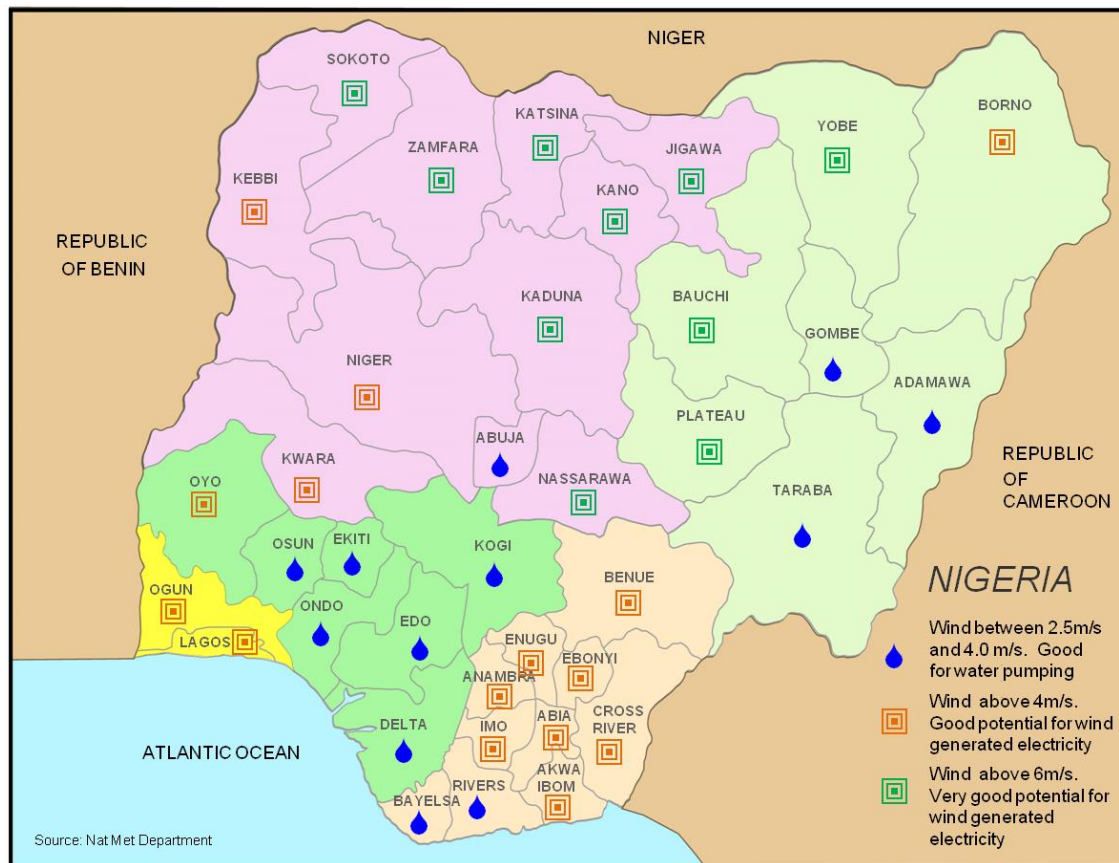


Figure 4-11: Nigeria's wind map¹⁷

4.2.2.3 Temperature Data

Temperature is one of the main resource components HOMER uses in the simulation of both solar PV and wind energy outputs. By selecting the Temperature key under the Resources tab in the toolbar, the temperature resource page appears showing monthly average data.

The ambient temperature for the year with regards to PV and wind components can be specified in HOMER. The user can either enter twelve monthly numbers or import a time-series data file. For this study, temperature data from NASA Surface Meteorology and Solar Energy database (NASA, 2017) are used as inputs into HOMER.

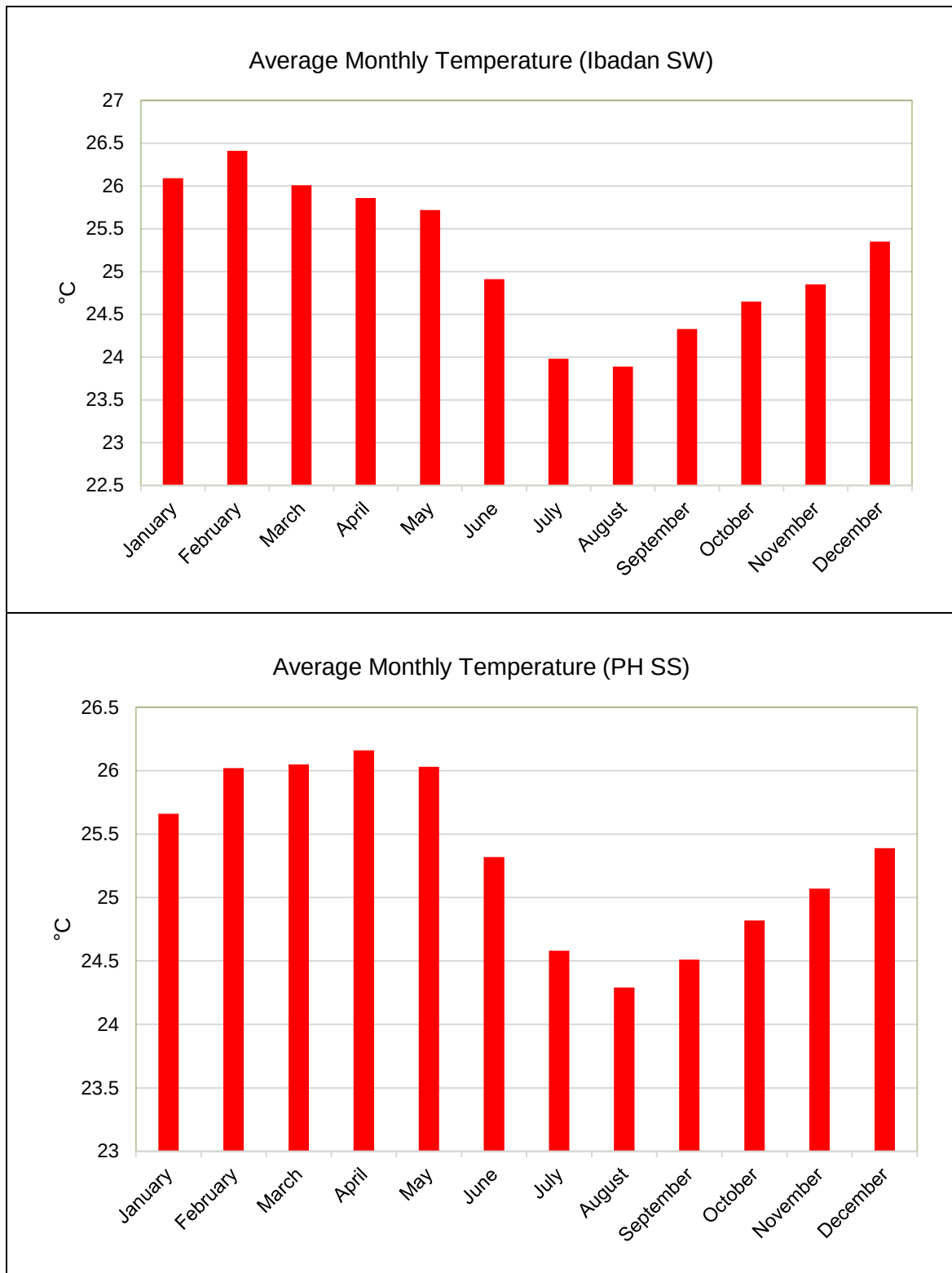
¹⁷ Source: RECP (2017a)

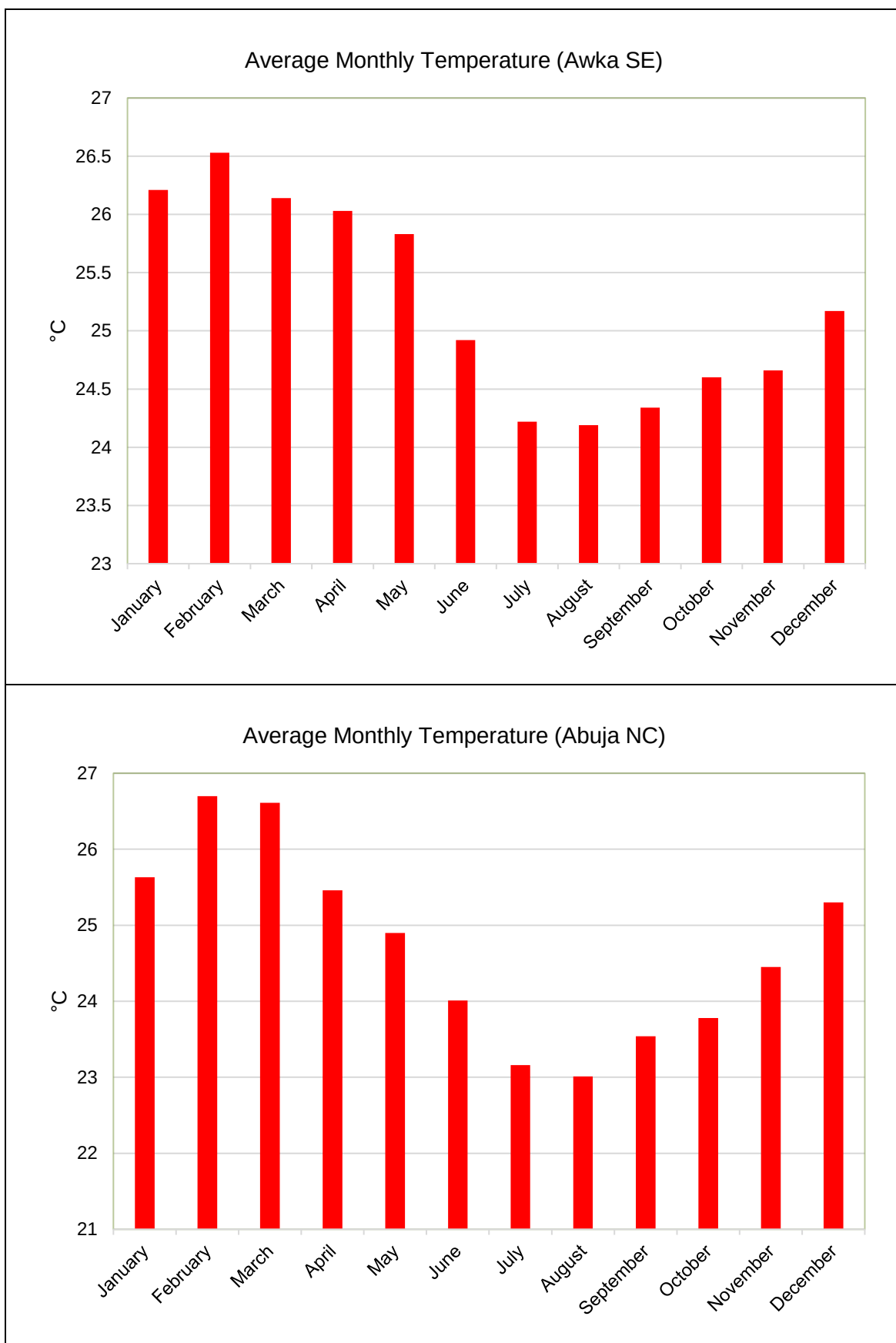
HOMER uses ambient temperature values to calculate the PV cell temperature. The temperature resource is used when modelling a Wind Turbine Component if the option to consider ambient temperature is selected on the component page. For the simulations conducted in this study, PV cell temperature is considered whereas, the “Consider ambient temperature data” option for wind turbine considerations is not selected. These options were selected because, after conducting some test run models, ambient temperature proved to have considerable effect on solar PV output. On the other hand, the effect of ambient temperature on wind turbine output was negligible.

4.2.2.3.1 Choosing a Data Source

According to HOMER Energy (2017), the baseline temperature data is a time series that represents the average temperature for every time step of the year. HOMER shows the monthly average data in the monthly average temperature graph and table. There are two methods of creating baseline data, by using HOMER to synthesise hourly data from monthly averages, or by importing hourly radiation data from a file.

This research utilises solar data through HOMER Energy website, which is linked to NASA’s Surface Meteorology and Solar Energy database, by first selecting the project’s location – cities in Nigeria’s six geopolitical regions. Then, twelve monthly average temperature values are downloaded based on the location’s latitude and longitude. The average monthly temperature data for each city considered are presented in the graphs in Figure 4-12 below.





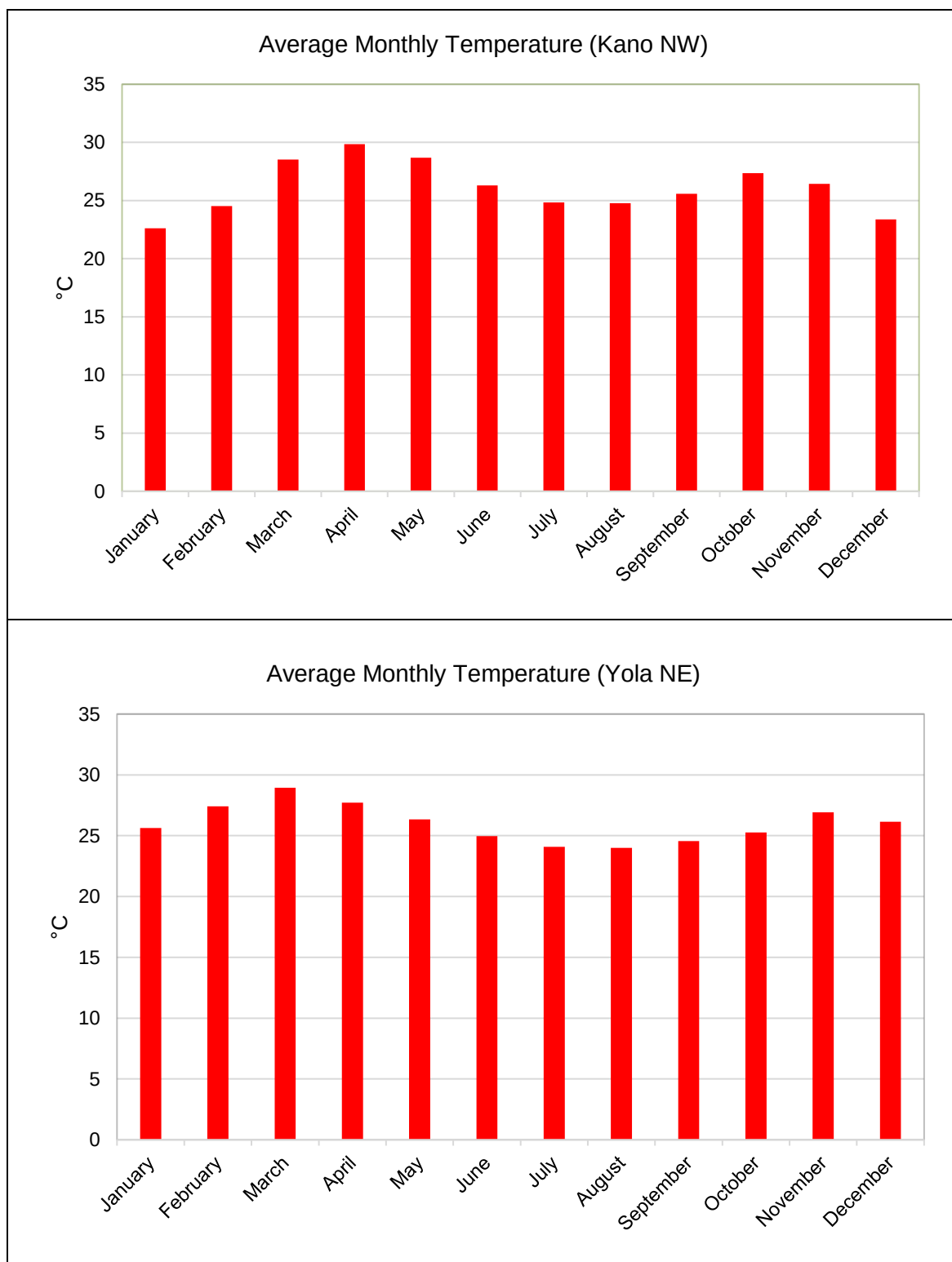


Figure 4-12: Monthly average temperatures. Source: Researcher's elaboration using air temperature data averaged over 22 years (July 1983 – June 2005) from NASA Surface Meteorology and Solar database.

From the monthly average temperature analysis above, it is evident that cities in the northern parts of Nigeria are exposed to higher temperatures all year compared to southern Nigeria. Furthermore, the temperature range in the northern cities is close meaning that high temperatures are maintained throughout the year allowing for better predictability of solar resources when compare with southern and central cities in Nigeria.

4.2.2.3.2 How HOMER Calculates the PV Cell Temperature

the temperature of the surface of the PV array is referred to as, the photovoltaic cell temperature (HOMER Energy, 2017). At night, this is the same as the ambient temperature, but cell temperature can become higher than ambient temperature by more than 30°C under full sunlight.

Provided that the effect of temperature on a PV array is considered, HOMER will calculate the cell temperature in each time step (monthly in this research) and use it in evaluating the power output of the PV array. Below is a description of how HOMER computes cell temperature from the ambient temperature and incident radiation.

First, the energy balance for the PV array is determined using equation (4-8) from Duffie and Beckman (1991):

$$\tau\alpha G_T = \eta_c G_T + U_L(T_c - T_a) \quad (4-8)$$

Where:

- τ = the solar transmittance of any cover over the PV array [%]
- α = the solar absorptance of the PV array [%]
- G_T = the solar radiation striking the PV array [kW/m²]
- η_c = the electrical conversion efficiency of the PV array [%]
- U_L = the coefficient of heat transfer to the surroundings [kW/m²°C]
- T_c = the PV cell temperature [°C]
- T_a = the ambient temperature [°C]

Equation (4-8) implies that there is a balance between, the solar energy absorbed by the PV array, on one side, and the electrical output plus the heat transfer to the surroundings, on the other side. The equation for cell temperature can be solved to yield:

$$T_c = T_a + G_T \left(\frac{\tau\alpha}{U_L} \right) \left(1 - \frac{\eta_c}{\tau\alpha} \right) \quad (4-9)$$

According to HOMER Energy (2017), the value of $\left(\frac{\tau\alpha}{U_L} \right)$ is difficult to measure directly. Instead, PV manufacturers provide the nominal operating cell temperature (NOCT). In a 2007 survey by HOMER, about 60% of product data sheets specified the NOCT, with values varying narrowly between 45°C and 48°C (HOMER Energy, 2017). NOCT is the cell temperature that results at an incident radiation of 0.8 kW/m², an ambient temperature of 20°C, wind speed of 1m/s, and no-load operation (i.e. $\eta_c = 0$) (Duffie and Beckman, 1991). Substituting these values into equation (4-9) yields:

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \quad (4-10)$$

Where:

- $T_{c,NOCT}$ = the nominal operating cell temperature [°C]
- $T_{a,NOCT}$ = the ambient temperature at which the NOCT is defined [20°C]
- $G_{T,NOCT}$ = the solar radiation at which the NOCT is defined [0.8 kW/m²]

Assuming that $\frac{\tau\alpha}{U_L}$ is constant, equation (4-10) can be substituted into the cell temperature equation (4-9) to give:

$$T_c = T_a + G_T \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \right) \left(1 - \frac{\eta_c}{\tau\alpha} \right) \quad (4-11)$$

HOMER postulates that PV arrays always operate at maximum power point, as they would when controlled by a maximum-power point tracker. This implies that HOMER assumes that a cell's efficiency is always equal to the efficiency at its maximum power point:

$$\eta_c = \eta_{mp} \quad (4-12)$$

Where:

- η_{mp} = the efficiency of the PV array at its maximum power point [%]

η_c can then be replaced with η_{mp} in the equation (4-9) for cell temperature, to yield:

$$T_c = T_a + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left(1 - \frac{\eta_{mp}}{\tau\alpha} \right) \quad (4-13)$$

However, η_{mp} is dependent on cell temperature T_c . HOEMR, therefore, assumes that PV array efficiency varies linearly with temperature according to equation (4-14) below:

$$\eta_{mp} = \eta_{mp,STC} [1 + \alpha_p (T_c - T_{c,STC})] \quad (4-14)$$

Where:

$\eta_{mp,STC}$ = the maximum power point efficiency under standard test conditions [%] (see equation (4-17))

α_p = the temperature coefficient of power [%/°C] (see equation (4-18))

$T_{c,STC}$ = the cell temperature under standard test conditions [25°C]

The temperature coefficient of power is typically negative, because the efficiency of a PV array decreases as cell temperature increases (HOMER Energy, 2017). The efficiency equation (4-14) can then be substituted into the cell temperature equation (4-13) and calculate for cell temperature as follows:

$$T_c = T_a + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left(1 - \frac{\eta_{mp,STC} [1 + \alpha_p (T_c - T_{c,STC})]}{\tau\alpha} \right) \quad (4-15)$$

Simplifying equation (4-15) yields:

$$T_c = \frac{T_a + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left[1 - \frac{\eta_{mp,STC} (1 - \alpha_p T_{c,STC})}{\tau\alpha} \right]}{1 + (T_{c,NOCT} - T_{a,NOCT}) \left(\frac{G_T}{G_{T,NOCT}} \right) \left(\frac{\alpha_p \eta_{mp,STC}}{\tau\alpha} \right)} \quad (4-16)$$

All temperature values must be in Kelvin. Equation (4-16) is used to calculate the cell temperature in HOMERT for every time step.

4.2.2.3.3 PV Efficiency at Standard Test Conditions (%)

The efficiency with which a PV array converts sunlight into electricity at its maximum power point under standard test conditions (STC) is called the photovoltaic (PV)

efficiency at standard test conditions. Its unit is in % and is given as $\eta_{mp,STC}$. HOMER employs the PV efficiency in calculating the PV cell temperature T_c .

PV makers seldom report this efficiency in their manufacturer's brochures, but it can be calculated for any PV module by using:

$$\eta_{mp,STC} = \frac{Y_{PV}}{A_{PV}G_{T,STC}} \quad (4-17)$$

Where:

$\eta_{mp,STC}$ = the efficiency of the PV module under standard test conditions [%]

Y_{PV} = the rated power output of the PV module under standard test conditions [kW]

A_{PV} = the surface area of the PV module [m²]

$G_{T,STC}$ = the radiation at standard test conditions [1 kW/m²]

For this research, a PV efficiency of 13% is used for the generic flat plate PV used in HOMER modelling. A 2007 HOMER Energy survey of manufacturer brochures for some commonly available PV modules identified the average values of the efficiency under standard test conditions as shown in Table 4-4 below:

Table 4-4: Average efficiency at STC for PV module types (HOMER Energy, 2017)

PV Module Type	Modules in Survey	Average Value of Efficiency at STC [%]
Polycrystalline silicon	10	13.0
Monocrystalline silicon	8	13.5
Monocrystalline/amorphous silicon hybrid	1	16.4
Thin film amorphous silicon	4	5.5
Thin film CIS	1	8.2

4.2.2.3.4 PV Temperature Coefficient of Power (%/°C)

This function shows how strong the effect of temperature is on the PV array power output. It has a negative value because power output decreases with increasing cell

temperature (Amin and Al-Maghrabi, 2017; Merabet and Birouk, 2017; Pradhan and Panda, 2017; Zhijun, Mohammad R. and Yiming, 2017). PV modules manufacturers often present this coefficient in product brochures as temperature coefficient of power, max. power temperature coefficient, or power temperature coefficient.

A HOMER-specified flat plate PV array of temperature coefficient -0.5 is used in this study as it is one of the most common polycrystalline silicon PV module types. The average values of the temperature coefficient of power for different types of PV modules in a 2007 HOMER survey of product brochures is shown in Table 4-5.

Table 4-5: Average Temperature Coefficient of Power for PV module types (HOMER Energy, 2017)

PV Module Type	Modules in Survey	Modules Reporting α_P	Average Value of α_P [%/°C]
Polycrystalline silicon	10	7	-0.48
Monocrystalline silicon	8	4	-0.46
Monocrystalline/amorphous silicon hybrid	1	1	-0.30
Thin film amorphous silicon	4	4	-0.20
Thin film CIS	1	1	-0.60

If the product brochure does not indicate temperature coefficient of power, but provides the temperature coefficient of the open-circuit voltage, the coefficient of power can be calculated using the approximation equation in Duffie and Beckman (1991):

$$\alpha_p \approx \frac{\mu_{Voc}}{V_{mp}} \quad (4-18)$$

Where:

μ_{Voc} = the temperature coefficient of the open-circuit voltage [V/°C]

V_{mp} = the voltage at the maximum power point under standard test conditions (STC) [V]

4.2.2.4 Water Speed Data

In HOMER, the Hydrokinetic Resource page (see Figure 4-13) allows the user to define the flow available to the hydrokinetic turbine. This information is then used to calculate the output of the turbine in each time step. The baseline data is a one-year time series indicating the water speed in meters per second for each time step of the year.

There are two methods of creating baseline data. The user can either enter monthly averages or import time series data from a file. For this research, monthly averages were entered directly into HOMER. When the user enters each month's average water speed, HOMER builds a set of 8,760 values representing one water speed value for each hour of the year. This is done by assuming that water stream flow is constant throughout each month, that is, HOMER assigns the monthly average value to each hour in the month.

4.2.2.4.1 Determining Monthly Average Water Speed

Data on the flow speeds (m/s) of Nigerian rivers are not readily available in literature. Where they are available, they are in volume per second (m^3/s), which is not appropriate for HOMER modelling. To convert m^3/s to m/s, the depth or width of the spot where the measurement was taken would be required. Resource and time constraints meant that real data from rivers in the Nigerian cities explored cannot be obtained. Nevertheless, the origin of flow regimes is mainly from precipitation over the river basin (Michaud and Wierenga, 2005; Welcoome, 1985). Changes in precipitation is therefore related to seasonal water flow speeds. Hence the average water speeds used in the HOMER models are estimates based on average monthly precipitation figures for each case study city. Although there are other factors responsible for river flow velocity (such as terrain, vegetation cover and river size), it is possible to create flow speed estimates from a known river speed and the precipitation level of its catchment area.

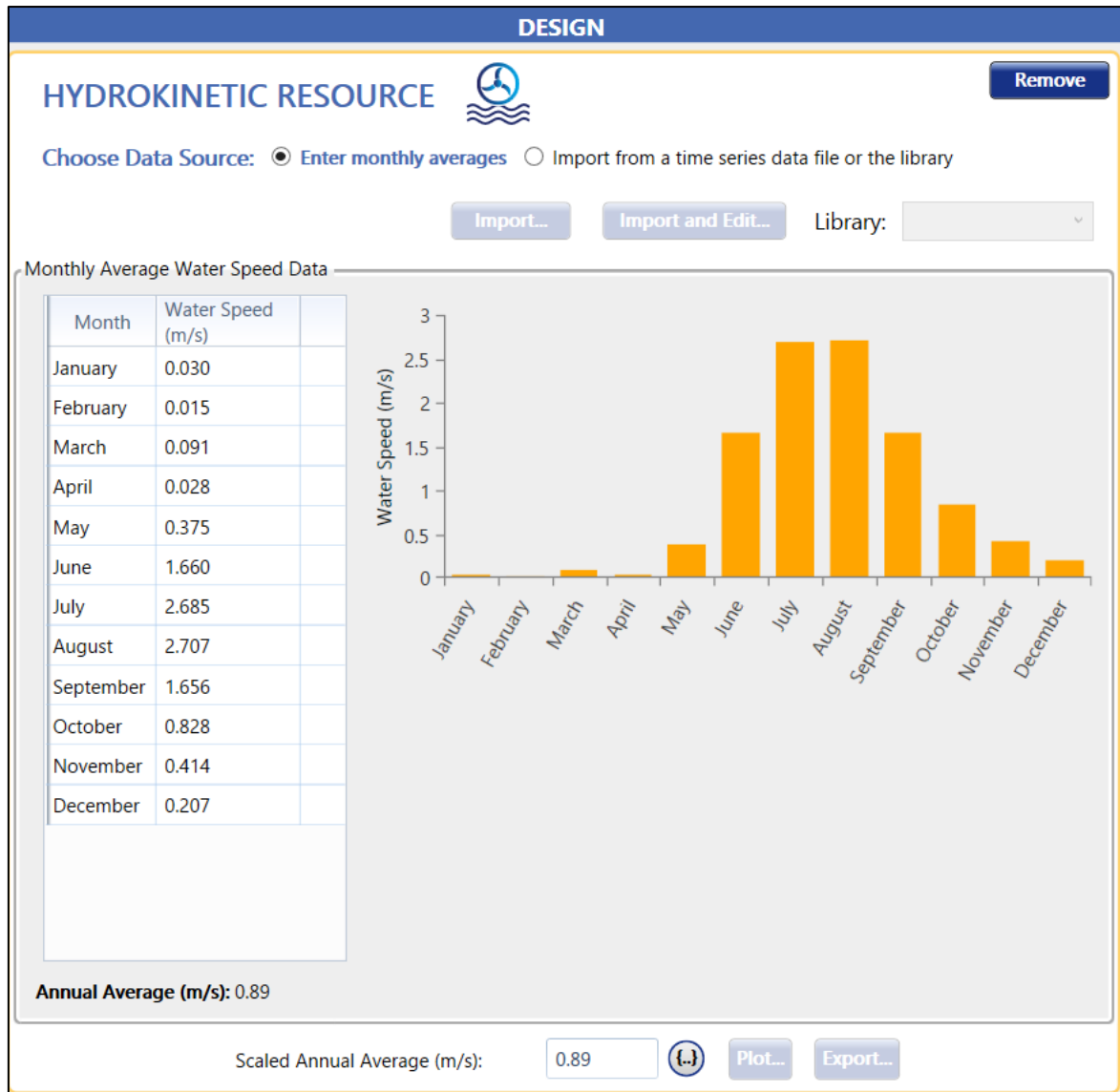


Figure 4-13: Hydrokinetic resource page in HOMER model

Therefore, the highest national flow velocity (6m/s) estimate from the Food and Agriculture Organisation (FAO) for Nigeria (AQUASTAT, 2016) in 2016 is used to extrapolate flow speeds for other cities in Nigeria. Equating this highest flow speed (6m/s) to Port-Harcourt's highest national monthly average precipitation in June of 2016 (520mm), a linear divider of 87 (520 divided by 6) was used to estimate the average monthly flow speeds for other cities. For months without precipitation, average river flow speeds are estimates as half of that of the preceding month. Average monthly precipitation data are collected from (World Weather Online, 2016). Comprehensive evaluation of different methods of estimating water flow speeds are included in FAO (2017), and Michaud and Wierenga (2005) for evaluation of actual river flow speeds.

Typical figures of average monthly precipitation and average monthly river flow speed are shown in Table 4-6:

Table 4-6: Hydrokinetic resource: Average monthly water speed (Kano NW)
(Precipitation data source: World Weather Online (2016))

Months in 2016	Average Monthly Precipitation	Estimated Average Monthly River Flow Speed (=Precipitation/87)
Jan *	0	0.030
Feb *	0	0.015
Mar	7.92	0.091
Apr	2.4	0.028
May	32.59	0.375
Jun	144.38	1.660
Jul	233.62	2.685
Aug	235.49	2.707
Sep	144.04	1.656
Oct	0.49	0.828
Nov *	0	0.414
Dec *	0	0.207

** Water speeds for months with zero precipitation is estimated as half that of preceding month*

The analysis of the average monthly precipitation and average monthly river entered in HOMER are presented in Figure 4-14 below:





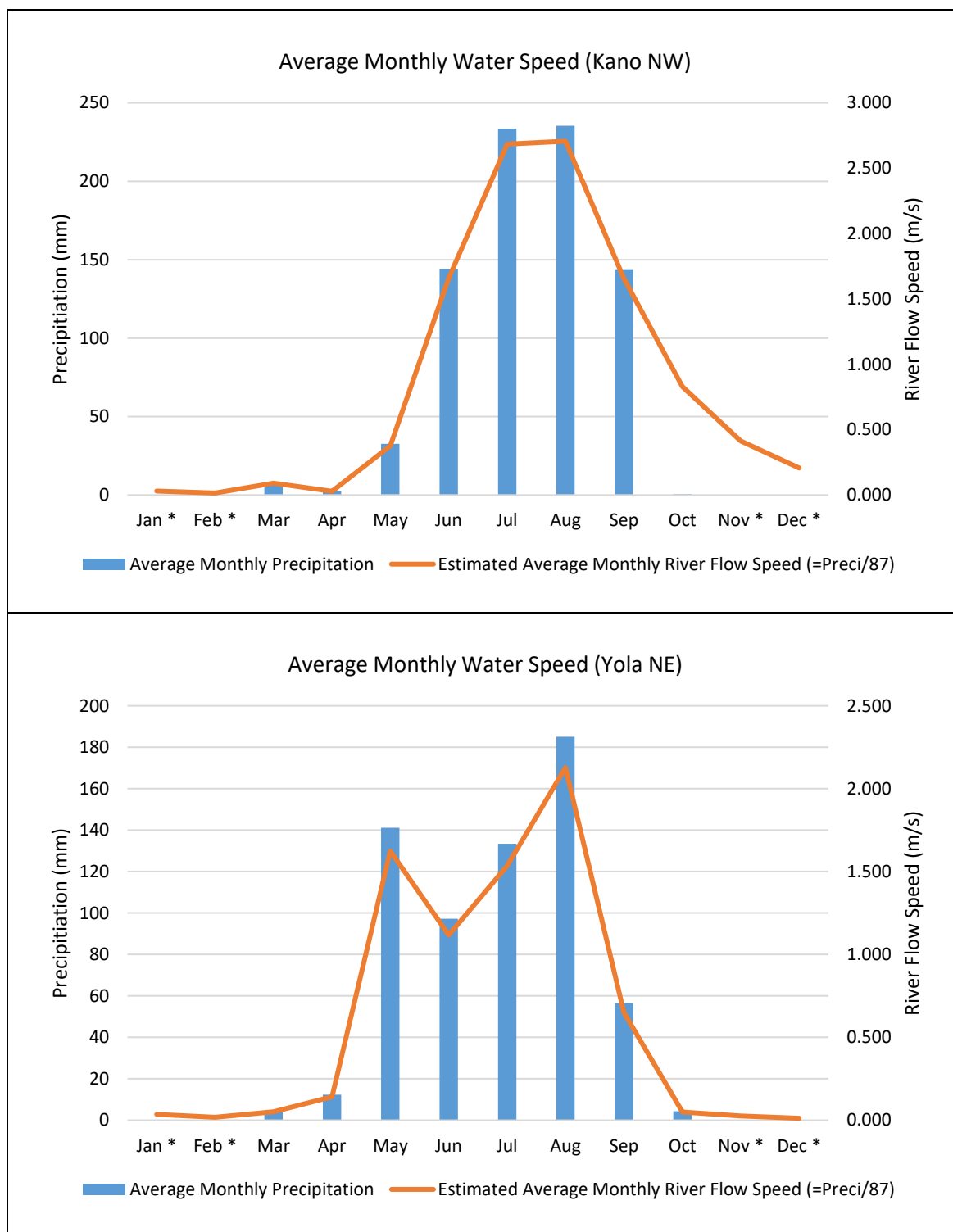


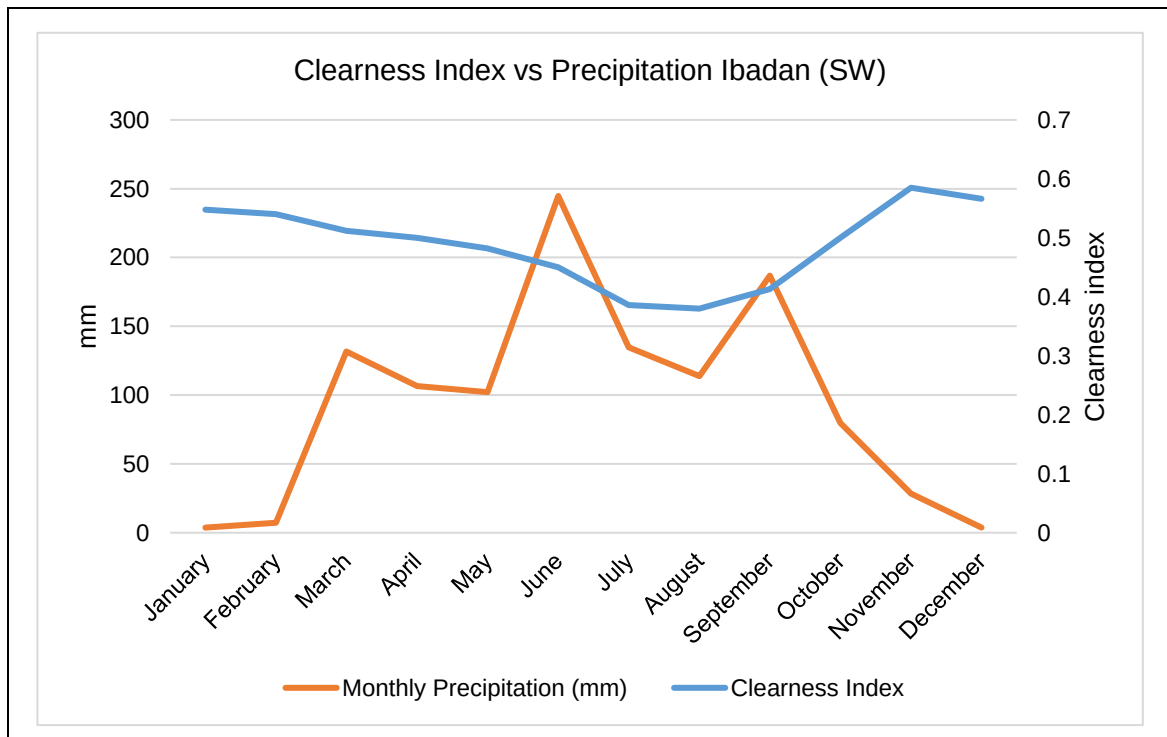
Figure 4-14: Average monthly precipitation and water flow speed in Nigeria's regions (Source: Researcher's elaboration using precipitation data)

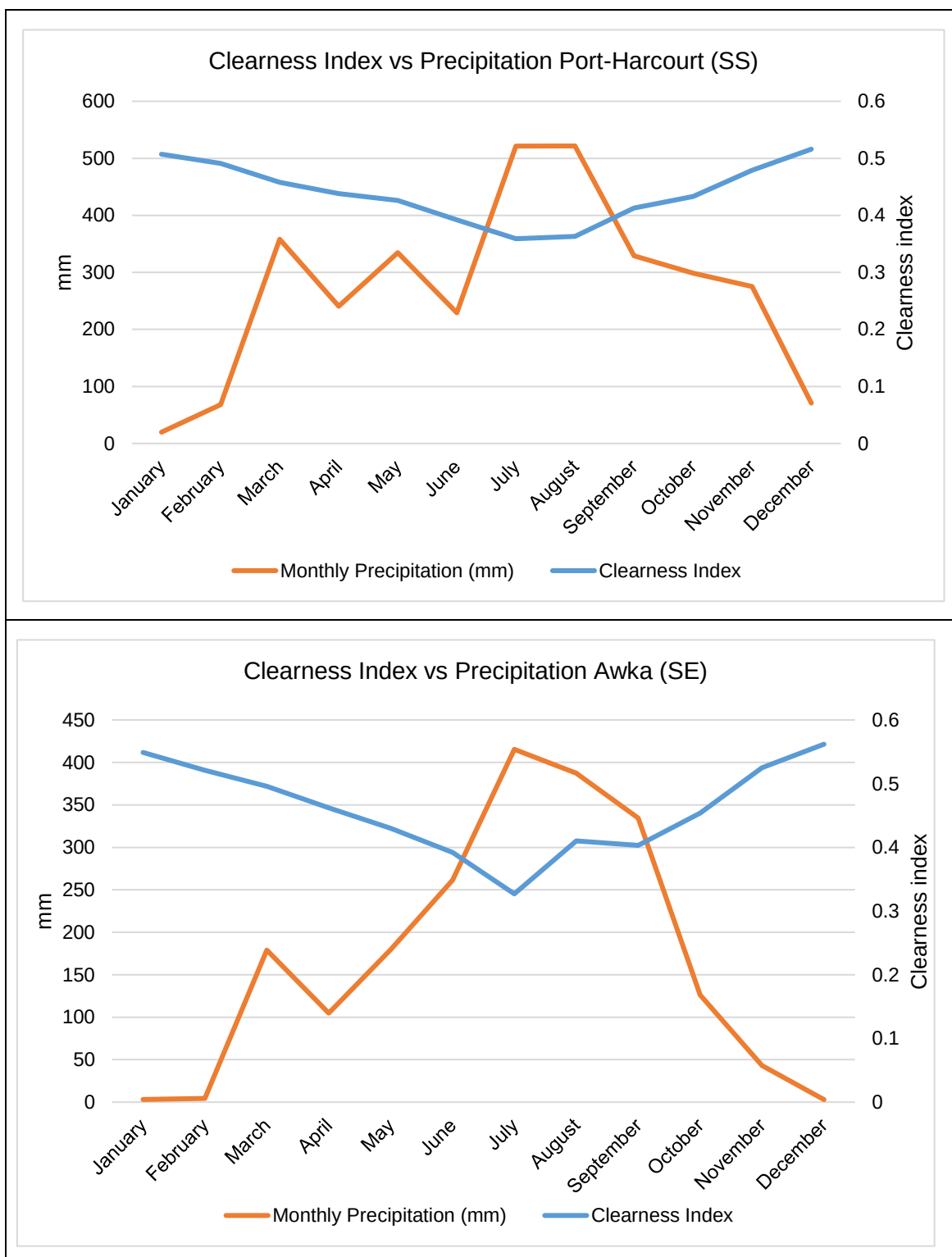
4.2.2.4.2 Relationship between Clearness Index and Precipitation

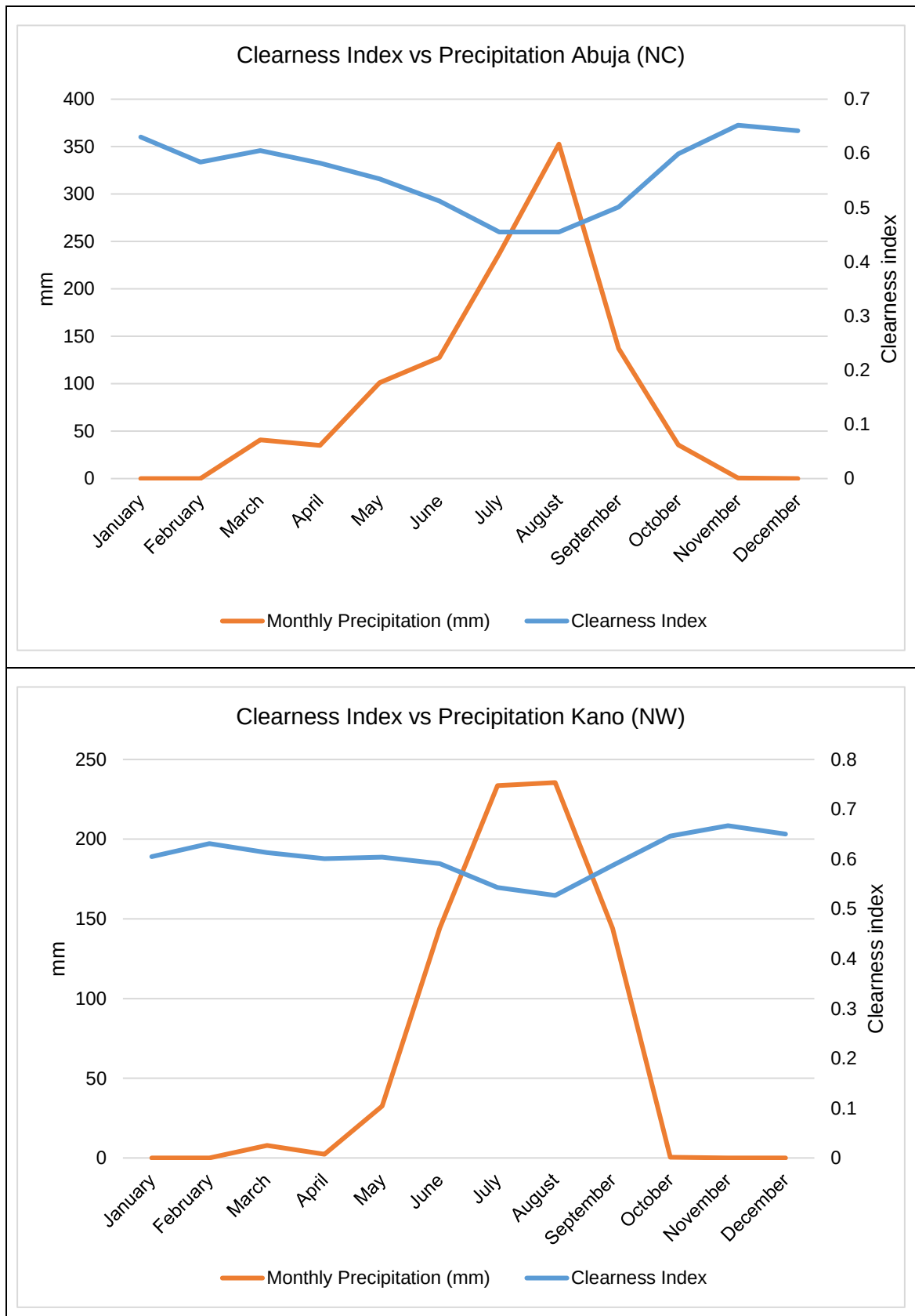
While the analysis presented in Section 4.2.2.1.3 shows that there is a strong direct correlation between radiation and clearness index, the comparative analysis of

monthly clearness index figures and monthly average precipitation, as shown in Figure 4-15, confirms that there is an inverse relationship between the two variables. This aligns with the results of the Angstrom page regression model by Falayi and Rabiou (2008) that showed higher clearness index where temperature is high and precipitation is low in some major Nigerian cities.

This indicates that, where there is a lot of precipitation or rain, there will be a lot of cloud cover resulting in lower values of clearness index. Consequently, it is likely that conditions in northern Nigeria are more favourable towards solar power generation and less so for cities in the south. On the other hand, a far less exploited hydrokinetic source of power generation is likely to be more suitable in southern Nigeria with higher precipitation values.







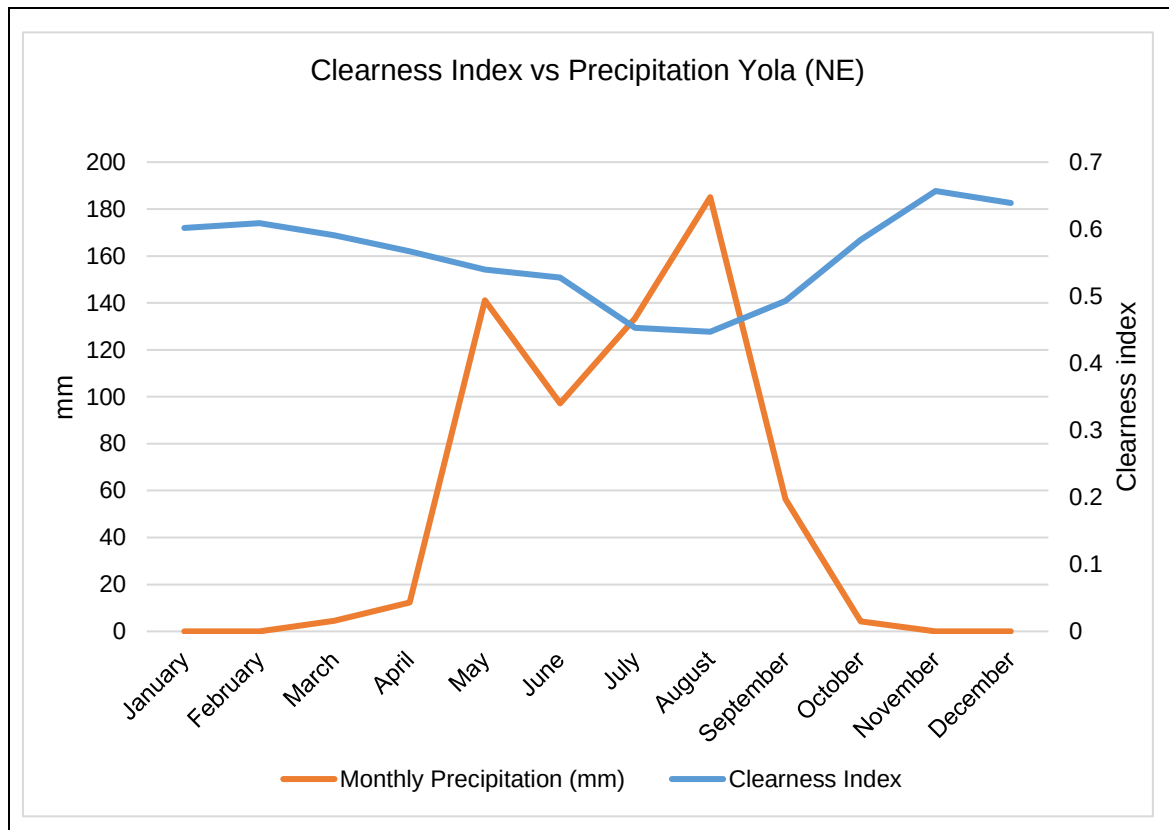


Figure 4-15: Clearness Index vs Precipitation analysis (Source: Researcher's elaboration using clearness index and precipitation data)

4.2.2.5 Fuel Data

It is necessary to select a fuel in HOMER's fuel design page, shown in Figure 4-16, when adding a generator, boiler or reformer component. Since an internal combustion engine (ICE) diesel generator is used for modelling, the standard diesel fuel in HOMER is selected. Other fuels available for selection through a drop-down menu in the fuel design page include arctic diesel, arctic heating oil, biodiesel, biogas, ethanol, gasoline (or petrol), HFO (heavy fuel oil), LP-vapour, natural gas, propane and stored Hydrogen.

DESIGN

FUEL RESOURCE

You may add a fuel from the library to model:

Arctic Diesel

Add

FUELS AVAILABLE IN MODEL

Name	LHV	Density	Carbon	Sulfur	Special
Diesel	43.2	820	88	0.33	

Selected Fuel

Name:

PROPERTIES

Lower Heating Value (MJ/kg):

Density (kg/m3):

Carbon Content (%):

Sulfur Content (%):

Fuel Type

☒ Conventional

☐ Stored Hydrogen

☐ Uses biomass resource

Limits and Prices

Diesel Fuel Price (\$/L):

☐ Limit Consumption (L):

Units: L

Copy To Library

Figure 4-16: Fuel resource page in HOMER model

If a component that uses fuel is selected and a fuel is not added to the design, HOMER will bring up an error message showing the user which component uses fuel. After selecting a fuel, the user can adjust the properties of the fuel as described in Table 4-7.

Table 4-7: Fuel properties used in HOMER for this research (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Variable	Description	Comment
Name	Unique name of the fuel	Diesel
Lower Heating Value (MJ/kg)	Energy released per kg of fuel combusted	43.20 MJ/kg
Density (kg/m ³)	Density of fuel in kg/m ³ (density of water is 1000 kg/m ³)	820.00 kg/m ³
Carbon Content (%)	The percentage mass-based carbon content of the fuel	88%
Sulphur Content (%)	The percentage mass-based sulphur content of the fuel	0.33%
Fuel Type	This can be Conventional, Stored Hydrogen or Biomass resource	Conventional
Fuel Price	Default price for selected fuel. The fuel price or sensitivity values can be chosen for different scenarios in the model	\$0.73/Litre (Nigeria's per Litre diesel price 2016)
Limit Consumption	This is ignored if Bio Fuel or Stored Hydrogen is selected. Fuels with limited quantity cannot be used in Boiler or Reformer Components	Not applicable
Quantity Available	The maximum quantity of fuel the system can use per year. This input is only used if Limit Consumption is selected.	Not applicable
Units	Preferred units for amount and price of fuel: Litres, kg, or m ³	Litres

4.2.3 Components

A component is a piece of equipment constituting a power system (HOMER Energy, 2017). Components in HOMER include a Boiler, Controller, Converter, Custom Component, Electrolyser, Generator, Grid, Hydro, Hydrogen Tank, Hydrokinetic, PV, Reformer, Storage, Thermal Load Controller and Wind Turbine. A user can select a combination of as many components as required to form parts of a power system.

HOMER also allows for the combination of more than one particular component. This makes it possible to analyse the cost and performance sensitivity of the system to any power source. Different types and makes of the same component can also be modelled to compare efficiencies, costs, emissions and other power-related factors. The components used in the models created for this research are shown in the labelled schematic diagram in Figure 4-17 and described in Table 4-8 below.

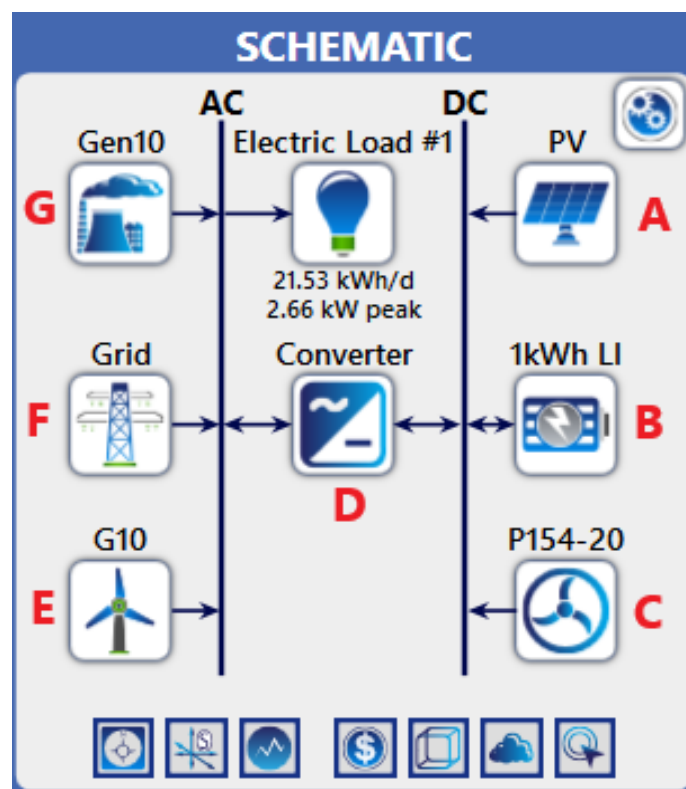


Figure 4-17: Layout of system components used in HOMER

Table 4-8: Description and specification of components in Figure 4-17

Label	Component	Specification
A	Photovoltaic Panels	Flat panel
B	Storage	1kWh per unit Lithium-Ion Batteries
C	Hydrokinetic Turbine	20kW Guinard P154 River and marine current turbine
D	Converter	1kWh per unit HOMER-designed system converter
E	Wind Turbine	10kW HOMER-designed wind turbine
F	Grid	Nigeria national grid
G	Generator	10kW Fixed capacity ICE diesel generator

4.2.3.1 Photovoltaic (PV) Panels

The HOMER software can model two types of photovoltaic arrays: flat panel and concentrating. Flat panel PVs are common and are lower in cost than the higher cost, higher performance concentrating PV arrays. Concentrating PV (CPV) arrays have reached above 40% efficiency in commercial installations. An efficiency of 15% is typical of flat panel PV arrays (HOMER Energy, 2017; Pradhan and Panda, 2017).

Because CPVs use optics to focus solar irradiation, they generally also require active tracking to follow the sun resulting in additional costs. Due to higher capex and opex, more frequent maintenance and higher technicalities associated with CPV arrays, the flat panel PV array is selected for this study.

Furthermore, CPVs only collect direct solar radiation incident normal to the surface of the panel, whereas, flat panel PVs can capture radiation striking the panel at a range of angles. This irradiance of a flat panel PV is calculated using the solar global horizontal irradiance (GHI), which includes direct and indirect radiation (see Section 4.2.2.1). Concentrating PVs use the direct normal irradiance (DNI) solar resource, which only includes the portion of solar that can be captured by CPV.

4.2.3.1.1 PV Properties used in HOMER

The PV page in HOMER allows the user to enter cost, performance characteristics, and orientation of an array of photovoltaic (PV) panels and choose the sizes to consider as HOMER searches for the optimal system. The PV component can represent both flat panel and concentrating PV technologies. The flat plate PV is used for the optimisation modelling executed in this study with rated capacity of 22kW, temperature coefficient (α_p) of -0.5, operating temperature of 47°C and efficiency ($\eta_{mp,STC}$) of 13% (see circled area labelled **A** in Figure 4-18). Figure 4-18 shows the PV design page with the variables specified in HOMER for the simulations in this section of the research.

DESIGN

Add/Remove Generic flat plate PV

PV 

Name: Generic flat plate PV

Abbreviation: PV

Properties

Name: **Generic flat plate PV**

Abbreviation: **PV**

Panel Type: **Flat plate**

Rated Capacity (kW): **22**

Temperature Coefficient: **-0.5**

Operating Temperature (°C): **47**

Efficiency (%): **13**

Manufacturer: **Generic**

www.homerenergy.com

Notes:

This is a generic PV system.

B

PV	Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	3,000.00	3,000.00	3,000.00	10.00

Lifetime

time (years): 25.00

More...

C

Remove

Copy To Library

Capacity Optimization

☐ HOMER Optimizer™

☒ Search Space

kW

0

5

10

22

D

Electrical Bus

☐ AC ☒ DC

E

Site Specific Input

Derating Factor (%): 80.00

F

MPPT Advanced Input Temperature

Ground Reflectance (%): 20.00

Tracking System: No Tracking

☒ Use default slope Panel Slope (degrees): 12.00

☒ Use default azimuth Panel Azimuth (degrees West of South): 0.00

Figure 4-18: Photovoltaic PV design page in HOMER (Source: Researcher's HOMER model design page)

4.2.3.1.2 PV Costs

The cost table allows the entry of capital cost and replacement cost per kilowatt of PV system including annual operation and maintenance (O&M) costs. The capital cost refers to the initial purchase price, the replacement cost is the cost of replacing the system at the end of its useful life, and the O&M cost is the annual cost of system operation and maintenance (HOMER Energy, 2017).

It is important to account for all costs associated with PV systems when specifying costs. These include PV panels, mounting hardware, tracking system (not included in this study due to capital and O&M costs), wiring and installation. For this study, a capital cost of \$3,000 per kilowatt is assumed for the PV system (see circled area labelled **B** in Figure 4-18). A review of WHO (2015a) indicated a PV system cost of \$4,320/kW. However, Energysage (2017) revealed a drop to \$1,800/kW in the US in 2017. While costs vary significantly in the Nigerian solar market, \$3,000/kW suggested by HOMER in 2017 when the simulations were conducted seem appropriate to reflect the additional cost of importation and transportation of the PV panels and installation hardware into Nigeria.

It is possible to model PV cost curve in HOMER, that is, the way cost varies with size. However, a linear variability is assumed between PV system costs and size in this research meaning that capital costs increases in multiples of 3,000 per kW increase in size. While it may be reasonable to factor in economies of scale and reducing cost of PV in capital cost calculations, the high rate of inflation (17%) and its monthly volatility in Nigeria means that costs would usually increase between the time of design and time of purchase.

Similarly, the cost of replacement is maintained at \$3,000. It is possible to specify a replacement cost of \$2,500/kW since some components such as mounting hardware may not need replacement. Nevertheless, the cost is fixed to ensure full coverage.

4.2.3.1.3 Search Space

The search space section is a capacity optimisation tool in HOMER (see circled area labelled **C** in Figure 4-18). It allows the user to model different sizes or quantities of an energy component. This tool is also available in the design page of

the other energy technologies and is useful for sensitivity analysis. There is a choice to enter a nominal capacity of the PV in kW or enter several capacity sizes for HOMER to consider in system optimisation. As shown in Table 4-9, capacity sizes 0, 5, 10 and 22 kW were considered to match the energy demand profiles determined in Chapter 5.

Table 4-9: PV capacity sizes used in HOMER

PV Capacity (kW)	Justification
0	For configurations without a PV system and sensitivity analysis with other energy systems
5	To fully cover load 3,925 W and partially cover load 5,278 W in a hybrid system
10	To fully cover loads 3,925 W & 7,762 W and partially cover load 10,134 W in a hybrid system
22	To fully cover all possible demand configurations, allow for future loads and generate income from sale of excess energy for the facility

4.2.3.1.4 PV Inputs

There are other PV related variables that can be entered during the design of the PV system. The electrical bus determines whether the PV array produces AC or DC output. While the electrical output of all PV cells is DC, some PV systems have inverters built-in to convert this to AC. In this instance, the PV system would be on the AC electrical bus and would require an inverter to convert the AC output to DC for battery charging.

However, for this investigation, the PV system selected is on a DC electrical bus (see circled area labelled **D** in Figure 4-18). A converter that contains both an inverter (converts DC to AC) and a rectifier (AC to DC) is used. This allows for ease of hybridisation of the PV array with other power supply systems with either AC or DC outputs.

The lifetime entry refers to the number of years before the PV panels must be replaced at the specified replacement cost. A lifetime period of 25 years prescribed by Jordan and Kurtz (2013) and used as default PV lifetime value in HOMER was retained in the optimisation models executed. Although degradation figures for regions of Nigeria are not readily available in literature, values for comparable climates can be used in estimating the rate of degradation of PV panels in Nigeria. It is estimated that crystalline silicon PV modules in desert areas of the United States exhibited about 1% decrease in production per year due to high levels of UV exposure.

While many parts of Nigeria are close to the Sahara Desert, the climate is not as extreme. Therefore, a 0.8% per year degradation is assumed. This accounts for the derating factor of 80% used in the PV design, that is, the panel should produce 80% of its rated power after 25 years. The derating factor (see circled area labelled **E** in Figure 4-18) is a scaling factor applied to the PV array power output to account for reduced output in real-life operating conditions compared to the operating conditions the array was rated by its manufacturers. The derating factor is used to account for degrading factors such as dust cover, wiring losses, shading and ageing.

4.2.3.1.5 Advanced Inputs

The advanced input tab on the PV design page (see circled area labelled **F** in Figure 4-18) leads to options that influence the calculation of the power output. These are described in Table 4-10 below. Section 4.2.2.1 above contains more information relating to ground reflectance, panel slope and azimuth.

Table 4-10: Advanced inputs in HOMER PV design (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Variable	Description	Comment
Ground Reflectance	The fraction of solar radiation incident on the ground that is reflected, in %	20
Tracking System	The type of tracking system used to direct the PV panels towards the sun	No tracking
Use default slope	If this input is checked, the slope input is disabled and the slope is set to match the latitude	Yes
Panel Slope	The angle at which the panels are mounted relative to horizontal, in degrees	4.82° default used
Use default azimuth	If this input is checked, the azimuth input is disabled and the azimuth is set to 0 or 180 degrees for projects in the northern or southern hemisphere, respectively	Yes
Panel Azimuth	The direction towards which the panels face, in degrees	Default 0° West of South used

4.2.3.1.6 Temperature

The temperature tab allows the user to specify or disregard the effects of temperature on the PV array. Sections 4.2.2.3.2, 4.2.2.3.3, and 4.2.3.1.7 provide detailed information regarding temperature effects on nominal operating cell temperature, efficiency at standard test conditions and power output respectively. Table 4-11 provides brief descriptions of each variable and their usage in this research while the area labelled **G** in Figure 4-19 shows the temperature tab and associated variables on the HOMER PV design page.

Table 4-11: Temperature effects variables (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Variable	Description	Comment
Consider Effect of Temperature	Whether HOMER considers the effect of PV cell temperature on the power output of the PV array	Yes
Nominal Operating Cell Temperature	The cell temperature at 0.8 kW/m ² and 20°C ambient temperature in degrees Celsius	47°C
Efficiency at Standard Test Conditions	The maximum power point efficiency under standard test conditions, in %	13%
Temperature Coefficient of Power	A number indicating how strongly the power output of the PV array depends on cell temperature, in %/degrees Celsius	-0.5%/°C

Figure 4-19: Temperature effects tab in HOMER PV design page

4.2.3.1.7 Calculation of PV Array Power Output in HOMER

HOMER uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_p (T_c - T_{c,STC})] \quad (4-19)$$

Where:

- Y_{PV} = the rated power output of the PV module under standard test conditions [kW]
- f_{PV} = the PV derating factor [%]
- $\bar{G}_T$ = the solar radiation incident on the PV array in the current time step [kW/m²]

- $G_{T,STC}$ = the radiation at standard test conditions [1 kW/m²]
 α_p = the temperature coefficient of power [%/°C]
 T_c = the PV cell temperature in the current time step [°C]
 $T_{c,STC}$ = the PV cell temperature under standard test conditions [25°C]

If the user chooses not to model temperature effects in the design, the ‘Consider temperature effects?’ option can be deselected. HOMER will assume that the temperature coefficient is zero and equation (4-19) simplifies as:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \quad (4-20)$$

4.2.3.2 Wind Turbine

In HOMER, the Wind Turbine page allows the user to choose wind turbine type, specify cost and the number of turbines to model in search for the optimal system. A HOMER specified 10kW wind turbine is selected for the models conducted (see area labelled **A** in Figure 4-20).

Furthermore, this page gives access to three input tabs as shown in the area labelled **F** in Figure 4-20. The power curve tab is used to view and edit the power curve for the selected wind turbine. A range of wind speeds from 0 to 8 m/s are used to reflect the wind speeds obtainable in Nigeria. HOMER then calculates the wind turbine power output using these values and other parameter as detailed in Section 4.2.3.2.1 below.

Turbine Losses tab is used to specify different loss modes. No turbine loss consideration is factored into the models produced in this research because they appear insignificant when factored into experimental models (Igba et al., 2015). The maintenance tab is used to consider maintenance tasks, costs and downtime. Since a fixed cost for operation and maintenance is specified under the cost section of the wind turbine design, this tab is left unchecked.

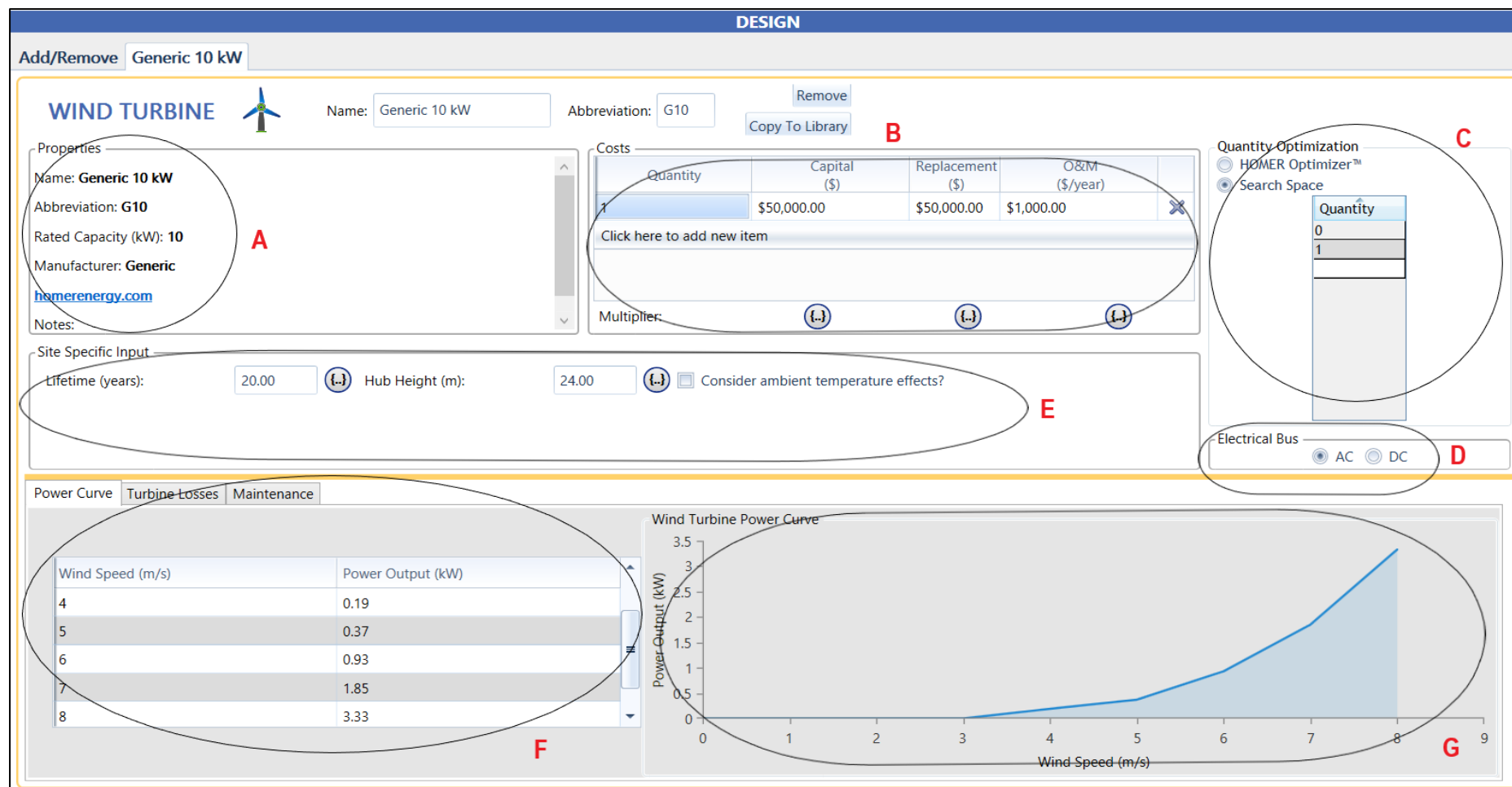


Figure 4-20: Wind turbine design page in HOMER

4.2.3.2.1 Wind Turbine Costs

The costs section of the Wind Turbine page in HOMER (see area labelled **B** in Figure 4-20) allows the input of the capital cost, the replacement cost and the operation and maintenance cost of the wind turbine. The capital cost is the initial purchase price of the turbine. The price of \$50,000 prescribed for a 10kW wind turbine by HOMER is used. This price tallies with the price of similarly rated wind turbines from wind turbine manufacturers, Xzeres (2017). This price includes: the cost of turbine rotor and tower; control system; wiring; and installation.

Replacement cost represents the cost of replacing the wind turbine at the end of its useful life. The capital cost of \$50,000 is retained for the replacement cost for this study considering that Nigeria's inflation factors and the reducing cost of wind technology will cancel each other out. Operation and maintenance (O&M) cost is the cost of operating and maintaining the turbine annually. This is typically 2% of the capital cost (HOMER Energy, 2017) equating to \$1,000 per annum, which is applied to the models used in this research.

4.2.3.2.2 Search Space

Defined in Section 4.2.3.1.3, the search space is a capacity optimisation tool. The search space inputs for the wind power component used are 0 and 1 (see area marked **C** in Figure 4-20) to model systems that have no wind turbine and those with one 10kW wind turbine. Using more than one wind turbine will be unrealistic and too expensive for the size of facility powered.

4.2.3.2.3 Electrical Bus and Site-Specific Inputs

As shown in the area labelled **D** in Figure 4-20, the wind turbine is placed on an AC electrical bus (see description in Section 4.2.3.1.4), that is, the turbine produces and supplies AC power into the system. Site specific inputs include local variables that influence the cost and performance of the wind turbine such as lifetime in years, hub height and consideration for ambient temperature effects.

A study of 3,000 onshore wind turbines by Professor Gordon Hughes (Mendick, 2012) at Edinburgh University revealed that they will generate electricity effectively for just 12 to 15 years. Nevertheless, an industry-based lifetime of 20 years is used

in this study due to improvements in material technology and turbine designs since 2012.

A hub height of 24 meters is used since a 10kW wind turbine is a small turbine (HOMER Energy, 2017; Xzeres, 2017). Ambient temperature effects on wind turbines in the experimental models conducted were negligible and are therefore not considered in the actual models used in the research (see area labelled **E** in Figure 4-20).

4.2.3.2.4 Power Curve

The power curve of a wind turbine defines the amount of power it will produce based on wind speed at standard atmospheric conditions (HOMER Energy, 2017). This tab in HOMER allows the user to view the power curve of the selected wind turbine model and accompanying wind speeds in both tabular and graphical format as shown in areas labelled **F** and **G** respectively in Figure 4-20.

4.2.3.2.5 Calculation of Wind Turbine Power Output in HOMER

The wind turbine power output is calculated using a three-step process in HOMER. HOMER calculates wind speed at hub height of the turbine first. The second step is the calculation of the power the wind turbine produces at standard air density. Lastly, HOMER corrects the power output for local air density.

4.2.3.2.5.1 Hub Height Wind Speed Calculation

The hub height wind speed of the wind turbine is calculated using the inputs specified in the wind resource page (see Section 4.2.2.2). Two laws, logarithmic and power, govern this calculation and the logarithmic law is selected. The difference between the outcomes of both formulas is insignificant. Using the logarithmic law, HOMER uses the following equation to determine the wind speed at hub height:

$$U_{hub} = U_{anem} \cdot \frac{\ln(z_{hub}/z_0)}{\ln(z_{anem}/z_0)} \quad (4-21)$$

Where:

U_{hub} = the wind speed at the hub height of the wind turbine [m/s]

U_{anem} = the wind speed at anemometer height [m/s]

- z_{hub} = the hub height of the wind turbine [m]
 z_{anem} = the anemometer height [m]
 z_0 = the surface roughness length [m]
 $\ln(.)$ = the natural logarithm

4.2.3.2.5.2 Turbine Power Output at Standard Air Density Calculation

Following the determination of the wind speed at hub height, HOMER then uses the turbine's power curve to determine the expected power output of the turbine at that wind speed under standard temperature and pressure conditions. If the wind speed at hub height is outside the limits defined in the power curve, the turbine will produce no power (HOMER Energy, 2017). This assumes that wind turbines generate zero power at wind speeds below and above the minimum cut-off and maximum cut-out wind speeds respectively.

4.2.3.2.5.3 Applying Density Adjustment

A typical power curve specifies a turbine's performance under standard temperature and pressure conditions. To correct to actual site conditions, HOMER calculates the product of the air density ratio and the power value prediction of the power curve using equation (4-22) below:

$$P_{WTG} = \left(\frac{\rho}{\rho_0} \right) \cdot P_{WTG,STP} \quad (4-22)$$

Where:

- P_{WTG} = the wind turbine power output [kW]
 $P_{WTG,STP}$ = the wind speed at anemometer height [m/s]
 ρ = the hub height of the wind turbine [m]
 ρ_0 = the anemometer height [m]

4.2.3.3 Hydrokinetic Turbine

The Hydrokinetic component in HOMER represents different types of low-head hydro power generation such as run-of-the-river, tidal and wave energy electricity generation (HOMER Energy, 2017). Low head hydro generally means hydro power projects where the vertical difference between high and low water (also known as

“head”) is less than 15m (NRCan, 2014). As shown in Figure 4-21, the Hydrokinetic design page in HOMER allows the user to choose the type and model of hydrokinetic turbine to simulate, input costs and specify the quantity HOMER should consider in the search for the optimal configuration.

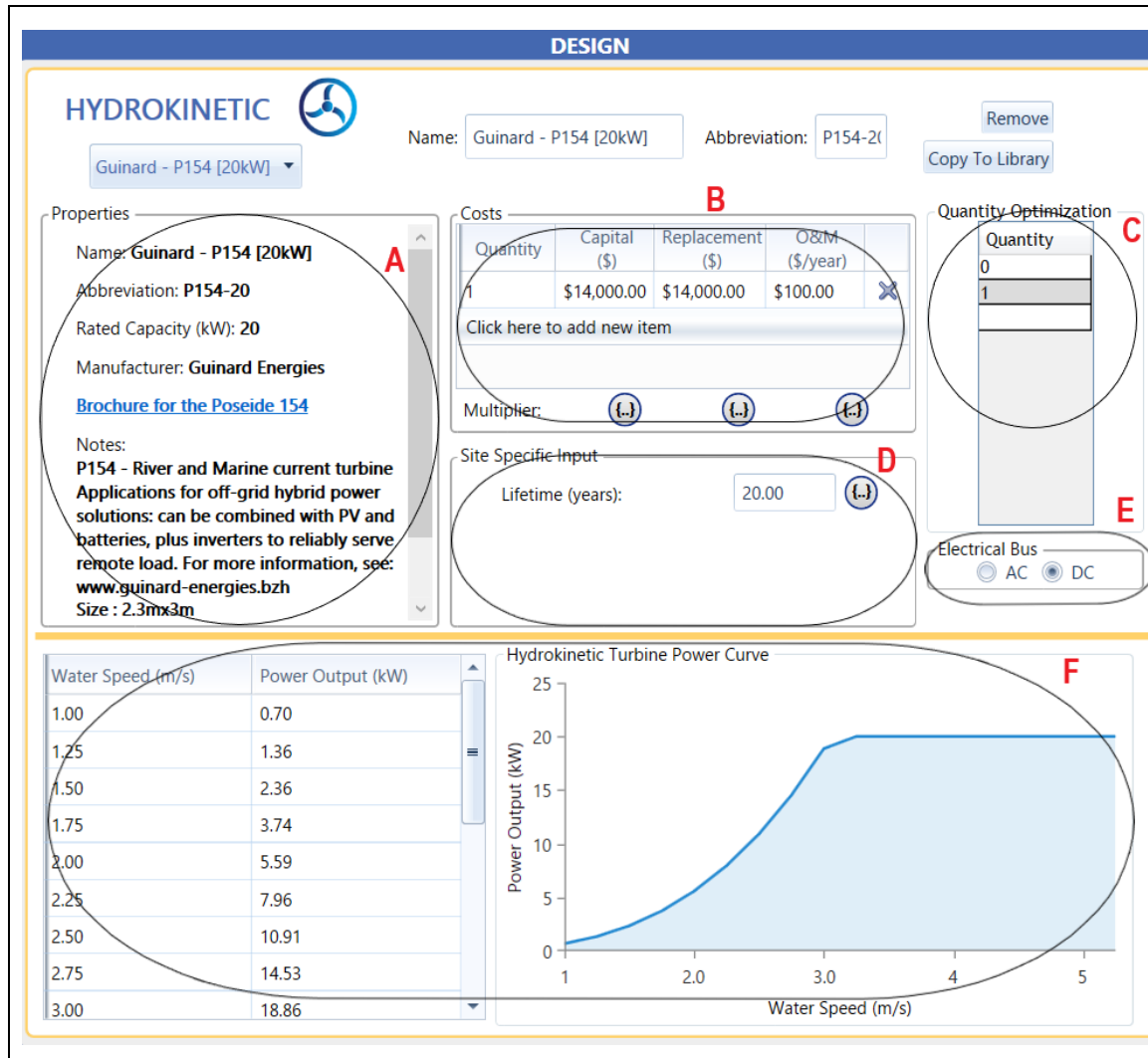


Figure 4-21: Hydrokinetic turbine design page in HOMER

HOMER allows the user to pick from a selection of ten turbines with varying power rating and from different manufacturers. In this study, the HOMER-embedded 20kW Guinard-P154 (Poseide 154) river and marine current turbine is selected as shown in the circled area **A** in Figure 4-21. Its power rating closely matches the energy demand profile for all the demand scenarios determined in Chapter 5. It

has a rotor diameter of 1.54m and requires a water depth of at least 3 m. The actual dimensions and image of the turbine can be shown in Figure 4-22.



Figure 4-22: Hydrokinetic turbine from manufacturer 9 Source: Guinard Energies)

4.2.3.3.1 Hydrokinetic Turbine Costs

As with the other components, the costs section allows for the capital, replacement and operation and maintenance costs to be entered in HOMER. The cost figures used for the hydrokinetic modelling in this study were sourced directly from Guinard Energies, the manufacturer of the selected hydrokinetic turbine. The capital cost is \$14,000 and the same is retained as replacement cost as shown in the area labelled **B** in Figure 4-21. As a low maintenance alternative to many other renewable power sources, the company stipulates that it will cost approximately \$100 per annum to maintain the turbine.

This maintenance cost is relatively high compared with \$20/year in Kusakana and Vermaak (2013). Generally, hydrokinetic turbines for run-of-the-river applications require minimal maintenance. They operate with a self-defence mechanism that

ensures continual energy generation and resilience even under flooding events with intense sedimentary transport conditions (Musa and Guala, 2018). Nevertheless, more studies need to be conducted to evaluate the long term maintenance cost of hydrokinetic turbines.

4.2.3.3.2 Quantity Optimisation, Electrical Bus and Lifetime

Instead of *search space*, HOMER uses *quantity optimisation* to describe the capacity optimisation tool in the hydrokinetic design page. 0 and 1 unit options are specified to model systems containing zero or one hydrokinetic turbine (see area marked **C** in Figure 4-21). The DC electrical bus is selected as shown in area of Figure 4-21 labelled **E** because the turbine produces DC electricity output. A manufacturer-prescribed lifetime of 20 years is factored into the design (see area marked **E** in Figure 4-21).

4.2.3.3.3 Turbine Power Curve

The turbine's power curve section in HOMER allows the user to view the power curve of the turbine model selected. The power curve defines the turbine's rated power output based on water speed. For Guinard-P154, it starts producing power at about 1 m/s and its power rating is maxed out at 3.25m/s of water speed as shown in the graph in the area labelled **F** in Figure 4-21.

4.2.3.4 Generator

The generator design page in HOMER allows the user to input cost and capacity features of a generator. A HOMER prescribed 10kW fixed capacity diesel generator is used in the models conducted. In the design page, there is access to other tabs that allow for the addition of other variable specifications to the model as described in Table 4-12 and shown in Figure 4-23 below.

Table 4-12: Generator design parameters Source: Researcher's elaboration based on HOMER Energy (2017) definitions

Variable	Description	Comment
Fuel resource	Generator fuel specification, cost per volume and consumption setting	See Section 4.2.2.5 and area A in Figure 4-23
Fuel curve	Fuel consumption setting	See area F in Figure 4-23
Emissions	Emission factors for generator	See area A in Figure 4-23
Maintenance	Maintenance cost and generator downtime settings	Fixed maintenance cost of \$0.30/ operational hour. Default downtime settings used
Schedule	Settings for generator to be forced on, off or optimised	Optimised settings according to HOMER dispatcher used

4.2.3.4.1 Generator Size and Costs

A HOMER-designed 10 kW fixed capacity generator is selected for modelling optimal power generation systems. For optimisation purposes, the option that allows for the simulation of systems with and without the generator is selected. A 10 kW sized generator is selected as it is large enough to adequately serve the peak load of all critical equipment, that is 7.281 kW, within the health facility as shown in Chapter 5.

A 10 kW generator in Nigeria as of June 2016 is priced at \$7,500 using the currency exchange rate at the time (Konga, 2016). The same amount is retained as replacement cost while a default HOMER valuation of \$0.30 per hour of operation is used as operation and maintenance cost. The search space tool for capacity optimisation is not used in this section because systems with only one generator are required. HOMER allows the option to consider alternative systems without the generator, and this is selected (see area **B** in Figure 4-23)

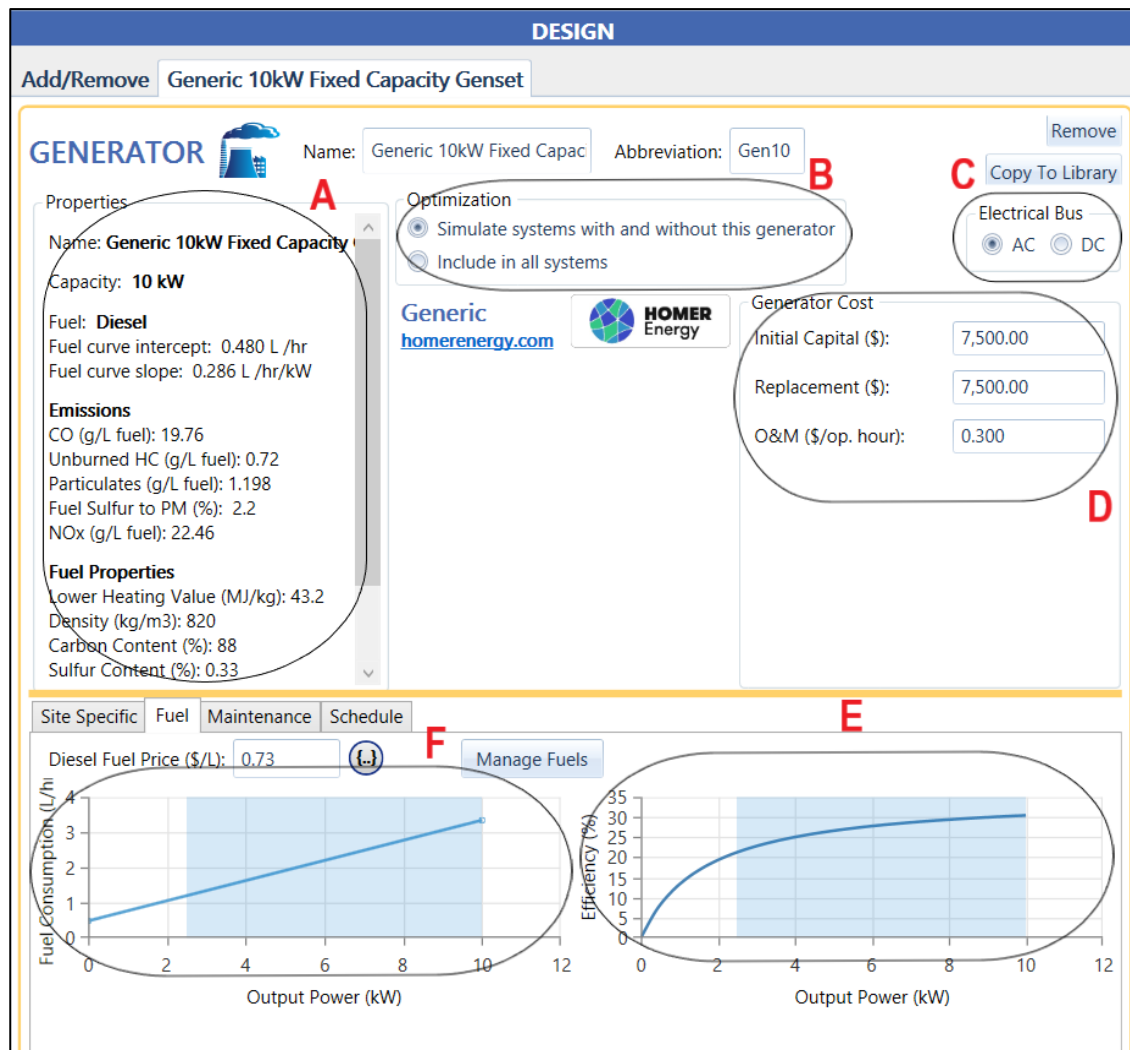


Figure 4-23: Generator design page in HOMER

4.2.3.4.2 Fuel Resource and Fuel Curve

Diesel is selected under fuel resource and the properties of the fuel is described in detail under Section 4.2.2.5 and a summary of the fuel properties is shown in area labelled **A** in Figure 4-23. HOMER plots fuel consumption data in the fuel curve shown in area **F** on Figure 4-23. A user can enter fuel consumption data for a specified generator if known. However, the fuel curve shown is HOMER's internal calculation for the specified 10 kW diesel generator. It shows that at peak power, the generator consumes about 3.4 L/hr per kW or 3.4 L/kWh.

The y-intercept of this curve is referred to as no-load fuel consumption, that is, the amount of fuel consumed while the generator is idling and not loaded. The generator fuel curve slope is the marginal fuel consumption of the generator in units of fuel per kWh. Employing a straight line fitted to the fuel consumption

figures, HOMER evaluates the generator's efficiency at various points between zero power output (fuel consumption while idling) and rated output (fuel consumption at maximum power output). As shown in Section E of Figure 4-23, the 10 kW diesel generator achieves maximum fuel efficiency of approximately 30% when operating at its rated power output.

Table 4-13: Generator emissions factors (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Emission Factor	Description	Model Value
Carbon Dioxide	Quantity of carbon in fuel not released as CO or unburned hydrocarbon (UH) is emitted as CO ₂	Based on CO & UH emissions
Carbon Monoxide	Quantity of CO emitted / unit fuel consumed by generator, in g/L	19.76 g/L
Unburned Hydrocarbons	Quantity of unburned hydrocarbons emitted / unit fuel consumed by generator, in g/L	0.72 g/L
Particulate Matter	Quantity of particulate matter emitted / unit fuel consumed by generator, in g/L	1.198 g/L
Sulphur Dioxide	Quantity of sulphur in burned fuel not released as PM	Based on PM sulphur
Proportion of Fuel Sulphur Converted to PM	Fraction of sulphur in fuel that is emitted as particulate matter (the rest is emitted as SO ₂), in %	2.2%
Nitrogen Oxides	Quantity of nitrogen oxides emitted / unit of fuel consumed by generator, in g/L	22.46 g/L

4.2.3.4.3 Emissions

For preselected generators like the one used in this study, HOMER calculates a generator's emissions using emissions factor for 50 kW – 450 kW diesel generators developed in an internal NREL report by Erin Kassoy titled: *Modelling diesel exhaust emissions in diesel retrofits* (HOMER Energy, 2017). The emissions tab in HOMER's generator design page allows a user to enter the variables shown in Table 4-13 if the generator is user defined. However, the 10 kW

generator selected for this study is system defined and the emissions factors are HOMER defined as shown in Section A of Figure 4-23.

4.2.3.4.4 Maintenance and Schedule

The cost and downtime for maintenance tasks can be specified in HOMER. The maintenance factors in Table 4-14 found under the maintenance tab in the generator design page is used to define maintenance requirements. The model values in the table are HOMER-prescribed using aggregated maintenance factor values from manufacturers of similar generators to the selected generator.

Table 4-14: Generator maintenance factors
(Source: Researcher's elaboration based on HOMER definitions)

Maintenance Factor	Description	Model Value
Procedure	Descriptive name for maintenance item	Oil change
Interval (hours)	Frequency of necessary maintenance, in number of hours the generator is operating or total (calendar) hours	1000
Type	Either maintenance interval is in Operating hours (only hours generator is on) or Calendar hours (hours including when generator is off)	Operating hours
Downtime (hours)	Number of hours generator is forced off during maintenance event	3
Cost (\$)	Cost of maintenance procedure incurred at the end of each maintenance interval	100
Marginal cost (\$/op. hour)	Additional cost added to maintenance event, per kW of generator capacity	0.3

The total cost of a maintenance event is calculated based on Cost, Marginal cost (see Table 4-14) and generator size. HOMER multiplies the Marginal cost by the generator size and adds this to the fixed Cost to derive the total cost of maintenance. For this study's 10 kW generator, the cost of oil change procedure

is \$100 and the marginal cost (that is, cost of oil based on quantity) is \$0.30/kW. The total cost of maintenance procedure is \$103 (that is, $\$100 + \$0.30 * 10\text{kW}$).

Automatically, HOMER decides for each time step whether to deploy the generator or not based on the power demand and the economics of the generator compared to competing power sources. However, a user can use the generator schedule inputs in the generator design page to allow or prevent the operation of the generator during certain times. The default optimised HOMER setting is used in this study.

4.2.3.5 Power Storage

The storage design page allows the user to choose an electrical power storage component from HOMER's library, review the technicalities of the technology and specify costs. The user can define their own storage models or select from predefined options in HOMER. There six types of storage components in HOMER namely, idealised battery; kinetic battery; modified kinetic battery; supercapacitor; flywheel; and pumped hydro. The idealised battery component is used in this study.

DESIGN

Add/Remove Generic 1kWh Li-Ion

STORAGE

Name: Generic 1kWh Li-Ion Abbreviation: 1kWh L

Properties

Idealized Battery Model

Nominal Voltage (V): 6
 Nominal Capacity (kWh): 1
 Nominal Capacity (Ah): 167
 Roundtrip efficiency (%): 90
 Maximum Charge Current (A): 167
 Maximum Discharge Current (A): 500

Batteries

Quantity	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	200.00	160.00	10.00

Lifetime

time (years): 3.00
 throughput (kWh): 3,000.00

Quantity Optimization

HOMER Optimizer
 Search Space

Site Specific Input

String Size: 1 Voltage: 6 V
 Initial State of Charge (%): 100.00
 Minimum State of Charge (%): 20.00
☐ Minimum storage life (yrs): 5.00

Figure 4-24: Storage design page in HOMER

The Idealised Storage Model allows the user to design the sizing of energy and power of the system independent of each other. The model assumes a flat discharge curve because supply voltage generally stays constant throughout discharge cycle. The Idealised Storage Model is well suited for the modelling of some high-performance Lithium Ion batteries (HOMER Energy, 2017).

A 1kWh Li-Ion battery component in HOMER, which uses the Idealised Storage Model, is selected to create the storage component for the power supply system in this study. The 1 kWh battery is then sized up by quantity using the search pace quantity optimisation tool to match different energy demand profiles. The storage component variables highlighted in Section A of Figure 4-24 are described in Table 4-15 below:

Table 4-15: General storage factors (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Variable	Description	Model Value
Nominal Voltage	The rated voltage.	6V
Nominal Capacity	The rated capacity in amp hours.	167 Amp hr (or 1 kWh)
Round Trip Efficiency	The round-trip is DC-to-storage-to-DC efficiency of the storage system.	90%
Minimum State of Charge	State of charge below which the storage bank is never drawn.	20%
Maximum Charge Current	Absolute maximum charge current	167 A
Maximum Discharge Current	Absolute maximum discharge current	500 A

4.2.3.5.1 Costs

The cost section on the storage design page includes tabs for initial capital cost, replacement cost and operation and maintenance costs per unit of storage. An initial capital cost of \$200, a replacement cost of \$160 and an annual O&M cost of \$10 is allocated to each unit of 1 kWh Lithium-Ion battery. The capital cost is prescribed by HOMER and conforms with the price of similar battery units from Nigeria's online retailer, Konga (2016). The total cost of battery is linked to the number of batteries deployed in the system and this is modelled based on the search space inputs.

Allocating \$160 as cost of replacement reflects the reducing cost of Lithium-Ion batteries globally and the fact that many installation components will be reused during replacement. The O&M cost OF \$10 is HOMER's estimation based on industry standards. HOMER also allows the user to create a maintenance schedule instead or using the O&M cost option, or a combination of both. Only the O&M option is used. The total cost of battery-related expenditure is linked to the

number of batteries deployed in the system and this is modelled based on the search space inputs.

4.2.3.5.2 Dispatch Strategy

This is a set of rules governing the operations of the battery bank and electric generator in the system. HOMER can model two dispatch strategies depending on which one is optimal. These are, load following and cycle charging strategies. HOMER will optimise either strategies if both are selected for simulation depending on different factors such as generator and battery bank sizes, amount and nature of renewable power in the system, fuel price, and O&M cost of generator.

The load following strategy enforces the generator in the system to produce only enough power to meet load demand instead of charging batteries at the same time. This strategy is usually optimal in systems with renewable power output that exceeds the system's load. The extra output is used to charge the batteries instead of using the generator to charge the batteries.

On the other hand, the cycle charging strategy forces the generator to operate at full capacity whenever it is required. The extra power goes to charging the battery bank in the system. This strategy is usually optimal in systems with minimal or no renewable power. The cycle charging strategy allows large systems to have the same renewable energy capacity and the same (or even less) number of batteries as smaller systems. However, the generator in the larger system will be put to more work than that of the smaller system, resulting in higher O&M costs.

4.2.3.5.3 Search Space

For capacity optimisation, HOMER was instructed to consider 0, 5, 10, and 22 units of 1 kWh Li-Ion battery in its simulations as shown in Figure 4-24. These are to cover the different energy demand scenarios under consideration detailed in Chapter 5. HOMER uses these figures to determine the total cost of storage for each model.

4.2.3.5.4 Site Specific Inputs

Table 4-16 below shows a description of some storage-related variables and how they have been used in the models conducted.

Table 4-16: Storage inputs in HOMER (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Variable	Description	Model Value
String size	A set of storage items connected in series. The number of storage items per string multiplied by the nominal voltage is the bus voltage.	1
Initial State of Charge	The state of charge of the storage bank at the beginning of the HOMER simulation, in %.	100%
Minimum State of Charge	A lower limit on the state of charge of the storage bank, in %.	20%
Enforce Minimum Storage Life	Enable the Minimum Storage Life constraint.	-

4.2.3.5.5 Battery Lifetime

The typical estimated lifetime of a Lithium-Ion battery is approximately two to three years or between 300 to 500 charge cycles (Tektronix, 2016). Battery lifetime in HOMER is limited by time, throughput, or time and throughput options. The time option, measured in years, indicate that the storage system requires replacement at the end of a fixed period. Whereas, the throughput option, measure in kWh, implies that the battery system should be replaced after a fixed number of energy cycles have gone through it.

The time and throughput option are selected in this study. This option dictates that the storage system requires replacement when the first of time and throughput options is reached. HOMER-prescribed lifetime values of 3 years and 3,000 kWh for time and throughput measures respectively are selected for the 1 kWh Lithium-Ion battery as shown in area **C** of Figure 4-24. These values are validated through Tektronix (2016) data, a power solutions company's lifetime estimates for Lithium-Ion batteries.

4.2.3.6 System Converter

This is an electrical device that converts alternating current to direct current and vice versa. A system converter combines the functions of an inverter (DC to AC conversion) and a rectifier (AC to DC conversion). An electrical system that contains both AC and DC components requires a converter. The Converter design page in HOMER allows the user to specify the costs of the converter and define inverter and rectifier parameters (HOMER Energy, 2017). A 1 kW capacity system-designed converter option was selected. Compared to using a fixed size converter, this can be easily scaled to match the different energy demand scenarios to be modelled using the search space capacity optimisation function.

4.2.3.6.1 Converter Costs

Like the other components, the cost section of the converter design page allows the user to enter capital, replacement and O&M costs. The capital and replacement costs of the converter include every cost associated with the selected converter including installation cost. As shown in Section A of Figure 4-25, these two costs are the same under converter costs because there are usually no reusable installation parts associated with converter replacement. HOMER prescribes a \$350/kW cost of converter.

This was verified through one of HOMER's approved converter dealers, Sensata Technologies, where the 4400 W 48VDC Pure Sine Inverter Charger *MS-PAE* costs \$1,675 according to a 2015 listing. This amounts to approximately \$380/kW. The cost of converter modelled in a system is based on multiples of this \$/kW value defined by the search space inputs. O&M cost is set at zero because regular maintenance is not required for the system converter. However, a replacement cost is factored in since its lifetime of 15 years is shorter than the projected system lifetime of 25 years.

DESIGN

CONVERTER **System Converter** **Complete Catalog**

Name: System Converter Remove
Abbreviation: Convert Copy To Library

Properties
Name: **System Converter**
Abbreviation: **Converter**
www.homerenergy.com
Notes:
This is a generic system converter.

Costs

Capacity (kW)	Capital (\$)	Replacement (\$)	O&M (\$/year)
1	\$350.00	\$350.00	\$0.0

Click here to add new item

Multiplier:

Capacity Optimization
☐ HOMER Optimizer
☒ Search Space

Search Space

Size (kW)
0
5
10
22

Inverter Input
Lifetime (years): 15.00
Efficiency (%): 90.00
☒ Parallel with AC generator?

Rectifier Input
Relative Capacity (%): 100.00
Efficiency (%): 85.00

Generic
[homerenergy.com](http://www.homerenergy.com)

Figure 4-25: Converter design page in HOMER

4.2.3.6.2 Search Space

Four different quantities of the 1 kW converter are specified for HOMER to consider in system optimisation including a zero quantity for systems without a converter – an unlikely scenario. Like the storage search space, 0, 5, 10 and 22 units of the 1 kW converter are specified in the search space capacity optimiser to match the energy demand profiles modelled (see Section **B** in Figure 4-25).

4.2.3.6.3 Inverter Input

Within the system converter, an inverter converts DC electricity to AC electricity. The inverter factors shown in Table 4-17 are prescribed by HOMER with respect to the system converters deployed in the models conducted.

Table 4-17: Inverter factors modelled in HOMER (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Inverter Factor	Description	Model Value
Lifetime	Expected lifetime of inverter in years	15 years
Efficiency	Efficiency with which the inverter converts DC electricity to AC electricity, in %.	90%
Parallel with AC generator?	This box is checked if an inverter can operate concurrently with one or more AC generators.	Yes

4.2.3.6.4 Rectifier Input

In contrast with the inverter, a rectifier converts AC electricity to DC electricity. Table 4-18 lists the rectifier factors and their values used in the Rectifier section of the converter design page.

Table 4-18: Rectifier factors modelled in HOMER (Source: Researcher's elaboration based on HOMER Energy (2017) definitions)

Rectifier Factor	Description	Model Value
Relative Capacity	The rated capacity of the rectifier relative to that of the inverter, in %	100%
Efficiency	Efficiency with which the rectifier converts AC electricity to DC electricity, in %.	85%

4.2.3.7 Advanced Grid

The Advanced Grid section in HOMER is like the sections of other components in the software. HOMER considers it as another part of the hybrid system being modelled. There is an option to run an off-grid system by telling HOMER not to add a grid component on the grid design page (see Section C in Figure 4-26). The grid design page allows the user to specify the grid using different options shown in Section A of Figure 4-26 and described in Table 4-19 below:

Table 4-19: Grid Modes in HOMER. (Source: Researcher's elaboration based on HOMER definitions)

Grid Mode	Description	Comment
Simple rates	Allows user to specify fixed power price, sell back price and sale capacity	Not selected due to limited options
Real time rates	Requires the definition of prices on hourly basis using a text file with time-series data	Not selected because hourly price data not available for the Nigerian electricity market
Scheduled rates	Different prices at each time of the day and month of the year can be specified including grid properties such as reliability and emissions	Selected because mode combines the functions of the other modes and allows user to deselect unwanted options
Grid extension	Allows for comparison between the cost of grid extension and cost of each independent system configuration in the model	Not selected because grid is to be considered along with the other systems not independently

4.2.3.7.1 Scheduled Rates

This option allows the user to specify grid prices assigned to a regular schedule in line with time of day, month, weekdays or weekends. In Figure 4-26, the Scheduled Rates section of the Advanced Grid design page gives the user control over prices, supply limits, demand charges, power outages and emissions under the Parameters, Demand Rates, Reliability and Emissions buttons respectively.

4.2.3.7.1.1 Parameters

This tab allows for the setting of many variables to meet prevailing or desired grid conditions to be modelled. The description and explanation of application or non-application of each variable are presented in Table 4-20 below. Some variables such as interconnection charge and grid capital charge are not selected because the facility whose power system is being modelled is considered to have an existing grid connection. Standby charge is not select because this service is not provided

by the Nigerian power utility. Justification for the selection and non-selection of all the parameters are provided in the comment column of Table 4-20.

Table 4-20: Grid parameters

Variable	Description	Comment
Interconnection charge	One-time fee charged by the utility for allowing a facility to be connected to the grid	Not selected. Only connected facilities considered
Standby charge	Annual fee charged by the utility to provide back-up grid power for a grid-connected power system	This service is not applicable in Nigeria
Grid capital cost	One-time cost incurred for any system that includes the grid.	Not selected. Facility already connected
Maximum net grid purchases	Maximum net amount of energy that can be drawn from the grid, in kWh/year	Not considered. Health facility cannot have electrical power limits
Net metering	Is used to calculate grid energy charges based on net usage. Allows facility to sell power to the grid at grid's retail rate	Not selected. Grid rate is different from sellback rate
Net purchases calculated monthly	Net usage is calculated monthly	Not applicable. Net metering is not selected
Net purchases calculated annually	Net usage is calculated annually	Not applicable. Net metering is not selected
Simulates systems with or without the grid	Include grid-connected systems and standalone systems in the optimisation. Standalone systems only appear in results if load can be met without grid connection	Selected
Include the grid in all simulations	System is grid-connected in all models	Cannot be combined with option above
Sale capacity	Maximum instantaneous grid sales	999,999 kW. HOMER prescribed based on added components
Purchase capacity	Maximum instantaneous grid purchases (see Section B of Figure 4-26)	33,933kW and 44,386 kW based on total power rating of facility's devices. 999,999 kW is HOMER default value

DESIGN

ADVANCED GRID **A** Name: Abbreviation:

☒ Simple Rates ☐ Real Time Rates ☒ Scheduled Rates ☐ Grid Extension

Scheduled Rates ⓘ

Parameters **Rate Definition** Demand Rates Reliability Emissions

Sale capacity (kW): ⓘ

Purchase Capacity

☒ Annual Purchase Capacity

Capacity Optimization

33993
44386
999999

☐ Monthly Purchase Capacity

Distributed Generation Costs

Interconnection charge (\$): ⓘ

Standby charge (\$/yr): ⓘ

B

C

D

E

Figure 4-26: Grid design page in HOMER¹⁹

4.2.3.7.1.2 Rate Definition

The Rate Definition tab is used to set a schedule by stipulating the times when each rate applies. For the models in this research, a uniform schedule is used due to the erratic nature of Nigeria's power supply. The pricing structure of Nigeria's grid is uniform based on consumer class and geographic region, presenting the same rates at all times for different users in various locations. This, probably reflecting the level of simplicity of Nigeria's grid system, is unlike seasonal or peak and off-peak rates available in countries like the United Kingdom.

Hence, a uniform grid rate of \$0.07/kWh was applied as shown in Figure 4-27. This is the Nigerian Electricity Regulatory Commission (NERC)'s 2016 grid rate for Tariff Class A representing grid rates for consumers such as hospitals, schools and

¹⁹ Source: Researcher's HOMER model design page

religious houses. The Sellback rate or Feed-in-Tariff (FiT) was set at \$0.17/kWh according to the rate set in NERC (2016). However, due to poor application of the Feed-in-Tariff regime in Nigeria and the national grid's inability to absorb significant amounts of excess energy from distributed sources, each model was executed thrice. First with \$0.17/kWh FiT; second with the same sellback rate as the grid rate, that is, \$0.07/kWh and; third with zero FiT. These sensitivity (to FiT variations) analyses and their results are described in Chapter 6. As discussed in Chapter 2, affordability of proposed optimised systems is benchmarked against twice the grid rate, that is \$0.14/kWh.

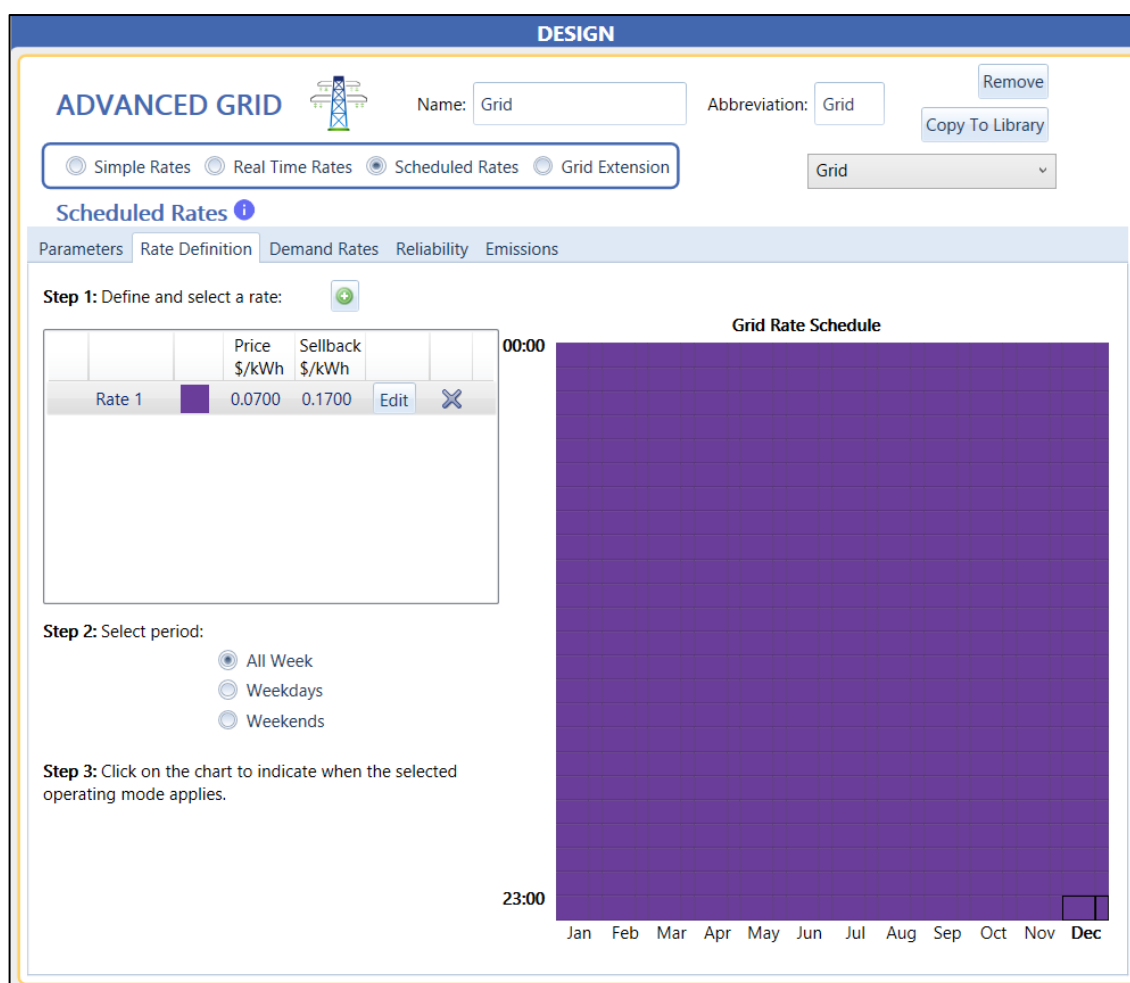


Figure 4-27: Rate definition tab

It is important to note that HOMER assumes that O&M cost for the grid is the annual cost of buying grid power less income earned through electricity sales to the grid. There are instances where the O&M cost of the entire system is negative. This happens when grid sales exceed grid purchases and O&M costs for the system combined.

4.2.3.7.1.3 Demand Rates

The demand rate function allows the user to indicate the monthly fee, in \$/kW/month, charged by the utility on the monthly peak demand. Several rates can be set for different months of the year and storage control settings for each rate period can be adjusted to reduce the cost of charging the batteries using the grid. However, this function was not employed in this study because the rating system of Nigeria's grid provider has no provision for different rates at different times of the year.

4.2.3.7.2 Grid Reliability

The Nigerian grid has gained notoriety over several decades for its unreliable supply of electricity. There are approximately 32.8 outages every month, 5 hours repair time and an outage can last up to 12 hours according to the World Bank (2015). Local commentators have described these values as conservative because the realities on ground present grimmer reliability statistics. Power outages are both frequent and unpredictable.

Since World Bank figures are the only structured and verifiable national grid reliability data available during this research, all grid reliability variables used in HOMER models are based on The World Bank (2015a)'s figures. Future studies may employ data collected on site from each of the cities explored. The mean outage frequency per year was set at 394 (that is 32.8 outages per month multiplied by 12 months). Mean repair time was set at 5 hours and repair time variability was set at 50% to reflect power outages that last up to 12 hours per day or 50% of a day.

These figures are used in the random outage calculation section as shown in the area labelled **A** in Figure 4-28. Whereas, if the outages are planned or predictable, it would have been possible to use the scheduled outage option (see area marked **B** in Figure 4-28). The dark areas in the Dmap in Section **C** of Figure 4-28 shows the percentage time there are power outages. Normally, HOMER's algorithms do not allow outages to overlap when using random outages calculations. However, if there are too many outages and/or the duration of outages are too long, the outages in successive time steps can overlap as evident in some clustered black lines in the Dmap. This is reflective of the grid power supply in Nigeria, usually

resulting in devastating effects on socio-economic activities in a rapidly modernising society.

The screenshot displays the HOMER software interface for the 'DESIGN' tab, specifically the 'ADVANCED GRID' section. The 'Scheduled Rates' tab is selected, and the 'Reliability' sub-tab is active. The 'Grid Reliability' section (labeled A) contains input fields for 'Mean outage frequency (1/yr)' (394.00), 'Mean repair time (h)' (5.00), and 'Repair time variability (%)' (50.00), with a 'Recalculate' button and a checkbox for 'Turn off Electric Load #2 when grid is off'. The 'Scheduled Outages' section (labeled B) shows a calendar view for the year 2020, with a legend for 'Normal/Outage' (Normal Operation, Outage) and 'Weekday/weekend' (All Week, Weekdays, Weekends). The 'Grid outages' section (labeled C) displays a bar chart of outages over the 365 days of the year.

Figure 4-28: Grid reliability inputs in HOMER

4.2.3.7.3 Emissions

HOMER evaluates the emissions of six pollutants for power generation technologies that burn fossil fuel. In this research, the 10 kW diesel generator and the grid are the sources that burn fossil fuel to generate electricity. The emission factors considered for the on-site generator are discussed in Section 0. Emissions considered for grid power generation in HOMER are described in Table 4-21 below:

Table 4-21: Emission factors considered for grid electricity²⁰

Pollutant	Description	Value used
Carbon Dioxide (CO ₂)	A nontoxic greenhouse gas	632 g/kWh
Carbon Monoxide (CO)	Poisonous gas produced by incomplete combustion of carbon in fuels. Prevents delivery of oxygen to organs and tissues with severe health consequences	0 g/kWh
Unburned Hydrocarbons (UHC)	Products of incomplete burning of hydrocarbon fuel. They lead to atmospheric reactions causing photochemical smog.	0 g/kWh
Particulate Matter (PM)	Mixture of soot, smoke and liquid droplets. Can result in respiratory problems and atmospheric haze	0 g/kWh
Sulphur Dioxide (SO ₂)	Corrosive gas released by burning fuels containing sulphur. It causes respiratory problems, atmospheric haze and acid rain	2.74 g/kWh
Nitrogen Oxides (NO _x)	Formed when any fuel is burned at high temperature, different nitrogen compounds like nitrogen dioxide (NO ₂) and nitric oxide (NO) cause respiratory problems, smog, and acid rain.	1.34 g/kWh

HOMER models the emissions of generators and boilers the same way because they both consume fuels with known properties. To model grid-related emissions, HOMER first calculates the net grid purchases, that is, the total grid purchases less the total grid sales. Then it calculates the emissions of each pollutant associated

²⁰ **Source:** Researcher's elaboration based on HOMER's definitions and aggregation of top polluting state grids in the USA in 2010

with these net grid purchases by multiplying the net grid purchases, in kWh, by the emission factor, in g/kWh (see Table 4-21), for each pollutant. This means that, a facility's pollutant emission footprint from the grid is offset by emissions saved from renewable power it sells back to the grid.

Emission factors for pollutants such as Carbon Monoxide, Unburned Hydrocarbons and Particulate Matter are not available for national grid power production, hence, these are given zero values as shown in Figure 4-29. Further research in the future can employ measured quantities of these pollutant emissions for every power generating plant in Nigeria for simulations.

Emissions	
Carbon Dioxide (g/kWh):	632.00
Carbon Monoxide (g/kWh):	0.00
Unburned Hydrocarbons (g/kWh):	0.00
Particulate Matter (g/kWh):	0.00
Sulfur Dioxide (g/kWh):	2.74
Nitrogen Oxides (g/kWh):	1.34

Figure 4-29: Emissions factors used in HOMER

4.2.4 Other Baseline Assumptions

These are the conditions the system modelled must satisfy. Besides the technical variables discussed in Section 4.4, some economic factors were modelled alongside technical factors. Except for Feed-in-Tariffs (FiT), these economic

variables were modelled using their 2016 values. The FiT was modelled using three values:

The first value assumes the current FiT rate, that is \$0.17/kWh according to (NERC, 2016). Compared with FiTs in many developed countries (\$0.116/kWh in the UK and \$0.0872/kWh in Germany), this is ambitious and makes independent generation of electricity seem attractive. However, the implementation of the FiT regime in Nigeria has been ineffective. It is still to be seen how the FiT system will come into play considering that the Nigerian utility is not adequately equipped to receive and redistribute low voltage electricity from distributed generation (Alike, 2015). Furthermore, the metering and billing system in Nigeria's utility is still rudimentary making the business of selling back excess electricity into the grid a complicated venture.

The second FiT rate is the same as 2016 grid rate of \$0.07/kWh. This was modelled with the assumption that excess power generated can be more readily sold to consumers near the facility at grid price than at the more expensive official FiT rate. Therefore, this third electricity sell back rate is regarded as a more realistic scenario.

Finally, the third FiT model rate is set at zero to mirror the current challenges in the Nigerian power utility's ability to be fed by independently generated power. The grid system in Nigeria will require significant upgrades to accommodate microgrids for the current FiT regime to take off realistically.

The other economic variables used in the HOMER models are presented in Table 4-22:

Table 4-22: Economic and general system variables modelled in HOMER²¹

Variable	Description	Comment
Discount rate	National rate at which money can be borrowed in %	14%*
Inflation	Inflation rate expected over the project lifetime	17%**
Annual capacity shortage	Maximum allowable value of the capacity shortage fraction i.e. total capacity shortage (or total unmet load when demand exceeds supply) divided by total electric load.	5% allowable capacity shortage allowed because the devices are all critical.
Project lifetime	Years over which the net present cost of the project is calculated	25 years, typical of industry standards

*Official Central Bank of Nigeria interest rate 2017

**Nigeria's average inflation rate between 2016 and 2017 (Trading Economics, 2017)

4.3 Sensitivity Analysis

Conducting sensitivity analysis is important for many reasons. In instances where the exact value of a variable is unknown, specifying a range of values can help a system's designer determine the importance of that variable and how the system's characteristics change based on its value. The sensitivity of cost of energy, net present cost, and capital cost to four demand load profiles and three feed-in-tariff (FiT) regimes are explored under economic factors analysis of the model results. For technical factors, the sensitivity of energy produced, energy sold, fuel consumption and pollutant emissions to the different load profiles and FiT regimes are analysed.

Since the aim of this research is to identify microgrid options to power different levels of critical healthcare applications, four pre-determined load profiles, are used to identify feasible combinations of DER components. These load profiles, described in Table 4-23, represent the different levels of criticality of energy demand in the pre-assessed treatment case in Chapter 5.

²¹ Source: Researcher's elaboration based on HOMER definitions

The unstable implementation of the feed-in-tariff system in Nigeria makes it impossible to accurately predict the amount of income or cost of energy savings that can be made from energy produced by the facility's microgrid system. It is therefore important to simulate different possible scenarios for the sale of additional energy generated by the distributed power system. Consequently, three scenarios were modelled, representing Nigeria's current feed-in-tariff regime, utility-based tariff regime and a zero feed-in-tariff regime (see Table 4-24).

The sensitivity analysis for each city includes twelve optimal systems solutions, four for each load profile. The results for the existing conventional power system are also included in the analysis for further comparison. These will help decision makers determine the level of investment to pursue based on the potential for cost recovery or cost saving, and on each system's level of pollutant emissions.

Export...

Export All...

Sensitivity Cases

Left Click on a sensitivity case to see its Optimization Results.

Sensitivity	Architecture														Cost				
Electric Load #1 Scaled Average (kWh/d)									PV (kW)	G10	Gen10 (kW)	1kWh LI	Grid (kW)	P154-20	Converter (kW)	Dispatch	COE (\$)	NPC (\$)	Operating cost (\$/yr)
21.5									22.0			5	33,993	1	22.0	LF	-\$0.0183	-\$25,141	-\$4,007
14.3									22.0			5	33,993	1	22.0	LF	-\$0.0270	-\$36,290	-\$4,319
7.31									22.0		10.0	5	33,993	1	22.0	LF	-\$0.0371	-\$48,942	-\$4,884
4.82									22.0		10.0	5	33,993	1	22.0	LF	-\$0.0412	-\$53,763	-\$5,020

A

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture														Cost						
								PV (kW)	G10	Gen10 (kW)	1kWh LI	Grid (kW)	P154-20	Converter (kW)	Dispatch	COE (\$)	NPC (\$)	Operating cost (\$/yr)	Initial capital (\$)	Fuel (\$/yr)
								22.0			5	33,993	1	22.0	LF	-\$0.0270	-\$36,290	-\$4,319	\$117,740	\$0
								22.0		10.0	5	33,993	1	22.0	LF	-\$0.0252	-\$34,071	-\$4,467	\$125,240	\$1
										10.0	5	33,993	1	22.0	CC	-\$0.0384	-\$25,401	-\$1,559	\$30,200	\$1
											10	33,993	1	22.0	CC	-\$0.0235	-\$21,679	-\$1,273	\$23,700	\$0
								22.0		10.0		33,993	1	22.0	CC	-\$0.0159	-\$21,387	-\$4,084	\$124,240	\$4
										10.0		33,993	1	22.0	CC	\$0.0107	\$7,076	-\$620.41	\$29,200	\$7
								22.0	1		5	33,993	1	22.0	LF	\$0.0277	\$38,140	-\$3,634	\$167,740	\$0
								5.00		10.0	5	33,993		5.00	CC	\$0.0912	\$38,492	\$186.25	\$31,850	\$2

B

Figure 4-30: Typical HOMER model result page²²²² Source: Researcher's HOMER model design page

Furthermore, performing a sensitivity analysis allows a single analysis to be applicable to multiple installations. Besides having six locations, four different energy demand profiles have been modelled. All locations are similar in many respects but have slight variations in wind speeds, solar irradiance and precipitation. Other variables such as economic (discount factor, inflation rate, feed-in-tariff and grid rate) and technical (component specifications, energy demand, grid reliability, fuel properties) variables are the same for all locations in Nigeria. Therefore, the same analysis was conducted for all six locations resulting in different solutions based on relative availability of resources in the locations.

Table 4-23: First Sensitivity analysis factor - Energy demand scenarios

Rank	Energy Demand Profile or Sensitivity	Scenario Description
1 st	21.53 kWh/day*	Total energy demand using conventional unprioritized medical devices
2 nd	14.29 kWh/day*	Total energy demand using energy-efficient unprioritized medical devices
3 rd	7.31 kWh/day**	Critical energy demand using conventional HFMEA-prioritised medical devices
4 th	4.82 kWh/day**	Critical energy demand using energy-efficient HFMEA-prioritised medical devices

* Figures obtained from energy assessment in next chapter

** Figures derived after prioritisation of treatment steps using HFMEA

Comparative analysis using the energy demand profiles shown in Table 4-23 above is conducted throughout according to the different FiT regimes described in Section 4.2.4. This reveals the effects of changing energy demand profiles on the capital cost, cost of energy, renewable energy fraction and emissions for each optimal system configuration. Changing the FiT values to reflect existing circumstances in the Nigerian energy market also helps in deciding the optimal system configuration to select based on the prevailing circumstance in any of the locations modelled. The FiTs are summarised in Table 4-24 below.

Table 4-24: Second sensitivity analysis factor – Feed-in-Tariff Regimes

FiT / Grid Sellback Price	Comment
\$0.17/kWh	This is the current utility Feed-in-Tariff in Nigeria
\$0.07/kWh	The current utility rates for healthcare facilities. This is to simulate instances where the FiT system fails but the facility can sell excess electricity produced to other users at utility rates
\$0.00/kWh	This represents the common instance of the failure of the FiT system and inability of the facility to sell excess power produced

4.4 Model Results and Discussions

HOMER displays the results of modelling calculations in tabular form after each calculation. There are two tables on the HOMER Results page, Sensitivity Cases and Optimisation Results tables (see Table 4-23). Selecting a sensitivity case on the Sensitivity Cases table reveals the feasible simulations that were successfully run for the case in the Optimisation Results table.

The Sensitivity Cases table presents a ranking by load of all the feasible systems from HOMER's sensitivity analysis. A HOMER sensitivity analysis can result in a large amount of output data usually in hundreds or thousands per sensitivity case. In the example shown in Figure 4-30, there were 12,032 solutions simulated for 4 sensitivity cases. There are two main type of sensitivity analysis conducted in this study. The first one involves the simulation of feasible system configurations for the four energy demand profiles determined from Chapters 3 and 5. These are presented as Sensitivity Cases in the Results page as shown in the area labelled **A** in Figure 4-30.

The second sensitivity analysis involves the simulation of different FiT regimes or grid sale prices to understand the effects of a functional, non-functional (zero

pricing for extra energy produced) and neutral (same grid purchase and sale price) FiT regimes. To achieve this, each city's model is run three times using the different grid sale values as shown in Table 4-24.

As shown in the area labelled **B** in Figure 4-30, the Optimisation Results table lists all feasible simulations for any selected sensitivity case. HOMER discards systems that are not feasible. The list of feasible systems under each sensitivity case are ranked by HOMER according to net present cost. The categorised rankings shown in the Optimisation Results of Figure 4-30 show the least-cost system of each possible system configuration under the selected sensitivity case.

The results of the HOMER models are analysed and discussed based on: each city's location described in Chapter 2 and this chapter; technical, economic and environmental factors discussed in Section 4.2 and; the different daily energy demand profiles determined in Chapter 5. The energy demand scenarios are summarised in Table 4-23 above.

4.4.1 Economic or Cost-related Results

The economic or cost-related results of the simulations run are listed and described in Table 4-25 below. They form the basis for cost considerations in the discussions of research findings. Oftentimes, the initial capital cost of DERs is one of the major barriers to their adoption in developing countries. Supportive policies such as favourable loan facilities and feed-in-tariffs can provide incentives for grid-connected healthcare facilities in low-income countries to deploy DERs for their needs and those of the community (WHO, 2015c).

There are instances where the sale of excess energy through the Feed-in-Tariff system generates revenue that takes the NPC into negative values that is, present value of costs is less than the present value of revenue from the system. This indicates that direct revenues from the sale of excess energy generated by the power system exceeds the cost of installing and operating the system over its lifetime. This happens without considering the monetary benefits of the power system to the healthcare facility.

In poor countries, budget constraints usually mean that the project with the highest present value may not necessarily be the most affordable alternative. For projects to be approved, funding constraints may necessitate the selection of an alternative project with a comparatively higher cost of operation or unit cost of energy as trade-off for a lower capital cost. Therefore, the 2016 national grid rate of \$0.07/kWh for hospitals is used as benchmark for affordability. As highlighted in Chapter 2, costs of unit energy that are less than or equal to twice the grid rate (i.e. $\text{CoE} \leq \$0.14/\text{kWh}$) are regarded as affordable or cost effective for the level of health facility studied in this research. Furthermore, analysis of levelized cost of energy (CoE) versus capital cost is conducted, by plotting graphs of CoE against capital cost, to compare the benefits of the alternative optimal system configurations calculated.

Table 4-25: Cost-related variables in model results

Variable	Description
Levelised Cost of Energy (CoE)	Average cost per kWh of useful electrical energy output of the system, correlates positively with NPC. This is benchmarked against \$0.14/kWh, which is twice Nigeria's utility tariff, for affordability considerations.
Net Present Cost (NPC)	<p>The net present cost of a system is the present value of all the costs of installing and operating all system components over its lifetime (25 years), minus the present value of all the revenue that the system earns in its lifetime. Instances where NPC is negative indicates total revenue is higher than the present cost the system incurs over its lifetime.</p> <p>Total NPC is HOMER's key economic output. It forms the basis for ranking of system configurations, and the calculation of the levelized cost of energy.</p>
Initial Capital (CapEx)	Total installed cost of all the components in the system at the beginning of the project.
Operating Cost (OpEx)	Annualised value of all costs and revenues other than the initial capital cost.
Energy Purchased	Annual quantity of electricity purchased from grid, in kWh.
Energy Sold	Annual quantity of electricity sold to the grid, in kWh.

Table 4-26 below contains the baseline value of each economic variable in systems under prevalent operational conditions in Nigerian healthcare facilities, that is, grid supply of electrical power supplemented by an ICE diesel generator. This system is hereafter referred to as “conventional” power supply system. In all simulated systems that include only grid and generator sources of electricity, the cost related

results came out the same for every city considered since the independent variables such as fuel cost and grid prices are assumed to be uniform all over the country. The values shown in Table 4-26 represent prevailing costs of running a facility with grid electricity supported with a 10 kW diesel generator.

There is currently no evidence from literature to suggest that any Nigerian health facility is benefitting from selling electricity back to the Nigerian grid at the official \$0.17/kWh FiT rate. Hence, an assumption in this research is that the \$0.07/kWh and \$0.00/kWh Feed-in-Tariff rates are the most feasible sellback rate for excess energy produced in Nigeria. Therefore, cost-related results of all sensitivity analysis conducted under these two FiT assumptions will be compared with prevailing costs of operating a healthcare facility in Nigeria as shown in Table 4-26. To achieve reliable supply of electricity in Nigeria, health facilities currently use a conventional system of grid connection with a back-up diesel generator.

Table 4-26: Cost-related results for conventional power supply systems containing only Grid and Gen10

Demand Profile (kWh/day)	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)
21.53	0.488	136,632	3,621	7,500	1,778	1,150
14.30	0.700	130,171	3,440	7,500	1,778	968.94
7.31	1.30	123,944	3,265	7,500	1,778	794.30
4.82	1.94	121,722	3,203	7,500	1,778	732
Average	1.107	128,117	3,382	7,500	1,778	911.31

Table 4-26 shows that the conventional power supply system for the 21.53 kWh/day load profile containing conventional and unprioritised devices presents the lowest cost of energy. Whereas, the system with the least energy demand profile presents the most expensive cost of energy. This is due to the system design containing a generator with a capacity that can supply the maximum power demand for all conventional devices of the hospital if necessary. It is important for a hospital to be able to operate at full capacity in situations where there are multiple patients requiring urgent treatments. Therefore, in systems where the total load is much lower than the generator's capacity, there will be a lot of redundancies and waste power when the generator is in use. This explains why the cost of energy for the

smaller energy demand profiles are higher than the CoE for the higher energy demand profiles.

In instances where the CoE of an optimal system is above the affordable benchmark of \$0.14/kWh, which represents twice the standard grid tariff for a health facility (see Table 2-3). A second affordability test compares the CoE of the system to a benchmark average CoE of a reliable conventional systems that is \$1.107 /kWh. These comparisons can be seen in sections where capital costs versus cost of energy are discussed across all optimal DER systems and conventional systems.

4.4.2 Technical or System-related Results

These outputs relate to the technical details of the system configurations from the optimisation results. All the variables under system-related factors have been discussed in Section 4.2.3 Components. The specific variables used in discussions are explained in Table 4-27 below.

Table 4-27: System-related variables in model results

Variable	Description
Renewable Energy (Ren) Fraction	Fraction of the energy delivered to the load originating from renewable sources, in %
*Electrical Energy Produced per Year	Total amount of electrical energy produced by power system in a year including, in kWh/yr (energy produced by components + energy purchased from grid)
*Electrical Energy Consumed per Year	Sum of electrical energy consumed by loads and sold to grid in a year, in kWh/yr (energy consumed by loads + energy sold to grid)
CO ₂	Number of kilograms of carbon dioxide produced from operating the system in a year, in kg/yr
*Generator (Gen) Output	Total amount of electrical energy produced by generator over the year, in kWh/yr
*PV Output	Total amount of electrical energy produced by PV array over the year, in kWh/yr
*Wind Turbine Output	Total amount of electrical energy produced by wind turbine(s) over the year, in kWh/yr
*Hydrokinetic Turbine Output	Total amount of electrical energy produced by hydrokinetic turbine(s) over the year, in kWh/yr
*Power Used by Loads	Electrical power used up by system load only. This is equal to Power Consumed minus Power Sold to the grid, in kWh/yr
*Not discussed but included in results presented in the Appendices and can form parts of future work and analysis	

4.4.3 Environmental or Emissions-related Results

These relate to the total amount of each pollutant produced annually by the electrical system, expressed in kg/year. Pollutants in this study emanate from the consumption of fuel in systems containing a generator and from the consumption of electricity from the grid. The pollutant emissions considered are carbon dioxide (CO₂), carbon monoxide (CO), unburned hydrocarbons, particulate matter, sulphur

dioxide (SO₂) and nitrogen oxide (NO). These have been defined in Sections 0 and 4.2.3.7.3 for generator and grid pollutant emissions respectively.

It is important to note that there are net CO₂ and actual CO₂ emission results. The actual CO₂ emission represents the amount of carbon dioxide produced by the microgrid components of each optimal system including the allocated emissions from grid power used. On the other hand, the net CO₂ emissions indicate the total carbon dioxide produced by CO₂ emitting components (the ICE generator) and the CO₂ allocated to grid electricity less the CO₂ emissions saved by using renewable energy components. Equation (4-23) shows how net CO₂ emission is calculated.

$$\text{Net CO}_2 = \text{Actual CO}_2\text{Emission} - \text{CO}_2\text{Emission Saved} \quad (4-23)$$

Where:

Actual CO₂Emission = Total CO₂ emitted by diesel generator +
CO₂ allocated to grid power

CO₂Emission Saved = CO₂ emission prevented by using
renewable energy

CO₂ allocated to grid power = Power purchased from the grid ×
632g/kWh (see Table 4-21)

In cases where net CO₂ emissions are presented as negative figures, these represent net CO₂ savings. Negative net emissions indicate that the CO₂ saved by using renewable energy components is more than the sum of CO₂ from the operation of the microgrid and CO₂ due to grid purchases.

For example,

1. Say 12,600 kg/year of CO₂ emission is normally associated with the production of 20,000 kWh/year grid power.
2. However, the use of a microgrid enables a facility to generate 15,000 kWh/year locally while relying on the national grid for the remaining 5,000 kWh/year.
3. Assume that the microgrid produces 2,000 kg/year of CO₂ as a result of the locally produced energy.

4. The grid will produce 3,160 kg/year of CO₂, which equates to 5,000 kWh/year × 632 g/kWh of CO₂.
5. Then, the *actual* CO₂ emitted is: 2,000 kg/year + 3,160 kg/year = 5,160 kg/year of CO₂.
6. The *net* CO₂ will be: 5,160 kg/year (actual CO₂ emitted) - 12,600 kg/year (CO₂ emission if all energy came from the grid) = -7,440 kg/year or 7,440 kg/year of CO₂ emission saved.

(Please note that the above example is for demonstration purpose only)

Since carbon monoxide, unburned hydrocarbons, and sulphur dioxide emissions are considered only for generator operations and not for grid electricity supply, they present the same figures across the different load profiles as shown in Table 4-28 below. Fuel consumption is also a generator-only variable and is therefore the same across all the load profiles because the generators are considered to operate the same number of hours when grid power is down. The other emission factors are considered for both grid and genset power supplies and they present increasing emission quantities proportional to the size of the loads in the systems.

Table 4-28: Emission figures for conventional systems

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)			
	1 st	2 nd	3 rd	4 th
	21.53	14.30	7.31	4.82
Carbon Dioxide*	10,134	8,866	7,643	7,207
Carbon Monoxide	48.1	48.1	48.1	48.1
Unburned Hydrocarbons	1.75	1.75	1.75	1.75
Particulate Matter	2.92	2.92	2.92	2.92
Sulphur Dioxide	29.2	23.7	18.4	16.5
Nitrogen Oxides	62.7	60.0	57.4	56.5
Fuel Consumption (L/yr)	2,435	2,435	2,435	2,435

* CO₂ emission is benchmarked against WHO-prescribed permissible emissions per unit energy produced for a Tier 3 facility i.e. ≤1000 gCO_{2-eq}/kWh

For comparisons with optimised DER systems, the emissions results for the conventional system under the 1st load profile are used. Hence the emission results under the 1st system (load profile 21.53 kWh/day) are used as benchmark for emissions result comparisons. As revealed in Section 4.4.1, this is because it is more economical to use all the facility's equipment when running the genset rather than prioritising some over the others. Therefore, the 1st system, which employs the generator the most for each city, is benchmarked against the conventional system for the same load profile.

Using the multi-tier benchmark measurements for electricity supply from WHO, (2015a) and presented in Chapter 2, system CO₂ emissions are benchmarked against the intermediate access tier for environmental sustainability and health. The facility modelled in this study fall under the Tier 3 intermediate access facility band. Therefore, the benchmark figure of ≤ 1000 gCO_{2-eq}/kWh emission for electricity supply in Tier 3 health facilities to be environmentally sustainable and healthy is used.

For the above conventional 1st system, the resulting energy produced is 11,063 kWh/year and actual CO₂ produced is 10,134 kg/year with both equating to CO₂ emission per unit energy produced of 916 gCO_{2-eq}/kWh. This is close to the upper limit of the benchmark figure. However, the objective of optimised DER systems in this study is to produce CO₂ emissions below this figure.

4.5 Summary and Contribution to Knowledge

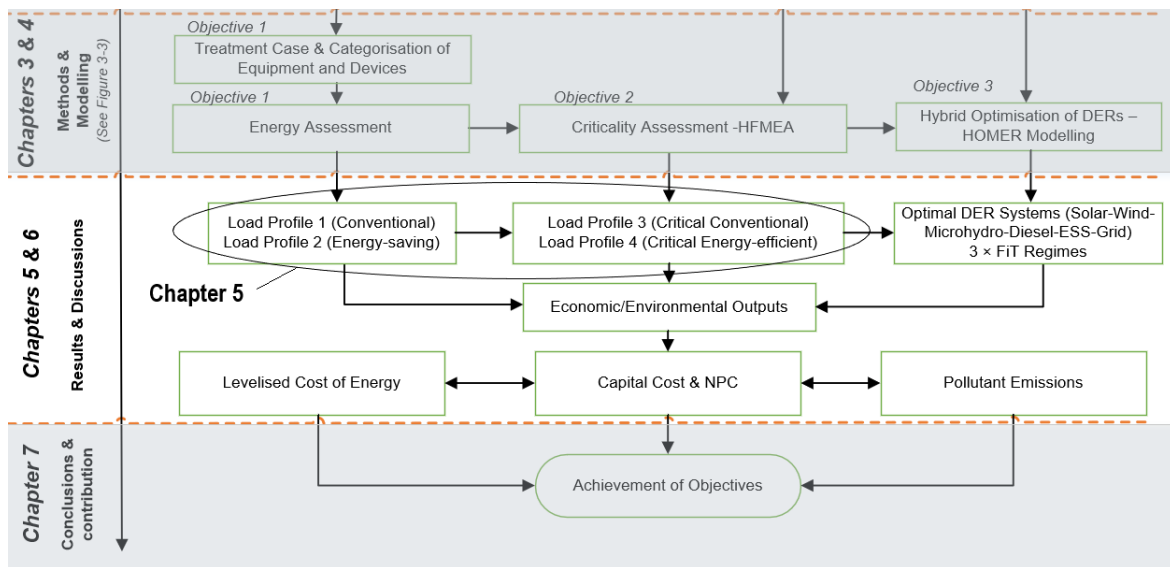
The variables used in the modelling of hybrid power generating components have been discussed in this chapter. It also includes evaluation of techniques employed in the HOMER software to assess energy demand and resource potential, and to create optimised power generating systems matching energy supply with demand. The energy resource potential of each city studied was analysed. Comparisons were drawn between average solar radiation, wind speed, temperature and water speed figures from each city. These will help in validating the optimal systems generated by HOMER later on. For example, it is expected that solar PV will contribute more prominently in systems for cities like Kano and Yola with higher solar potential. The modelling of system components in HOMER for solar, wind,

hydrokinetic, diesel generator, energy storage, converter and rectifier, and the utility grid has been demonstrated. Cost of energy and CO₂ emissions were benchmarked at $\leq \$0.14/\text{kWh}$ and $\leq 1000\text{gCO}_2\text{-eq}/\text{kWh}$ for affordability and environmental sustainability respectively.

The following contributions to knowledge have been identified:

- A method of calculating water flow speeds in m/s for settings with unknown speeds was developed using known precipitation and water speed figures for similar settings.
- This study presents three different scenarios for cost recovery through the sale of excess energy generated. The first scenario is a $\$0.17/\text{kWh}$ FiT regime, which represents the 2016 Nigeria's official feed-in-tariff for renewable power generation. The second scenario mirrors the official grid tariff in Nigeria, that is $\$0.07/\text{kWh}$ FiT regime, for settings where excess power generated cannot be fed into the grid but can be sold to other users. The last scenario is a $\$0.00/\text{kWh}$ feed-in-tariff regime created to represent a zero income potential for excess power generated.
- Four energy demand profiles can be proposed when evaluating low cost, reliable and environment-friendly distributed power generating systems. First, to represent all the essential electrical loads required in the selected process using conventional devices. The second load profile represents all essential loads using energy-efficient devices. The third profile represents the reduced loads required for prioritised conventional devices after the treatment process has been risk-assessed. The fourth load profile represents the lowest energy demand scenario where prioritised loads are energy-efficient devices. The first and second load profiles will represent the achievement of research objective 1. Whereas, the third and fourth profile will be created in fulfilment of the second research objective.

5 PRIORITISATION OF TREATMENT APPLICATIONS



5.1 Introduction

This chapter covers the demand-side analysis conducted in this research to identify essential and critical health service load profiles. It presents the results of the treatment case determination; spatial analysis for the treatment process; energy demand assessment for essential electrical devices required in the treatment; the criticality assessment employed in prioritising essential loads; and the calculation of the Event Resilience Index (ERI) required for electricity generation systems.

The methods used in obtaining the above results have been described in Chapter 3. The results presented and discussed in this chapter represent the achievement of research Objectives 1 and 2. All the activities culminating in the energy assessment of essential treatment devices address Objective 1. Whereas, the criticality assessment and ERI evaluation achieve Objective 2 which is intended to create lower levels of energy demand. The next chapter addresses the 3rd and final objective of this research.

5.2 Typical Emergency Treatment Case

After initial deliberations among the focus group of hospital staff identified in Chapter 3, three examples of trauma incidents were agreed as representative of frequent emergency treatment cases in the health facility. The first case is of a 27-year-old man with a pulsating bleed from a punctured abdomen resulting from a motorcycle

accident. A 35-year-old woman with 33-weeks pregnancy involved in a motor accident is presented as the second case. The third case is of a 10-year-old child with a deep gash on the head resulting from a fall.

Before the experts were asked to select the most severe case, each case was first adapted to a secondary hospital in Nigeria and subjected to triaging and Glasgow Coma Scale scoring as described in Chapter 3. Thereafter, each respondent was asked to select an emergency case out of the three and describe the treatment steps. The two main criteria for selection include: the case with highest treatment priority and; the case requiring the most extensive use of electrical devices.

5.2.1 Case Selection through Triaging and Glasgow Coma Scale

Of the three cases, the pregnant woman was classified as Priority 1 (immediate) of Triage as depicted in Figure 5-1. Whereas, the other two cases are usually conscious and breathing without aid. Although it is important to note that the condition of these patients can rapidly deteriorate to P1. The P1 classification indicates that the patient requires immediate life-saving intervention and its colour code is red. After a quick physical check, it is determined that the woman is sub-conscious, bleeding from one of her orifices, has a few broken bones and can only breath when airway is physically kept open.

Further observation using the Glasgow Coma Scale (GCS) presented in revealed a declining score of 10 out of 15 as follows:

1. E2 (Eye opening) – 2 points for Eye opening in response to pain
2. V3 (Verbal response) – 5 points for Inappropriate speech
3. M5 (Best motor response) – 5 points for Localising response to pain.

A deteriorating score of 10 in a heavily pregnant patient is deemed critical as her condition can become a 3 with 60% chances of death happening quickly (Teasdale et al., 2014). There was a consensus among the respondents that the pregnant woman, hereafter referred to as 'Patient A', must be prioritised because the survival of the unborn child, considered an individual, is equally at risk.

Furthermore, her treatment will require more electrical devices than the other two patients. Patient A, unlike the others, must go through more scans and laboratory tests. It was agreed that the other two patients can be stabilised using manual

treatment procedures while Patient A must go through imaging and tests that have no manual alternatives.

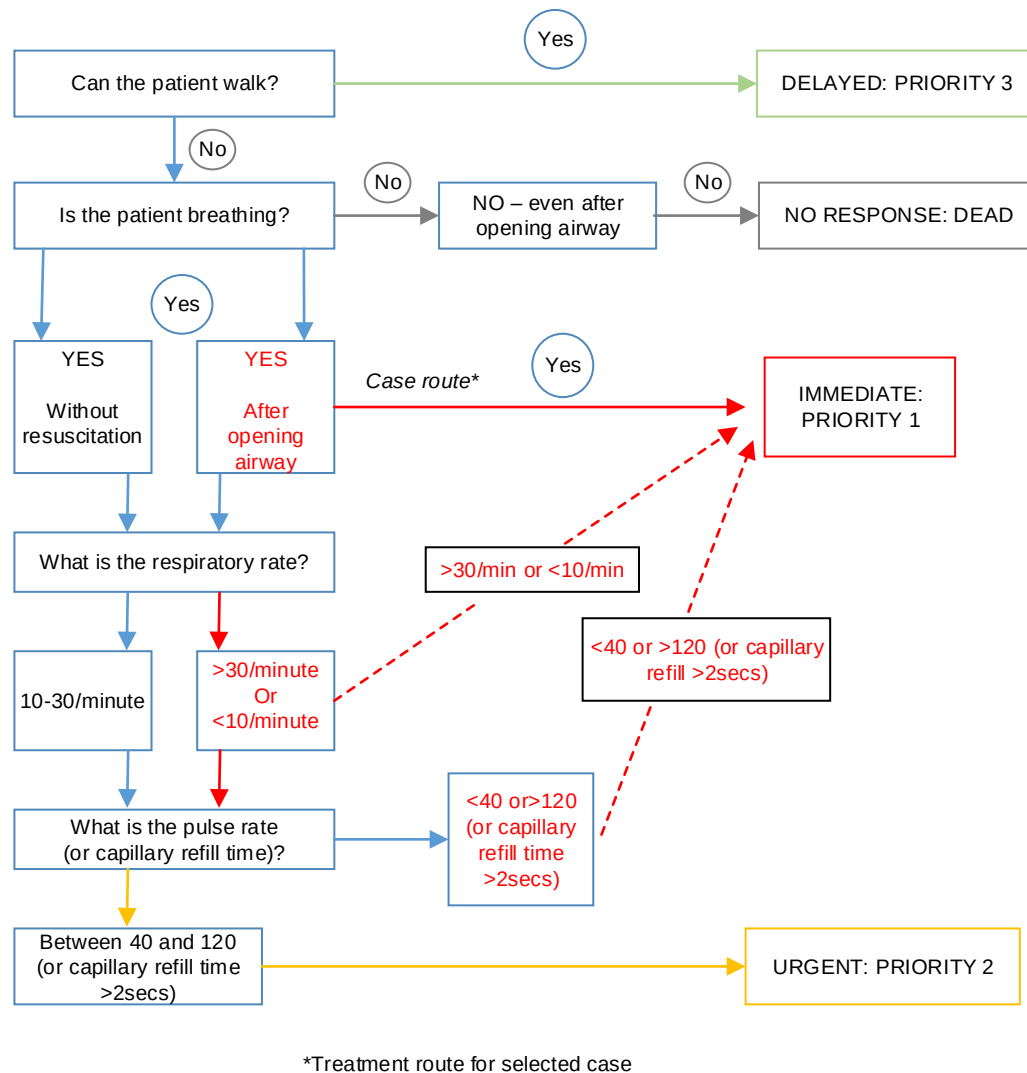


Figure 5-1: Triage Patient

5.2.2 Spatial Analysis

The focus group of hospital staff determined the necessary treatment route for Patient A. This is highlighted in red and numbered from 1 to 5 in the Figure 5-2. As described in Chapter 3, the spatial arrangement of an A&E department in the UK is adopted in this research. In all, the treatment of the patient required an area totalling 131 m² of treatment space. This is just 28% of the 464 m² functional space consideration for emergency treatments in a UK A&E department (see 3.4.2). The spatial analysis discussion in Appendix Q provides a breakdown of the spaces the

emergency case described above passed through from entry to discharge from the emergency labour ward.

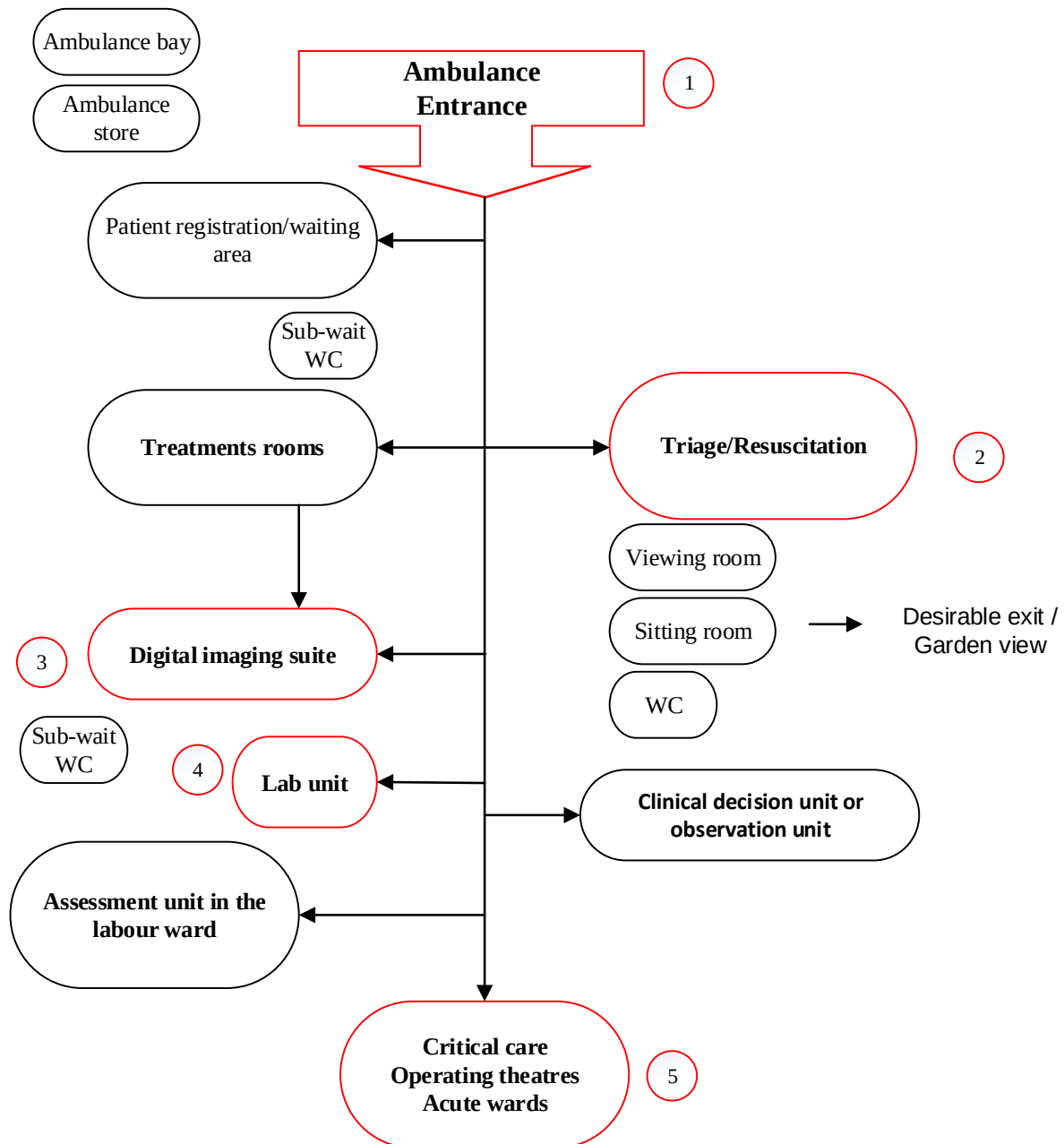


Figure 5-2: Spatial Analysis of Patient's Journey through A&E²³

5.3 Energy Demand Assessment

Due to the ability of healthcare facilities to offer a wide variety of services, ranging from catering to emergency treatments, a systematic approach to defining energy

²³ Researcher's elaboration using NHS Estates (2013). See Figure 3-5 for original layout

needs in terms of equipment required is yet to be achieved universally. Nevertheless, health infrastructure surveys such as WHO's Service Availability and Readiness Assessment have detailed inventories of available equipment in healthcare facilities. As discussed in Chapter 3, the SARA inventory was used to determine the specifications of equipment identified by the members of the focus group.

5.3.1 Electrical Demand Loads

Using the spatial analysis in Figure 5-2 above, two scenarios of electric loads were built. In the first scenario, power ratings for medical devices and electric appliances are assumed to be standard. The second scenario is based on the use of energy efficient devices. Table 5-1 presents minimum and maximum energy demand for power-efficient and standard devices respectively. Table 5-2 is used as the legend highlighting the colour codes employed in the results presented in Table 5-1.

To be able to maintain emergency service availability and readiness for the selected emergency case, the health facility requires 21.53 kWh/day and 14.29 kWh/day of energy to power 10.13 kW and 7.76 kW of conventional and energy-efficient devices respectively. Twelve highly essential medical equipment were identified and listed in Table 5-3. These require 12.51 kWh/day and 9.73 kWh/day to operate conventional and energy-efficient medical devices respectively. However, the aim is to create a lower level of demand that requires the operation of only the most critical devices at the same time. Normally, all the devices will not be required to operate at the same time. Therefore, these highly essential medical devices were subjected to an additional criticality analysis to determine each device's priority in the treatment process.

Table 5-1: Energy demand assessment for conventional and energy saving equipment and devices

Area	Equipment/load	Qty	Rating (W)		Early hours (0000-0759)	Daytime hours (0800-1759)	Night hours (1800-1159)	Total hours / day	Total Energy kWh/day		Non-critical / Contact / No-contact	DC Alternative?
			Min	Max					Min	Max		
Ambulance entrance (12.0 m ²)	Security lighting, outdoors (LED)	2	10	100	3		9	12	0.24	2.4	Contact	Y
Triage / resuscitation Room (89.0 m ²)	CFL (~45–65 lm/W)	2	10	20			4	4	0.08	0.16	Contact	Y
	Ceiling fan	1	30	100		4		4	0.12	0.4	Non-critical	Y
	Defibrillator with ECG	1	100	130		1		1	0.1	0.13	No-contact	Y
	Pulse oximeter	1	50	50		1		1	0.05	0.05	No-contact	Y
Imaging suite (15.0m ²)	CFL (~45–65 lm/W)	2	10	20		2	4	6	0.12	0.24	Contact	Y
	Ceiling fan	1	30	100		4		4	0.12	0.4	Non-critical	N
	Portable X-ray	1	3000	4000	0.5	0.5		1	3	4	No-contact	N
	Ultrasound scanner	1	800	1000		1		1	0.8	1	No-contact	N
	ECG	1	100	130		1		1	0.1	0.13	No-contact	Y
Lab unit (12m ²)	CFL (~45–65 lm/W)	2	10	20		2	4	6	0.12	0.24	Contact	Y
	Ceiling fan	1	30	100		4		4	0.12	0.4	Non-critical	N
	Autoclave	1	630	630		1		1	0.63	0.63	Contact	N
	Microscope	3	20	30	1	3		4	0.24	0.36	No-contact	N
	Blood chemistry analyser	1	45	88		4		4	0.18	0.352	No-contact	N
	Laboratory refrigerator	1	60	160	3	5	2	10	0.6	1.6	Contact	N
	Centrifuge (low-medium speeds)	1	240	250		4		4	0.96	1	Contact	Y
Operating room (15m ²)	Operating table light (~70–90 lm/W)	2	5	13		2	4	6	0.06	0.156	Contact	Y
	Air conditioning	1	1000	1500		2		2	2	3	Non-critical	N
	Anaesthesia machine	1	1440	1440		2	1	3	4.32	4.32	No-contact	Y
	Suction apparatus	1	90	200		1	1	2	0.18	0.4	No-contact	Y
	Pulse oximeter	1	50	50		2	1	3	0.15	0.15	No-contact	Y
	Fetal heart monitor	1	1.5	3	3	2	1	6	0.009	0.018	No-contact	Y
131 m ²	Total		7762	10134	10.5	48.5	31	48.5	14.29	21.53		Y

Table 5-2: Load criticality colour code and power rating

Colour Code	Criticality	Total Rating (W)	
		Min	Max
	Critical No-contact Load*	5756.5	7281
	Critical Contact Load	285	423
	Critical Contact Load No DC Alternative	630	630
	Non-critical Load/Infrastructure	1090	1800
	Total for all energy-efficient devices	7762	-
	Total for all standard devices	-	10134
	Total for energy-efficient critical devices	3925	-
	Total for standard critical devices	-	5278

* Includes laboratory refrigerator, a critical contact load

Table 5-3: Load profile of all critical devices

Critical Devices	Power rating (W)		Energy demand (kWh/day)	
	Min	Max	Min	Max
Defibrillator with ECG	100	130	0.1	0.13
Pulse oximeter	50	50	0.05	0.05
Portable X-ray	3000	4000	3	4
Ultrasound scanner	800	1000	0.8	1
ECG	100	130	0.1	0.13
Microscope	20	30	0.24	0.36
Blood chemistry analyser	45	88	0.18	0.352
Laboratory refrigerator	60	160	0.6	1.6
Anaesthesia machine	1440	1440	4.32	4.32
Suction apparatus	90	200	0.18	0.4
Pulse oximeter	50	50	0.15	0.15
Fetal heart monitor	1.5	3	0.009	0.018
	5756.5	7281	9.729	12.51

5.4 Application of HFMEA for Criticality Analysis

A HFMEA team was organised to use process flow diagrams, a hazard scoring matrix and the HFMEA decision tree to identify and assess potential vulnerabilities in the treatment process identified earlier in this chapter. The HFMEA technique was used to identify and rank the most critical functions within the life-saving treatment process. This is achieved by giving highest priority to devices used in completing process with the highest severity score. For ease of comprehension, the HFMEA process was synthesised into a graphic flow diagram presented in Figure 3-6 for the team.

The results of this analysis show that decision makers can proactively assess, identify and rank critical functions and related devices for alternative energy supply prioritisation. This is important in situations where resources are limited. It is important to note that only electrical applications considered in this research are included in the analysis. The HFMEA contains 5 steps.

5.4.1 Step 1: Define HFMEA Topic

This involves the definition of the HMEA topic and the process to be studied. **‘Treatment Process for Patient A’** is the title selected for this analysis. The five main diagnostic processes requiring significant use of electrical equipment were selected. This was based on the team’s consensus after evaluating the potential severity of the failure of the diagnostic and laboratory processes. The availability of manual or battery-operated devices in the other main treatment processes also contributed to this choice.

5.4.2 Step 2: Assemble Team

As described in Chapter 3, a multidisciplinary team of two medical doctors, two laboratory technicians and two hospital facility managers from the same hospital and with 5 to 20 years’ experience were drafted to participate in the HFMEA process through brainstorming. It took 10 sessions to complete the criticality assessment.

5.4.3 Step 3: Graphically Describe the Process

Here, the treatment process was laid out using a flow diagram showing the steps consecutively numbered (see Figure 5-3). There is a list of four processes and corresponding sub-processes identified for Case A. Figure 5-4 shows the sub-processes under the diagnostic process. By focusing on specific aspects of the entire treatment process, the team could focus on timely completion of the prioritisation project without becoming overwhelmed by complexities. The sub-processes identified in the diagnostics process for the treatment process are not exhaustive but are the ones with the highest vulnerability to power outages.

Step 3A: Gather information about how the process works – describe it graphically

Step 3B: Consecutively number each process

Step 3C: If process is complex, select area to focus on

Step 3D: If necessary, list sub-process steps and number onsecutively

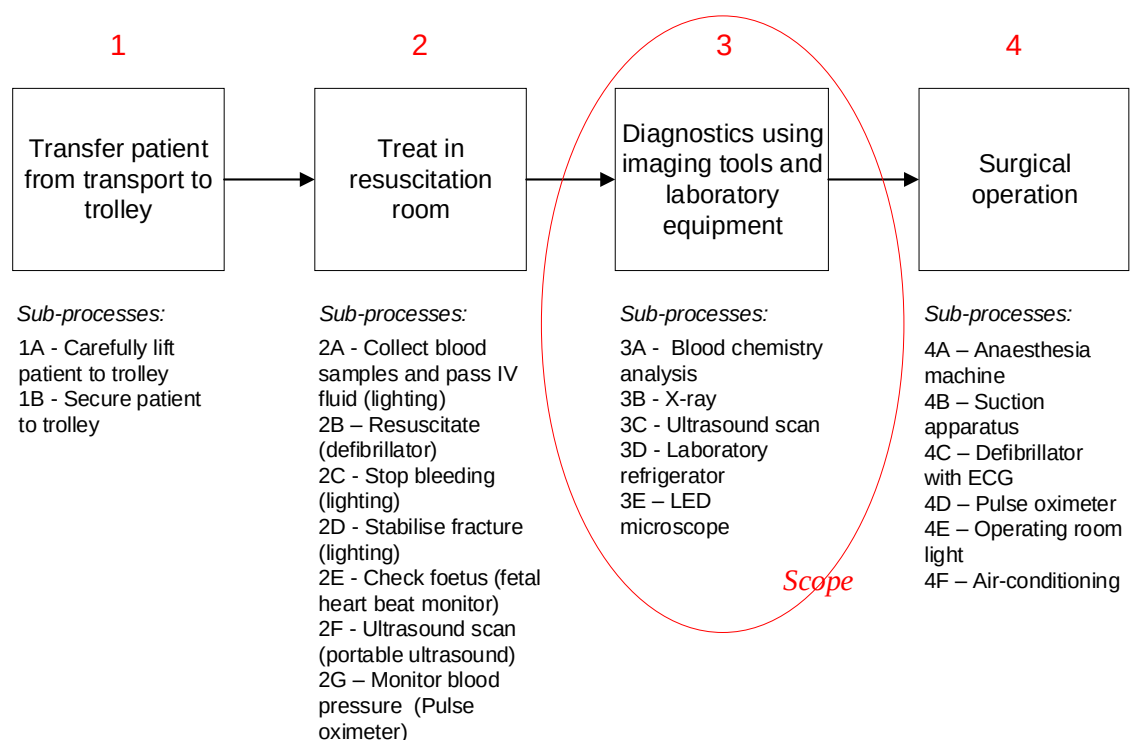


Figure 5-3: Graphical description of treatment process

Other processes such as filing blood test results in a computer medical record are not included as these are not critical to saving the life of the patient. These non-critical activities can be deferred till a time when grid power is available. It is also important for stakeholders to agree these non-critical processes and set out parameters for deciding priorities. However, this is not a consideration in this

research.

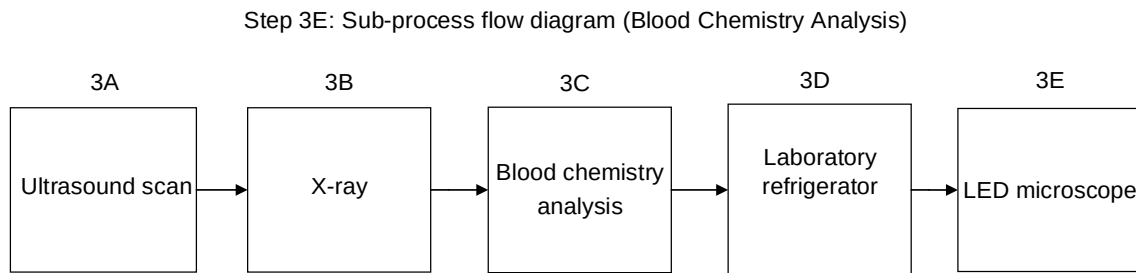


Figure 5-4: Step 3E - Sub-process flow diagram

An assessment of the power requirements of the devices in each step revealed that process 3 (diagnostics) requires the most amount of energy. This is mainly due to the x-ray machine. Having this result removes the burden of conducting the analysis on all the other processes and their sub-processes. This is based on the premise that any microgrid system designed to handle all the energy requirements for diagnostics will handle requirements from other processes. This is similar to the concept of critical paths in Project Management.

Furthermore, by highlighting a single part of the process for further analysis, the team can avoid the cost and frustration of being overwhelmed. Nevertheless, a facility with sufficient resources may opt for a full analysis of all the processes involved in their most common treatment cases to make it easier to update the assessment in case of future addition of devices.

5.4.4 Step 4: Conduct a Hazard Analysis

This step required members of the team to list all possible failure modes for every sub-process and number them consecutively. As discussed in Chapter 2, failure modes are the different ways a particular process or sub-process step can fail to accomplish its intended purpose. It is common for teams to use different sources and tools to identify potential failure modes. Examples of such tools include Institute for Safe Medication Practices (ISMP) information and Food and Drugs Administration databases to identify potential failure modes related to confirming known drug allergies.

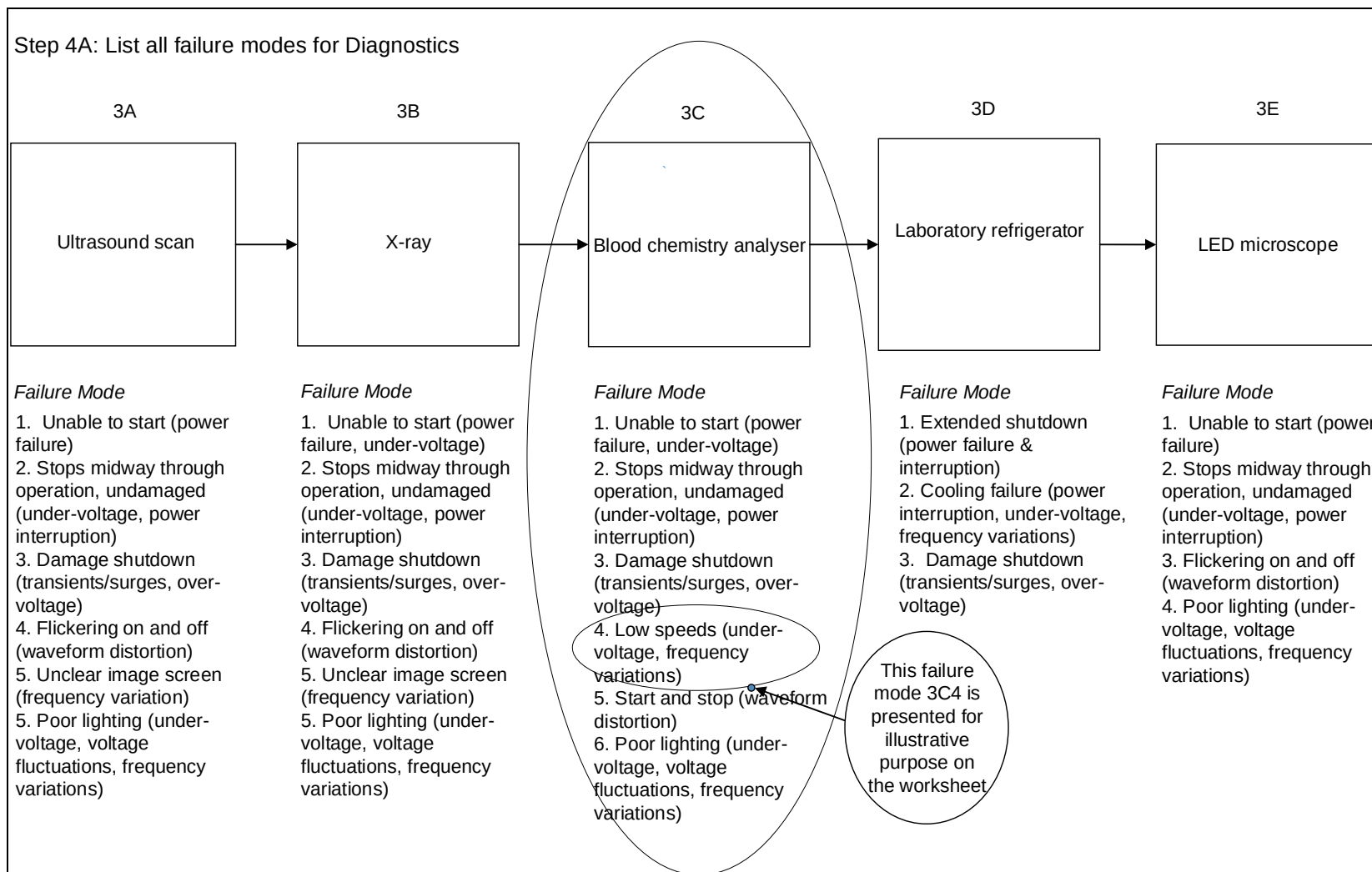


Figure 5-5: Step 4A - Hazard analysis listing potential failure modes

Presently, there are no standardised frameworks or databases for identifying potential failure modes in treatments requiring electrical equipment. This is possibly due to the unique nature of every healthcare setting and human factors making it extremely difficult to set out a universal format for potential failure mode identification. Nevertheless, the power quality attribute of power supply defined by the Institute of Electrical and Electronics Engineers (IEEE, 2009) has been adopted to determine the failure modes in a structured manner. Through brainstorming, triggering questions and cause-and-effect diagramming (see Figure 5-7), the potential failure modes associated with unreliable power supply in healthcare facilities in this research were determined. Step 4 of the HFMEA includes five sub-steps from A to E.

Figure 5-5 shows the identified failure modes for sub-processes from *Step 3* and its own sub-processes. Note that the failure modes are similar for most of the sub-processes. This is because of the similarities in the effects of poor power quality of electrical devices.

5.4.4.1 Step 4 A - Severity and Probability Ratings of Failure Modes

5.4.4.1.1 Severity Ratings of Failure Modes

The next step in the analysis is to determine the severity and probability of the potential failure modes and determine the hazard score using the Hazard Scoring Matrix. The severity score is the measure of the potential effect of a failure mode. It depicts the impact on the patient or patient care if failure should occur. In HFMEA, there are four categories of severity namely: catastrophic, major, moderate and minor with specific operational definitions agreed for each. The standard severity categories are shown in Table A-1. However, it is imperative to adjust these categories to reflect the dearth of economic resources in the environments under consideration. Consequently, the equipment or facility indicator of each severity category has been modified in this research, as presented in Table 5-4. Low speeds in blood chemistry analysers (i.e. Process 3C4) are evaluated as *Catastrophic Events* in the treatment process for Patient A.

Table 5-4: Severity ratings (Process 3C4 rating highlighted yellow)²⁴

Catastrophic Event (Rating of 4) <i>(Traditional FMEA rating of 10—Failure could cause death or injury.)</i>	Major Event (Rating of 3) <i>(Traditional FMEA rating of 7—Failure causes a high degree of customer dissatisfaction.)</i>
<p><i>Patient Outcome:</i> Death or major permanent loss of function (sensory, motor, physiologic, or intellectual), suicide, rape, haemolytic transfusion reaction, surgery/procedure on the wrong patient or wrong body part, infant abduction or infant discharge to the wrong family.</p> <p><i>Visitor Outcome:</i> Death or hospitalization of 3 or more visitors</p> <p><i>Staff Outcome:</i> A death or hospitalization of 3 or more staff</p> <p><i>Equipment or facility:</i> Damage equal to or more than \$10,000/or an amount equal to or more than costliest equipment on site.</p> <p><i>Fire:</i> Any fire that grows larger than an incipient stage</p>	<p><i>Patient Outcome:</i> Permanent lessening of bodily functioning (sensory, motor, physiologic, or intellectual), disfigurement, surgical intervention required, increased length of stay for 3 or more patients, increased level of care for 3 or more patients.</p> <p><i>Visitor Outcome:</i> Hospitalization of 1 or 2 visitors</p> <p><i>Staff Outcome:</i> Hospitalization of 1 or 2 staff or 3 or more staff experiencing lost time or restricted-duty injuries or illnesses</p> <p><i>Equipment or facility:</i> Damage equal to or more than \$4,000/ or an amount equal to or more than 40% of costliest equipment on site</p> <p><i>Fire:</i> Not applicable—See “Moderate” and “Catastrophic”</p>
Moderate Event (Rating of 2) <i>(Traditional FMEA rating of 4—Failure can be overcome with modifications to the process or product, but there is minor performance loss.)</i>	Minor Event (Rating of 1) <i>(Traditional FMEA rating of 1—Failure would not be noticeable to the customer and would not affect delivery of the service or product.)</i>
<p><i>Patient Outcome:</i> Increased length of stay or increased level of care for 1 or 2 patients</p> <p><i>Visitor Outcome:</i> Evaluation and treatment for 1 or 2 visitors (less than hospitalization)</p> <p><i>Staff Outcome:</i> Medical expenses, lost time, or restricted-duty injuries or illness for 1 or 2 staff</p> <p><i>Equipment or facility:</i> Damage more than \$1,500 but less than \$4,000</p> <p><i>Fire:</i> Incipient stage or smaller</p>	<p><i>Patient Outcome:</i> No injury nor increased length of stay nor increased level of care</p> <p><i>Visitor Outcome:</i> Evaluated and no treatment required or refused treatment</p> <p><i>Staff Outcome:</i> First aid treatment only, with no lost time or restricted-duty injuries or illnesses</p> <p><i>Equipment or facility:</i> Damage less than \$1,500 or loss of any utility without adverse patient outcome (e.g. natural gas, electricity, water, communications, transport, heat/air conditioning).</p> <p><i>Fire:</i> Not applicable—See “Moderate” and “Catastrophic”</p>

²⁴ See standard HFMEA severity rating scales in Appendix A

5.4.4.1.2 Probability ratings of Failure Modes

As discussed in Chapter 2 (Section 2.13.3), the conventional HFMEA has four probability ratings, which have been highlighted in Appendix A (Table A-2). However, these have been adjusted for this research in Table 5-5 below to reflect the high frequency of incidents of unreliable power supply in Nigeria. For the HFMEA conducted in this research, *Frequent* rating refers to events that may happen several times a day; *Occasional* for those that may occur several times in 2 to 5 days; *Uncommon* refers to events that may happen sometime in 5 to 14 days and *Remote* is associated with events that may occur sometime in 2 to 4 weeks. The HFMEA Team adjudged low speeds in blood chemistry analyser as occasional events i.e. probably will occur.

Table 5-5: Probability ratings

Probability Rating	Description	Score
Frequent	Likely to occur immediately or within a short period (may happen several times in a day)	4
Occasional	Possible to occur (may happen sometime in 5 to 14 days)	3
Uncommon	Possible to occur (may happen sometime in 5 to 14 days)	2
Remote	Unlikely to occur (may happen sometime in 2 to 4 weeks)	1

5.4.4.2 Step 4B – Hazard Analysis

This refers to the final step in hazard analysis for the failure mode such as the one at Step 3C4 in Figure 5-5. The hazard score is determined by multiplying the severity and probability ratings of the potential failure mode and recording the score on the Hazard Scoring Matrix. Failure mode at 3C4 produces a hazard score of **12** as shown in Table 5-6. This indicates that low speeds in the blood chemistry analyser is a catastrophic occasional event and is recorded on the HFMEA Worksheet in Figure 5-8 Table A-3. A comparison of the Hazard Score of all the failure modes in the treatment process helps determine the level of criticality of each sub-process and consequently, the need to prioritise for alternative power supply. According to standard HFMEA practice, hazard scores of 8 or higher requires further action and the rationale for any Stop decisions must be recorded.

Table 5-6: HFMEA Hazard scoring matrix

		Severity of Effect			
		Catastrophic	Major	Moderate	Minor
Probability	Frequent	16	12	8	4
	Occasional	12	9	6	3
	Uncommon	8	6	4	2
	Remote	4	3	2	1

5.4.4.3 Step 4C - HFMEA Decision Tree

The HFMEA team deployed the Decision Tree after Hazard Scoring the failure mode. Steps highlighted in red in Figure 5-6 shows the decision steps for failure mode 3C4. The next step involves using the HFMEA Decision Tree (Figure 5-6) to determine whether the failure mode requires further action based on criticality, absence of effective control measures and lack of detectability or to stop on the HFMEA Worksheet. Answers to questions relating to these three factors are used to determine if it is necessary to proceed to identify failure mode causes. Criticality or single point weakness measures whether the entire system will fail if this part of the process fails. In this case, the entire treatment process for the patient will fail if the blood chemistry analysis is not completed due to low speed of the analyser.

An existing effective control measure such as DC-powered alternatives eliminates or significantly reduces the likelihood of failure occurring. Having a battery powered hand-held blood chemistry analyser will reduce the probably of the failure of blood analysis in the treatment of *Patient A*. Detectability or obvious hazard refers to the likelihood of detecting failure or the effect of failure before it happens. Failure modes brought about by scheduled power outages are obvious however, failure due to sudden grid-based outages or fluctuations and backup system shutdowns can occur without prior knowledge.

Figure 5-6 shows the Decision Tree analysis for failure mode 3C4. The steps in red borders show the respondents' agreed answers to the Decision Tree questions. The resulting action is to proceed to Step 5. If the action is to stop, the

team would proceed to carrying out Step 4B on the next failure mode (3C5). Steps 4C and 4D are necessary to validate the Hazard Score. Steps 4D, 4E and 5 are all carried out in the Worksheet.

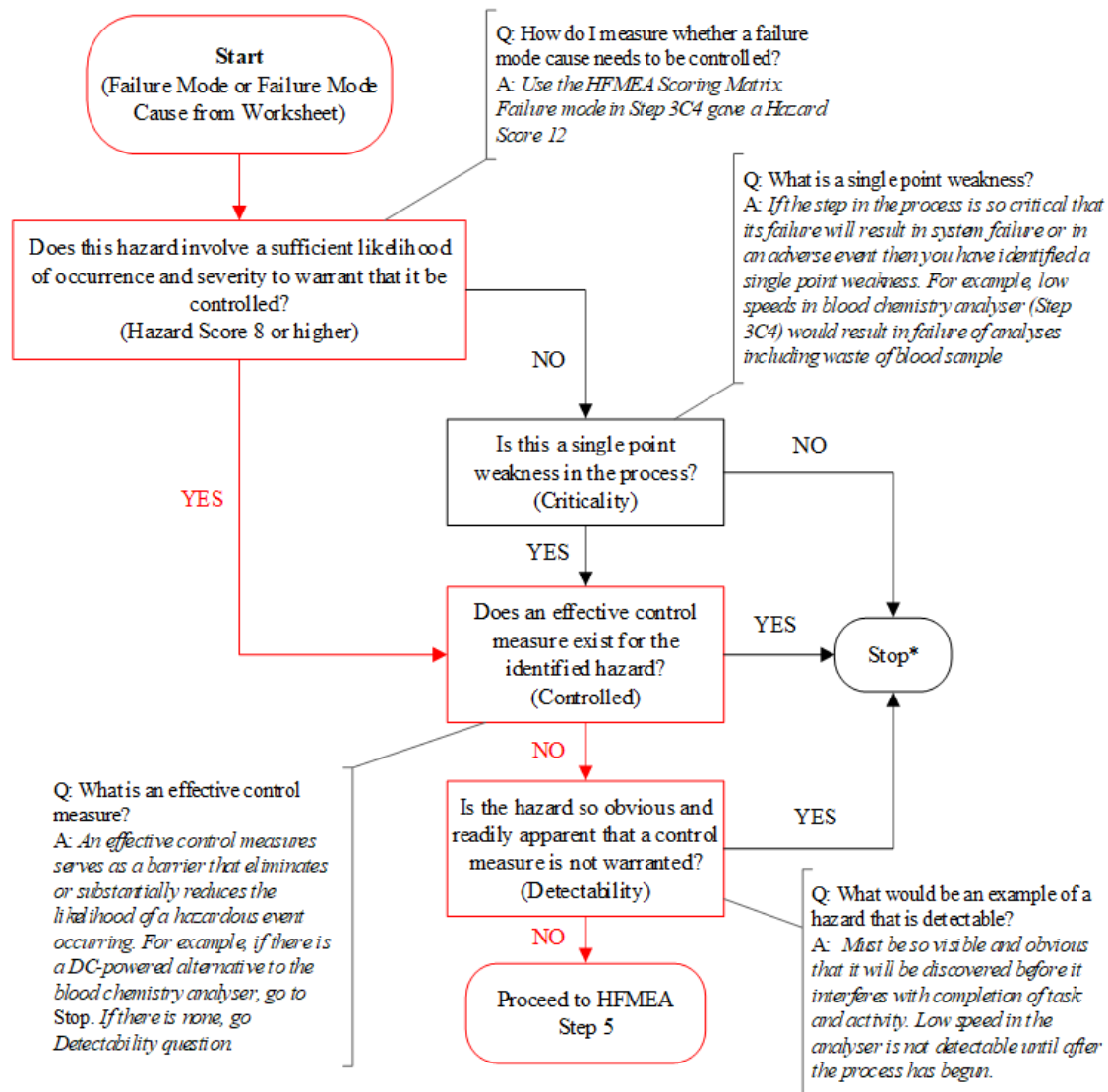


Figure 5-6: Decision tree for failure mode 3C4

5.4.4.4 Failure Mode Severity Considerations

The main causes of failure for electrical equipment considered in this study are based on the power quality component of the attributes of electricity supply developed by WHO (2015a) as reviewed in Chapter 2. The seven indicators of power quality developed by IEEE (2009) were explained to the HFMEA team and the causes of failure are categorised under these indicators. It is important to note that only the power quality attributes of supply were used in this HFMEA analysis

due to time and financial resource constraints. An area for future work will be to explore failure modes associated with each power supply attribute described below using a health facility as case study.

5.4.4.4.1 Power quality

As discussed in Chapter 2, the failure modes in this HFMEA task are primarily based on this attribute of power supply. Power quality has been defined in Chapter 2. When power quality is poor, critical services can be interrupted or associated devices may become damaged. Many devices using AC power do not work properly when there is low voltage or frequent power fluctuations.

The severity and effects of failure modes associated with each power quality definition are different and peculiar to every location. For instance, an interruption, whether it is instantaneous, momentary, temporary, or sustained, can cause disruption, damage, or downtime in the operation of different equipment. A health centre computer could lose valuable data when information is corrupted from momentary loss of power (catastrophic event) and an x-ray machine may require extended start-up (major event) due to a temporary power failure. Through a brainstorming session, the HFMEA team determined the power quality categories, associated failure modes and causes as shown in Table 5-7.

Table 5-7: Power quality categories for failure modes for diagnostic equipment²⁵

No	Power Quality Categories	Failure Modes	Causes
1	Transient (power surge)	Possible damage Damage shutdown	Lightning (no backup) Utility fault
2	Interruptions/power outage	Unable to start Undamaged shutdown Extended shutdown	Grid damage/fault Circuit breaker trip Power rationing Lightning strikes Destructive strikes Vehicular accidents Animal/tree falls
3	Under-voltage/sag	Undamaged shutdown Unable to start Low speed Cooling failure	Utility faults Start-up loads Load changes Overloading
4	Over-voltage/swell	Damage shutdown Light bulb blowouts	Load changes (sudden unloading) Utility faults
5	Waveform distortion	Start and stop	Variable speed drives Faulty equipment Electronic loads
6	Voltage fluctuations	Lights flickering on and off	Faulty equipment Heavy electrical load Ineffective grounding
7	Frequency variations	Low speeds Unclear image screen Poor lighting	Voltage imbalance due to intermittent operation of load equipment

5.4.4.5 Other Severity Considerations

In functions where sub-processes must be completed in a linear and consecutive manner, the failure of one or more devices may result in total failure of the headline process. The potential failure modes of such devices can be regarded as catastrophic because of the ripple effect their failure will cause. For example,

²⁵ Adapted from: IEEE (2009) and Seymour and Horsley (2011)

during the process of diagnosis, the failure of the blood chemistry analyser will render the process incomplete. Failure or success of a sub-process such as refrigeration of blood samples is also inconsequential because its usefulness is dependent on the results of a blood chemistry analysis. Beyond the diagnostic process, treatment operations such as surgery may have to be suspended as a result of the failure of the blood chemistry analyser.

The availability of DC powered alternatives can act to dampen the effects of the failure of the main AC-powered device. However, this is only for short periods of power failure. For instance, there are battery-powered hand-held blood chemistry analysers that can act as short-term alternative when the main analyser fails. The availability of this alternative can reduce the effect of mains power outage on the process to a minor event. However, frequent dependence on the alternative may increase the hazard score of the failure of the main blood chemistry analyser.

5.4.4.6 Step 4D – List Failure Mode Causes

Step 4D lists out all the failure mode causes for each failure mode where the decision from Step 4C (Decision Tree) is to *proceed* and records the causes on the HFMEA Worksheet. Each failure mode may have multiple causes. For example, failure mode 3C4 (low speed in blood chemistry analyser) can be caused by insufficient power from overloading of electrical system, low voltage from the grid, voltage fluctuations, or faulty backup generator. Listing of the failure mode causes is achieved through brainstorming and the use of cause-and-effect diagramming as shown in Figure 5-7.

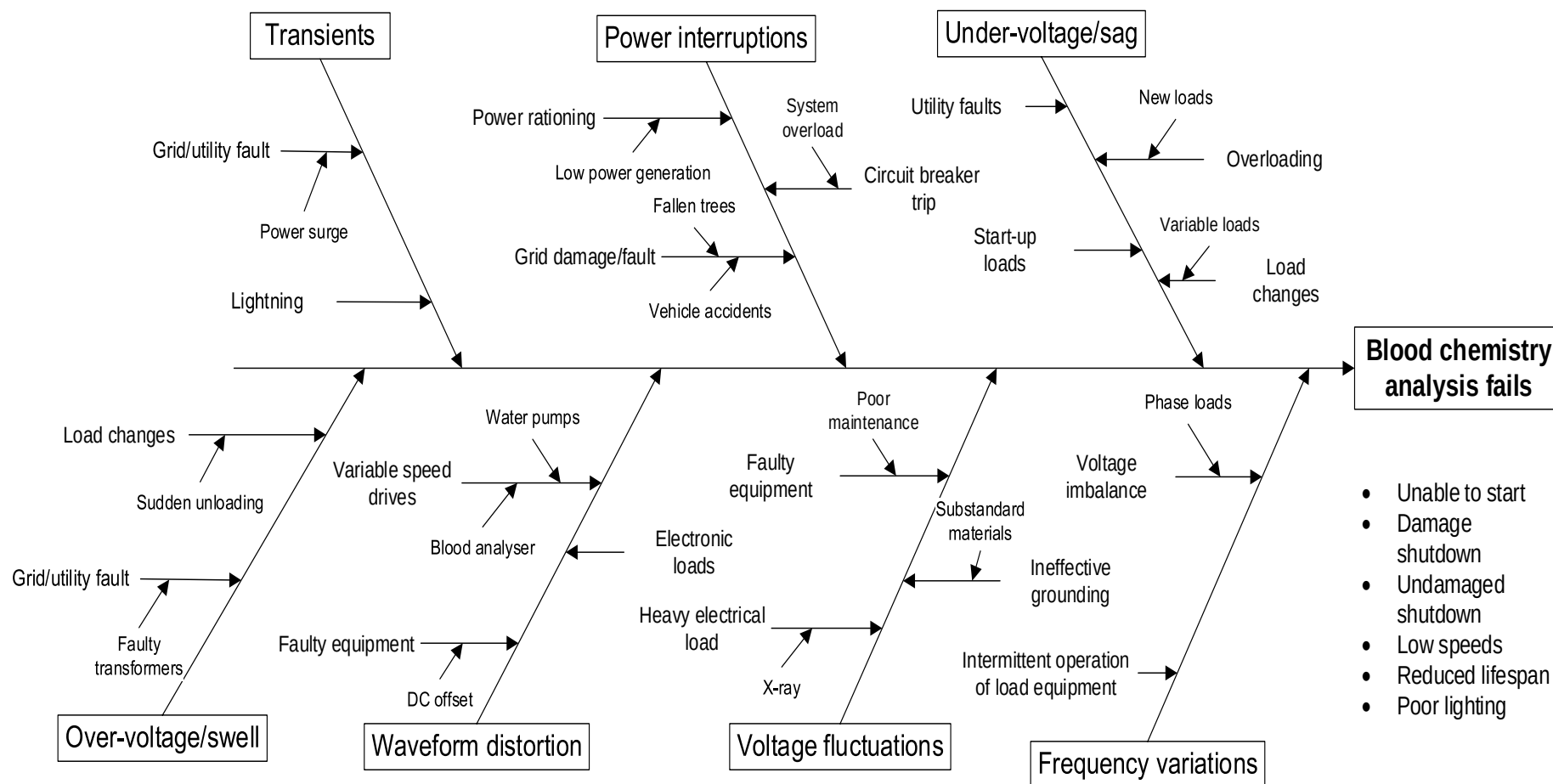


Figure 5-7: Fishbone diagram showing causes and effects of unreliable power on blood chemistry analysis²⁶

²⁶ Analysis based on power quality parameters in (IEEE, 2009)

5.4.4.7 Step 4E - Application of Steps 4B and 4C on each of the potential failure mode causes.

Steps 4E and 5 are carried out using the HFMEA worksheet in Figure 5-8 .

5.4.5 Step 5: Actions and Outcomes Measures

The following sub-steps represent the final stage of the HFMEA activity. However, they were not conducted for all the identified failure modes of critical equipment with Hazard scores below 8. A complete worksheet for the failure mode analysis of the Blood Chemistry Analyser is shown in Figure 5-8.

- A. Determine whether you want to eliminate, control, or accept the failure mode cause. Record this decision on the HFMEA Worksheet.
- B. Identify a description of action for each failure mode that will be eliminated or controlled.
- C. Identify outcome measures that will be used to analyse and test the redesigned process.
- D. Identify a single responsible individual by title to complete the recommended action.
- E. Indicate whether top management has concurred with the recommended action. HFMEA Step 5 is shown in Figure 5-8 below for Process Step 3C4 in the blood chemistry analysis process.
- F. Test to ensure that the system functions effectively and new vulnerabilities have not been introduced elsewhere in the system.

HFMEA Subprocess Step Title and Number															
HFMEA Step 4 - Hazard Analysis										HFMEA Step 5 - Identify Actions and Outcomes					
Failure Mode: First Evaluate failure mode before determining potential causes		Potential Causes		Scoring			Decision Tree Analysis				Action Type (Control, Accept, Eliminate)	Actions or Rationale for Stopping	Outcome Measure	Person Responsible	Management Concurrence
				Severity	Probability	Haz Score	Single Point Weakness?	Existing Control Measure ?	Detectability	Proceed?					
3C4	Low speed (blood chemistry analyser)	→		Catastrophic	Occasional	12	→	N	N	Y					
		3C4a	Insufficient power due to other users	Moderate	Uncommon	4	→	Y	→	N	N/A	Switch off less critical equipment			
		3C4b	Low voltage from grid	Major	Uncommon	6	→	N	N	Y	Control	Purchase voltage step-up device	New equipment on site	Facility Manager	Y
		3C4c	Grid voltage fluctuations	Moderate	Occasional	6	N	→	Y	N	N/A	Grid fluctuation is detectable.			
		3C4d	Backup generator develops fault	Catastrophic	Occasional	12	→	N	N	Y	Eliminate	Hire backup gen, send for mechanic, budget for new gen, acquire DC powered alternative	Make emergency hire funds available at all times	Facility Manager	Y

Figure 5-8: HFMEA Worksheet – Step 4

Table 5-8: HFMEA-determined critical devices

Devices from HFMEA	Qty	Power rating (W)		Early hours (0000-0759)	Daytime hours (0800-1759)	Night hours (1800-1159)	Total hours / day	Energy demand (kWh/day) *	
		Min	Max					Min	Max
Portable X-ray	1	3000	4000	0.5	0.5		1	3	4
Ultrasound scanner	1	800	1000		1		1	0.8	1
Microscope	3	20	30	1	3		4	0.24	0.36
Blood chemistry analyser	1	45	88		4		4	0.18	0.352
Laboratory refrigerator	1	60	160	3	5	2	10	0.6	1.6
Total		3925	5278	4.5	13.5	2	20	4.82	7.312

*Energy demand (kWh/day) = Power rating (kW) x Total hours/day (h/day)

above shows the resulting critical devices from further evaluation of both contact and no-contact critical equipment using the HFMEA method. They all have failure modes with hazard scores of 8 or more and are determined to enjoy

precedence over the other critical devices. Further analysis and consensus among the HFMEA team may be required to further evaluate level of prioritisation to be given to these devices on a case-by-case basis.

All the devices selected are no-contact critical loads without DC power alternatives except for the laboratory refrigerator, a critical contact load. The laboratory refrigerator is included because DC power alternatives are expensive and are not readily available in developing countries. They need to be operated at a very tight temperature range and require highly reliable supply of constant electricity to ensure their contents are not compromised to prevent almost certain loss of lives. Hence, the laboratory refrigerator has been included along with some no-contact critical loads in the evaluation of power supply systems for the most critical devices.

5.5 Four Energy Levels or Energy Demand Profiles

The conclusions of the energy assessment and criticality assessment of essential devices have resulted in four energy demand profiles representing four levels of essential power requirements in the health facility. These energy demand profiles are necessary to evaluate the power supply system options and their associated costs. The profiles are also used to evaluate the level of resilience required for the health facility to withstand grid power loss without stopping emergency operations. The loads under each energy demand profile are explained below.

5.5.1 Conventional Essential Loads - 1st Energy Demand Profile (21.53 kWh/day)

This profile represents the highest power level and maximum energy demand from the energy assessment of essential devices in section 5.3. It contains the essential equipment and devices with conventional power ratings and are not specially designed to be energy-efficient. Normally, conventional devices will be less expensive than their energy-efficient alternatives. This does not mean they are else effective in performing the tasks they are designed to execute. But they are generally more expensive to operate due to their higher power consumption during normal operations.

The 21.53 kWh/day energy demand from essential devices falls within the range of 1.6 and 31.99 kWh/day total energy demand proposed for tier 3 (secondary) facility in WHO, (2015a). It is expected that this profile will generally present the most expensive capital and operational costs out of the four demand profiles.

5.5.2 Energy-efficient Essential Loads - 2nd Energy Demand Profile (14.30 kWh/day)

The second highest energy demand profile level requires 14.30 kWh/day for the operation of all energy-efficient essential medical devices and equipment. This represents approximately 66% of total energy demand from conventional loads. This also falls within the range used by WHO to categorise a facility as tier 3 or secondary hospital using level of electricity access. Decision makers will need to evaluate the cost of replacing existing conventional devices with energy efficient alternatives versus the cost savings from 34% lower energy demand. This decision may be easier to make for new healthcare facilities.

5.5.3 Conventional Critical Essential Loads - 3rd Energy Demand Profile (7.31 kWh/day)

This profile represents the reduced energy demand resulting from the prioritisation of the conventional essential medical devices using HFMEA. This profile represents approximately 34% of the total conventional loads and 51% if energy efficient devices are considered. Ensuring that a facility can maintain this level of electrical energy capacity on a daily basis implies that the most critical services can be provided reliably from an energy supply perspective.

5.5.4 Energy-efficient Critical Essential Loads - 4th Energy Demand Profile (4.82 kWh/day)

The fourth energy demand profile is the lowest. It covers the energy demand from prioritised energy efficient devices in the facility. It covers 22% and 33% of total conventional and total energy efficient loads respectively. Managers of new facilities or existing facilities using energy efficient devices may choose to install distributed energy systems to cater to this level of energy demand and then scale up to the full energy demand over time or as more resources become available.

5.6 Resilience of Health Energy Systems

To determine the resilience of systems that will cater to the different levels of criticality assessed, the Event Resilience equation described in Chapter 3 was employed on the initial energy demand loads and the HFMEA-determined loads. Total facility load of 21.53 kWh/day, or 14.29 kWh/day for energy-efficient devices,

is regarded as loads served before the event. Results of the HFMEA assessment in Chapter 4 indicate further reduction of these total essential loads to critical loads of 7.31 kWh/day and 4.82 kWh/day respectively. Microgrid systems required to power these critical loads would be less expensive to set up and run than those required to supply the total load demand.

$$\text{Event Resilience Index (ERI)} = \frac{\text{Loads served during event}}{\text{Loads served before the event}} \quad (5-1)$$

Using equation (5-1), the ERI for the systems for both the conventional and energy-efficient critical loads are calculated as follows:

$$\text{System ERI (Conventional Loads)} = \frac{7.31}{21.53}$$

$$\text{System ERI (Energy efficient Loads)} = \frac{4.82}{14.29}$$

Both resulted in an ERI of 0.34. Provided that critical applications represent 34% or less of the total essential energy demand, this implies that, an energy system with a 0.34 ERI is 34% resilient can absorb the shock of an unexpected power failure in this health facility with critical applications remaining functional. This ERI figure can assist decision makers in channelling limited resources to set up a distributed microgrid that can supply 34% of a facility's power needs. As discussed in section 2.10, cost is one of the main barriers to the uptake of renewable energy technologies. Installing a system that covers 34% energy demand will certainly cost less than one that covers 100%.

However, any system installed, stepped-down or full capacity, should be scalable to allow for future expansion of services. Every facility should carry out their energy demand assessments at regular intervals to monitor patterns of energy use in relation to patient numbers at different times of the year and update the ERI required during these periods. It is possible to use a set of energy demand profiles different from the emergency service demand profiles used in this research. For example, a health facility may opt to prioritise maternity services or surgical operations over other services. The ERI evaluation will then need to consider the ratio of the energy

demand of the priority service (maternity or surgical operations) to that of the entire facility.

It is unlikely that the event resilience index can be used as a universal, or even national, indicator of priority energy demand for similar levels of health facilities. Nevertheless, it will be useful to carry out uniform structured studies of priority services in similar and different levels of healthcare facilities in a country to create national health energy supply benchmarks. Having a clear understanding of the range of priority energy demand in health facilities will aid the development of financial, technical and environmental policies related to healthcare.

Using the ERI can help planners and decision makers to evaluate the cost of the loss of a life versus the cost of the provision of a critical level of reliable power supply in a health facility. For example, Alkire et al. (2018) attributed a loss of \$6 trillion in economic welfare to eight million preventable deaths in 130 low- and middle-income countries in 2015. This places an economic welfare value of \$750,000 on each life in these countries. It then implies that, any life-saving intervention costing up to \$0.75 million should be acceptable in any health facility. The ERI will be useful in environments where investments of up to this amount is unrealistic by enabling investments in the most critical life-saving measure.

Although allocating a cost of life in medicine is usually controversial, attaching a monetary cost to an otherwise immeasurable loss of human life is important. These numbers can provide economic incentives that encourage changes in policy and life-saving investments in health care (Alkire et al., 2018; Harvard Medical School, 2018). It is unlikely that the cost of providing alternative power sources for a primary health facility will be near the economic welfare value of a human life. Nevertheless, it is important for decision makers to be able to evaluate the cost of providing quality health care against the cost of loss of life.

5.7 Summary and Contribution to Knowledge

To achieve research Objective 1, a life-threatening incident case of a near-term pregnant woman involved in a car accident was selected using the triaging and GCS methods of prioritising patients for treatments. This case was determined to require an electrical energy-intense treatment. The functional space required adds up to

131 m² for secondary hospital in Nigeria. This is far less than the 464 m² functional space requirement for the comparable A&E departments in the UK discussed in Chapter 3 (Section 3.4.2). The energy demand for all the electrical load required in the treatment within the functional spaces add up to 21.53 kWh/day and 14.29 kWh/day for conventional and energy-efficient devices respectively.

For the purpose of Objective 2, the diagnostics sub-process of the patient's treatment as the most critical and energy-intensive. Further risk assessment indicate that the blood chemistry analyser carries the highest risk of failure among the equipment in the diagnostics sub-process. Therefore, in the event where power available is insufficient for all the diagnostics equipment, the blood chemistry analyser will retain priority over all other medical devices until the process is completed. Objective 3 is achieved in the next chapter.

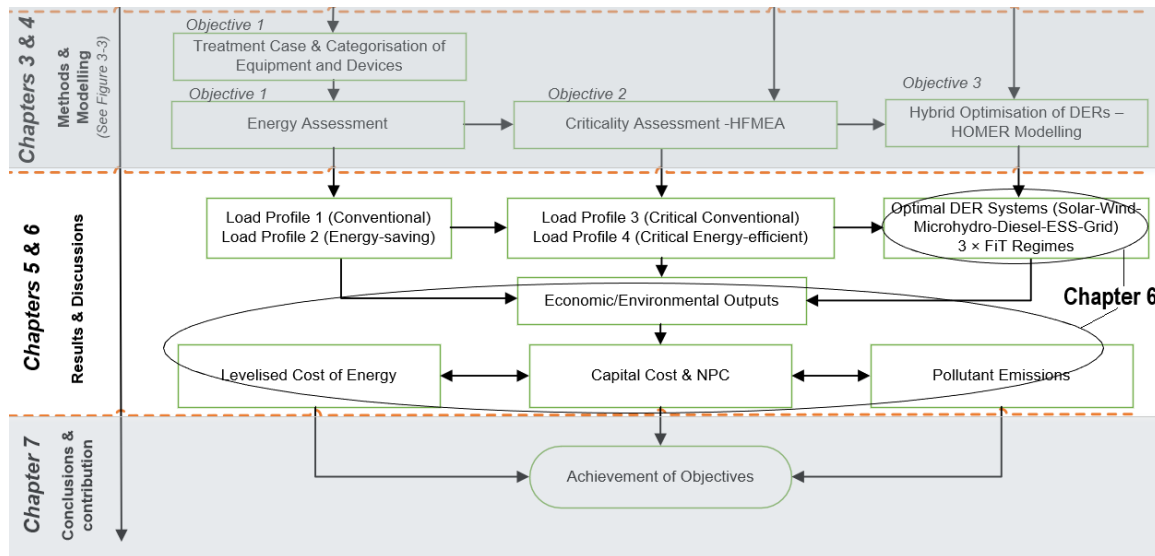
The following contributions to knowledge have been identified:

- The functional space area of a secondary Nigerian hospital with emergency health service capabilities is at least 131 m².
- The energy demand requirements for a systematically reduced load profile are 7.31 kWh/day and 4.82 kWh/day for conventional and energy-efficient devices respectively;
- The above generated an Event Resilience Index of 0.34 based on the initial energy demand profile for the secondary facility of 21.53 kWh/day and 14.29 kWh/day respectively. That is, a DER system or supply-side intervention must be designed to carry at least 34% of a facility's essential loads. This can be employed by facilities with little or no resources to conduct detailed risk assessment of their treatment processes;
- This research did not originally set out to investigate the event resilience index. But it became a very useful outcome during a search for methodologies used to measure systems resilience. Many resilience methodologies are supply-side focused. However, the demand-side approach to measuring resilience provides an upfront means of determining design requirements for energy systems to make health facilities more resilient to power failures. The ERI can become a useful tool for the

development of nation-wide health energy benchmarks for different level of healthcare provisions.

- Standard HFMEA severity rating and probability rating definitions have been modified to reflect the risks associated with events attributable to unreliable power in a Nigerian secondary health facility (see Table 5-4 and Table 5-5).

6 MODELLING OF OPTIMAL DER SYSTEMS



6.1 Introduction

This chapter presents and discusses the results of energy system models produced for the six case study cities from Nigeria. The results are discussed from both economic and technical (systems and emissions) perspectives. Each city's results are presented under two sections for both perspectives. The first section starts with the overall economic results presented in a tabular format. This is followed by the discussions comparing cost-related variables between the three feed-in-tariffs (FiT) and four load profiles modelled. The second section does the same for technical variables including component composition, renewable fraction of energy production, energy produced, energy sold, generator activity and pollutant emissions of each system.

At the end of the economic section, an overall comparison of capital costs and costs of energy for every system generated under each FiT regime is charted and discussed. A similar comparison between carbon dioxide (CO₂) and particulate matter (PM) emissions is discussed at the end of the technical section. The results and discussions of competing economic and technical factors provide decision makers with insights into the best system configurations for each city.

The last sections of this chapter contain rankings of economic (cost of energy and capital cost) and technical (actual CO₂ emissions and energy produced) results between all the cities studied under all the FiT schemes considered. However, only

economic and technical results of the 1st load profile (21.53 kWh/day) are considered in these final sections. This load profile represents the maximum electrical load demand of the facility, containing conventional and unprioritised loads. The ranking of economic and technical variables between the cities provide an understanding of the cities and regions of Nigeria that present the best cost of energy, capital cost, CO₂ emissions and PM emissions.

6.2 Ibadan (SW Nigeria) Results and Discussions

Other location specific variables used in the modelling of DEGs in Ibadan are presented in Section 4.2, Variables Modelled in HOMER.

12,032 solutions were simulated by HOMER for each feed-in-tariff sensitivity considered under Ibadan. Out of these, 8,604 were feasible and 3,428 were infeasible due to capacity shortage constraints under the \$0.17/kWh FiT regime. Under the \$0.07/kWh FiT regime, 9,176 solutions were feasible while 2,856 were not. 9,904 solutions were feasible and 2,128 were infeasible under the \$0.00/kWh FiT regime.

6.2.1 Costs of Optimal System Configurations for Ibadan

Table 6-1 below shows the costs associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Ibadan.

Table 6-1: Cost factors for system configurations in Ibadan

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	-0.0183	-25,141	117,740	1,153	31,059
	2nd	14.29	PV, Battery x 5, Grid, HydroK	-0.0270	-36,290	117,740	704	32,621
	3rd	7.31	PV, Gen10, Battery x 5, Grid, HydroK	-0.0371	-48,942	125,240	336	34,292
	4th	4.82	PV, Gen10, Battery x 5, Grid, HydroK	-0.0412	-53,763	125,240	221	34,872
\$0.07 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	0.0499	31,919	26,000	2,887	10,063
	2nd	14.29	Gen10, Battery x 5, Grid, HydroK	0.0341	19,874	26,000	1,919	11,136
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	0.0164	8,758	26,000	1,133	12,276
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	0.0113	5,814	26,000	767	12,681
\$0.00 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	0.1040	53,814	24,250	2,884	6,642
	2nd	14.29	Gen10, Battery x 5, Grid, HydroK	0.0965	44,487	24,250	1,916	7,715
	3rd	7.31	Gen10, Battery x 5, Grid	0.2760	26,285	10,250	2,748	0
	4th	4.82	Gen10, Battery x 5, Grid	0.3380	21,178	10,250	1,911	0

6.2.1.1 Costs under Ibadan's \$0.17/kWh FiT

The NPC figures for all the optimal systems identified under the \$0.17/kWh FiT regime are negative as shown in Table 6-1. This indicates that the present value of all the revenues earned from excess energy sales is higher than the present value of all the costs of installing and operating all the optimal systems identified. The optimal system for the 1st energy profile therefore has a Net Present Value of over \$25,000 over its 25-year lifetime while the 4th system has 153% more NPV of almost \$54,000. This means there is additional income from the operation of the systems alone without considering the other financial savings and healthcare benefits their operation will bring to the facility.

Figure 6-1 shows that the capital cost of systems for the two highest demand loads (1st and 2nd) are lower than the lowest demand profiles (3rd and 4th). However, the 3rd and 4th load profiles present far lower levelized cost of energy at -\$0.0371 and -\$0.0412 respectively compared to the two largest demand profiles with CoE of -0.0183 and -\$0.0270. These imply earnings, rather than expenses, of \$0.0183, \$0.0270, \$0.0371 and \$0.0412 per unit of energy (1 kWh) produced after cost of operation has been deducted from FiT income by the 1st, 2nd, 3rd and 4th system configurations respectively. The result is an average CoE of -\$0.0309 or income from energy used of \$0.0309 per kWh. These earnings are attractive, representing 103.75%, 103.86%, 102.85% and 102.12% less when compared with actual expenditure or CoE of \$0.488, \$0.70, \$1.30 and \$1.94 (see Table 4-26) respectively for the load profiles in the conventional scenario.

Furthermore, the system capital cost for the two lowest energy profiles (3rd and 4th) are 0.06% higher than for the two highest energy profiles (1st and 2nd) mainly because of the inclusion of a generator in each of the low energy systems. The generators are provided as backup to ensure that electricity is available in situations where the batteries have not been fully charged because the renewable energy components have prioritised sale of energy to the grid. The income from the official FiT is higher than the cost of generating electricity on site. It should also be noted that operating the generator in a low energy demand scenario produces lower emissions than in higher energy demand scenarios. Therefore, HOMER actively tries to avoid the inclusion of an electric generator in the higher energy

profiles. The consequence of this solution is that the batteries in the higher energy systems undergo more frequent charging cycles leading to the need for regular replacements and an overall higher Net Present Cost.

To determine the configuration that presents the best cost of energy to capital cost ratio, the two variables are plotted against each other for all the alternative systems as shown in Figure 6-1. The lower the cost of energy, the better the investment in terms of cost to the facility. Due to the inverse relationship between the cost of energy and capital cost, the intersection of the cost of energy and capital cost lines presents the best alternative. This is closest to the 14.29 kWh/day load, that is the 2nd load profile.

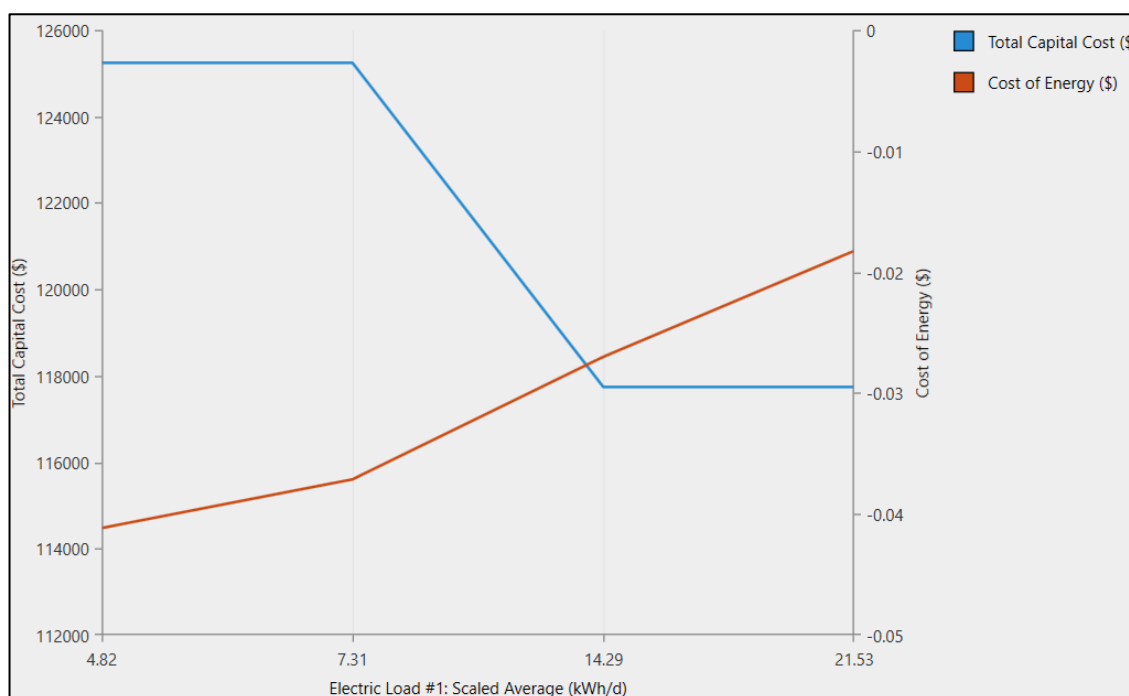


Figure 6-1: Capital cost vs. Cost of energy under \$0.17 FiT regime

Since the cost of energy under this FiT system results in revenues for all the optimal systems determined, the system configuration for the 2nd or 14.29 kWh/day load profile presents the most balanced return to capital cost ratio. That is, a moderately high income from unit energy generated is achieved with the least possible capital cost. For the 4.82 kWh/day load, the optimal system is achieved with a higher capital cost although it presents a lower CoE. Nevertheless, the 2nd load profile has the added advantage of allowing more devices to operate.

Therefore, a system that can power all power-saving medical devices is the best choice in Nigeria if and where FiT is fully operational.

It is important to note that there are many factors a facility will consider in selecting an alternative especially with regards to the factors that the decision makers are willing to trade off to guarantee reliable and sufficient supply of electricity. This study is not aiming to determine a singular best alternative but aims to identify the most viable options out of many alternatives. Hence, the four system configurations presented in this analysis, and subsequent ones, are the most viable options for the prescribed load profiles in the stated city and under the associated FiT regimes.

6.2.1.2 Costs under Ibadan's \$0.07/kWh FiT regime

Compared with the resultant income from the \$0.17/kWh FiT regime, Table 6-2 shows that the CoE and NPC under the \$0.07/kWh FiT regime remain positive expenses even after the excess electrical energy produced is sold at the same rate as the grid tariff. The positive NPV of all the systems under the \$0.17/kWh regime is a clear indication that the official FiT system in Nigeria is designed to make the generation and sale to the grid of renewable power supply profitable for adopters. All the optimal configurations under the \$0.07/kWh regime have the same components, the same initial capital cost of £26,000 and their NPCs are all positive. This shows that the present value of the revenue from each system is lower than the present value of the costs of installing and running the system over its lifetime.

Table 6-2: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	0.0499	31,919	26,000	2,887	10,063
	14.29	0.0341	19,874	26,000	1,919	11,136
	7.31	0.0164	8,758	26,000	1,133	12,276
	4.82	0.0113	5,814	26,000	767	12,681

The CoEs range from \$0.0113 to \$0.0499 per unit of energy used or an average CoE across the four systems of \$0.0279/kWh. These represent 373%, 226%,

144% and 127% increase in CoE over 1st, 2nd, 3rd and 4th energy profiles respectively from the \$0.17/kWh FiT regime. The capital costs of all the optimal systems are the same making the 1st and 2nd profiles under this FiT regime 78% less than under the previous regime. Similarly, the 3rd and 4th profiles are 79% less than their counterparts in the \$0.17/kWh FiT regime.

Unlike the inverse relationship between capital cost and CoE in the \$0.17/kWh FiT regime, there is a constant capital cost and an increasing CoE as energy demand increases. Since all the load profiles produced optimal systems with the same capital costs, it is up to the operators of the facility to select a system based on the need to power more devices and sell less amount of excess energy or have fewer critical devices to power and sell more energy which in turn reduces the CoE.

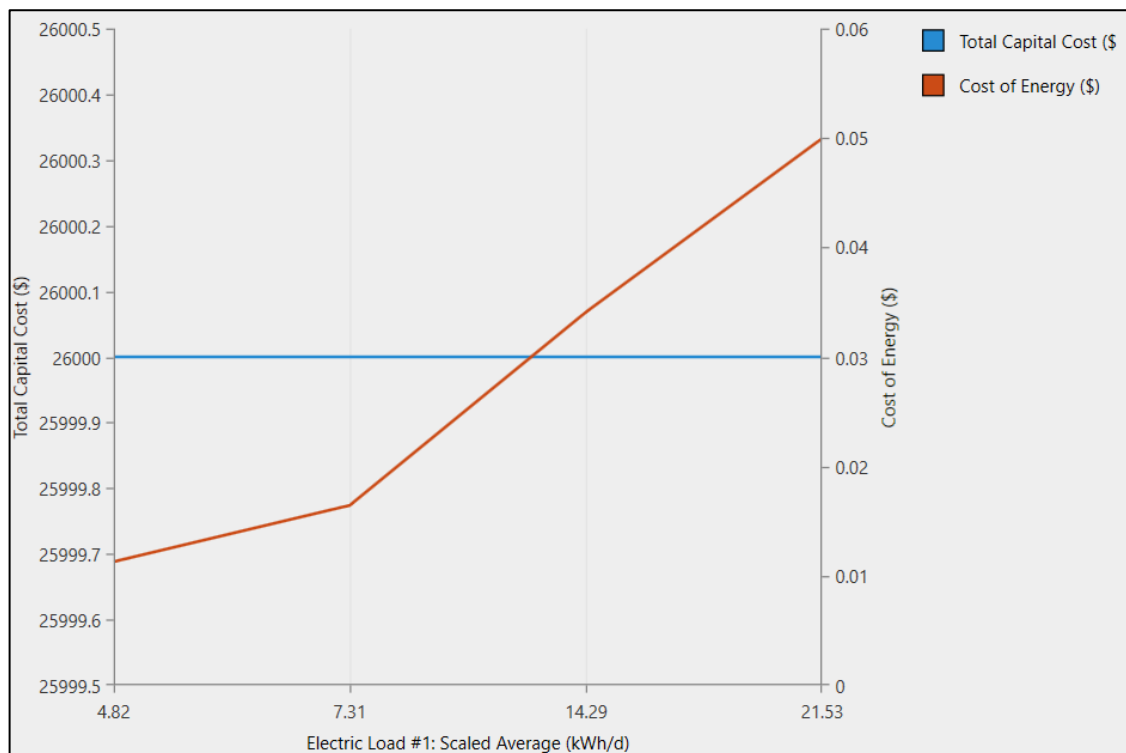


Figure 6-2: Capital cost vs. Cost of energy under \$0.07 FiT regime

Figure 6-2 shows that the lowest demand profile presents the lowest NPC overall, while the highest demand profile presents the highest NPC. Therefore, the 4th load of 4.82 kWh/day gives the best cost of energy to capital cost expended. Whereas, while the system for the 1st load profile (21.53 kWh/day) presents a higher CoE to

capital cost ratio, the benefit of that system's ability to power all the devices in the facility cannot be easily quantified in financial terms.

Compared to figures from the \$0.17/kWh FiT regime, the capital required for the optimal systems under the \$0.07/kWh FiT are significantly lower, with an average of 78% lower capital costs between comparable demand profiles. The higher FiT in the previous analysis resulted in negative cost of energy and produced real income generation for the facility from the sale of excess energy produced. For this to happen, HOMER produced a component-laden optimal solution that can generate enough sellable electrical power to cover all costs and yield income for the facility. However, since the cost of buying and selling electricity is the same under the \$0.07/kWh FiT scheme, the incentive to generate excess electricity is reduced. Therefore, the number and variety of components are reduced under this regime resulting in lower capital costs.

Table 6-3: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Ibadan (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0499	0.488	31,919	136,632	166	3,621	26,000	7,500
14.3	0.0341	0.7	19,874	130,171	-172	3,440	26,000	7,500
7.31	0.0164	1.3	8,758	123,944	-484	3,265	26,000	7,500
4.82	0.0113	1.94	5,814	121,722	-566	3,203	26,000	7,500

As stated in Section 4.4.1, cost figures for the \$0.07/kWh and \$0.00/kWh FiT options will be compared with figures for current operational costs in every city considered. Table 6-3 shows the comparison between cost figures from optimal systems for the \$0.07/kWh FiT regime in Ibadan and the prevailing cost of operating the facility using grid power and the 10 kW diesel generator. The CoE for the optimal DER systems where excess energy is sold back at grid rates are much lower than those for the current operational realities in Nigerian healthcare facilities.

The CoE of the 1st, 2nd, 3rd and 4th optimal systems are 90%, 95%, 98% and 99% less than their respective conventional systems. This indicates that, even in

instance where it is impossible to feed excess electricity back to the grid, selling excess energy to other users at the same rate as the grid will result in considerable reduction of energy costs compared with the current conventional system of ensuring reliable power supply. On the other hand, the capital costs of the optimal systems are each a 247% increase over their respective conventional systems. The higher capital cost is caused by the addition of bank of batteries and the hydrokinetic turbine. Nevertheless, the NPC of the 1st, 2nd, 3rd and 4th optimal systems are decreases of 77%, 85%, 93%, and 95% over those of their respective conventional systems over 25 years. This is indicative of the lower cost of running the optimal systems especially with regards to fuelling the diesel generator.

6.2.1.3 Costs under Ibadan's \$0.00/kWh FiT regime

The optimal system configurations under the zero FiT regime reveal the actual cost of providing distributed power supply under different loading conditions without recourse to selling excess energy back to the grid or other users. The systems under this FiT regime presented an average CoE of \$0.2036 per kWh of energy used. When compared with the CoE for configurations under the \$0.17/kWh and \$0.07/kWh FiT regimes, the CoE under the zero feed-in-tariff is much higher. This can be expected because there is no income generated from the sale of excess electricity generated.

Table 6-4: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	0.1040	53,814	24,250	2,884	6,642
	14.29	0.0965	44,487	24,250	1,916	7,715
	7.31	0.2760	26,285	10,250	2,748	0
	4.82	0.3380	21,178	10,250	1,911	0

On the other hand, the initial capital cost of the system when there is no expectation of excess energy sale is less than in the other systems (see Table 6-4). The energy sold column shows some figures despite zero sales because excess energy is generated and wasted by the 1st and 2nd systems. Unlike the 3rd and 4th systems, the 1st and 2nd systems under zero FiT contain renewable energy components – hydrokinetic turbine – resulting in generation of excess energy.

The 1st and 2nd load profiles generated systems with the same initial capital cost of \$24,250 while the 3rd and 4th presented the same cost of \$10,250, a 57.73% decrease. Similar to the results of the other FiT regimes, the NPC reduces as the energy demand profile reduces. This means that the costs of installing and operating the optimal systems for the heavier electrical loads are higher than those of the lighter loads.

However, the difference in NPC between the heavier loads and the lighter loads are not matched by the difference in load size. For example, the 1st load (21.53kWh/day) is 4.5 times the 4th load (4.82kWh/day) whereas, the NPC of the 1st load profile (\$53,814) is only 2.5 times that of the 4th load (\$21,178). Furthermore, in a departure from the trends in the two previous FiT regimes, the cost of energy for the heavier loads are lower than those of the lighter loads. These are caused by the removal of the Feed-in-tariff incentive to generate revenue from the sale of excess energy. Therefore, HOMER presented optimal systems that minimise the generation of excess energy leading to low capital and operating costs.

The optimal systems for the 1st and 2nd loads each contain a hydrokinetic turbine, a renewable energy supply component (see Table 6-1), while the 3rd and 4th profiles do not. This means that, although they will incur more expensive capital costs, the 1st and 2nd optimal systems have components that help them generate a large portion of total energy inexpensively. Whereas, the 3rd and 4th load profiles depend on the grid and generator to generate electricity while using battery banks to store excess energy from generator operation.

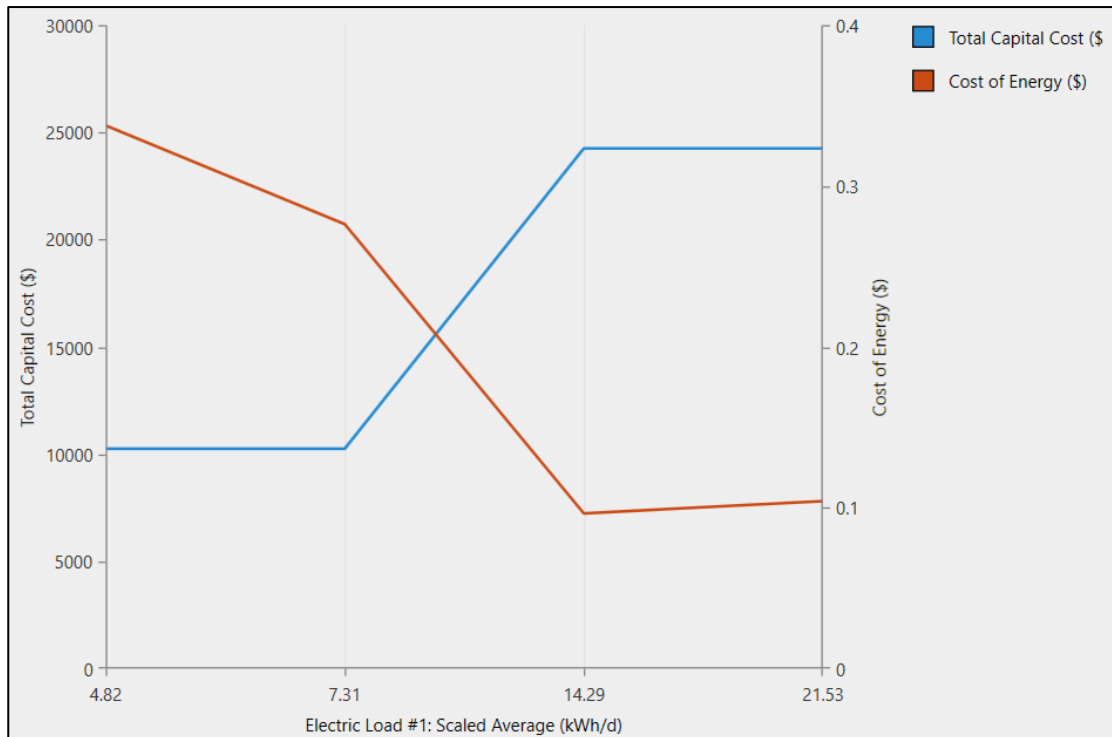


Figure 6-3: Capital cost vs. Cost of energy under \$0.00 FiT regime

As shown in Figure 6-3 above, the optimal system for the 2nd load profile (14.29kWh/day) under the zero FiT regime presents the lowest cost of energy while the 4th profile (4.82kWh/day) has the highest cost of energy. As would be expected, the optimal configuration for the 1st load profile has a cost of energy that is slightly higher than that of 2nd profile due to its higher energy demand. Whereas, the cost of energy for the 3rd load profile is less than that of the 4th profile despite having a larger electricity demand figure. This is due to the cost of operating the 10kW generator in both systems. The generator serves a bigger load in the 3rd profile than the 4th profile thereby giving a better return on costs for the larger 3rd energy demand profile.

The 3rd and 4th systems present unaffordable CoEs when benchmarked against the \$0.14/kWh affordable CoE. It is up to decision makers to purchase a lower capacity generator towards the reduction of the CoE in instances where loads are prioritised, and energy-saving devices are used. The trade-off is between having a system that can power all the devices in the facility whenever the need arises or curtailing cost by prioritising loads all the time. Under the zero FiT regime, the optimal system for the 7.31 kWh/day load profile presents the best CoE to capital cost ratio.

Table 6-5: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Ibadan (FiT \$0.00/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.1040	0.488	53,814	136,632	829	3,621	24,250	7,500
14.3	0.0965	0.7	44,487	130,171	568	3,440	24,250	7,500
7.31	0.2760	1.3	26,285	123,944	450	3,265	10,250	7,500
4.82	0.3380	1.94	21,178	121,722	306	3,203	10,250	7,500

Table 6-5 shows the comparisons between costs associated with the zero FiT optimised systems and with the commonly operated grid and generator power supply system in Nigerian healthcare facilities. The main differences between the two alternative systems are the inclusion of the hydrokinetic turbines and battery banks in the 1st and 2nd electric load systems, and the addition of battery banks only in the 3rd and 4th systems. Both alternatives contain grid and ICE generator sources of electricity.

It is interesting to note the significance of adding only power storage components to the presently common grid plus generator power system in many Nigerian healthcare facilities. In the optimal system for the 3rd load profile (7.31kWh/day), the addition of a bank of five 1kWh Li-Ion batteries, a converter and other ancillary components increased capital costs by only \$2,750, a 36.67% rise. However, the NPC over the course of 25 years of the system dropped by about 79% from current \$123,944 to \$26,285. This is caused mainly by the higher cost of operating the current system containing grid and ICE generator only. Furthermore, the cost of unit energy is almost five times less in the optimal distributed power system than in the conventional system with batteries.

Nevertheless, the CoE in the 3rd system is 2.86 and 2.65 times those of the 1st and 2nd systems that contain renewable energy components. If applied to the total conventional energy demand of the facility (21.53 kWh/d), the CoE of the 3rd system will amount to \$54,223 in 25 years compared to only 37.68% of this figure at \$20,432 using the CoE from the 1st system. This implies 62% less cost of energy

over the 25 year lifetime of the microgrid project, saving \$33,791, compared with a saving of \$14,000 (56%) on capital cost.

Therefore, the results suggest that it is beneficial to add only batteries to the current conventional energy supply infrastructure of facilities with low energy demand such as 8 kWh/day or less. When the daily electrical demand is 14 kWh/day or more, it becomes more economical to include renewable energy components in the mix of power sources.

6.2.1.4 Capital Cost and Cost of Energy Comparison between all Ibadan Systems

Figure 6-4 shows the comparison of all the capital costs and costs of energy across every system modelled under the city of Ibadan including cost for conventional systems containing only grid and genset components. The chart reveals that systems under the \$0.17/kWh FiT regime have significantly higher capital costs of up to 79% compared with the other regimes. This is due to the high number of renewable energy supply components in the \$0.17/kWh FiT regime. Whereas, the costs of energy across the \$0.17/kWh FiT regime are not as significantly lower than in the systems under the \$0.07/kWh FiT regime.

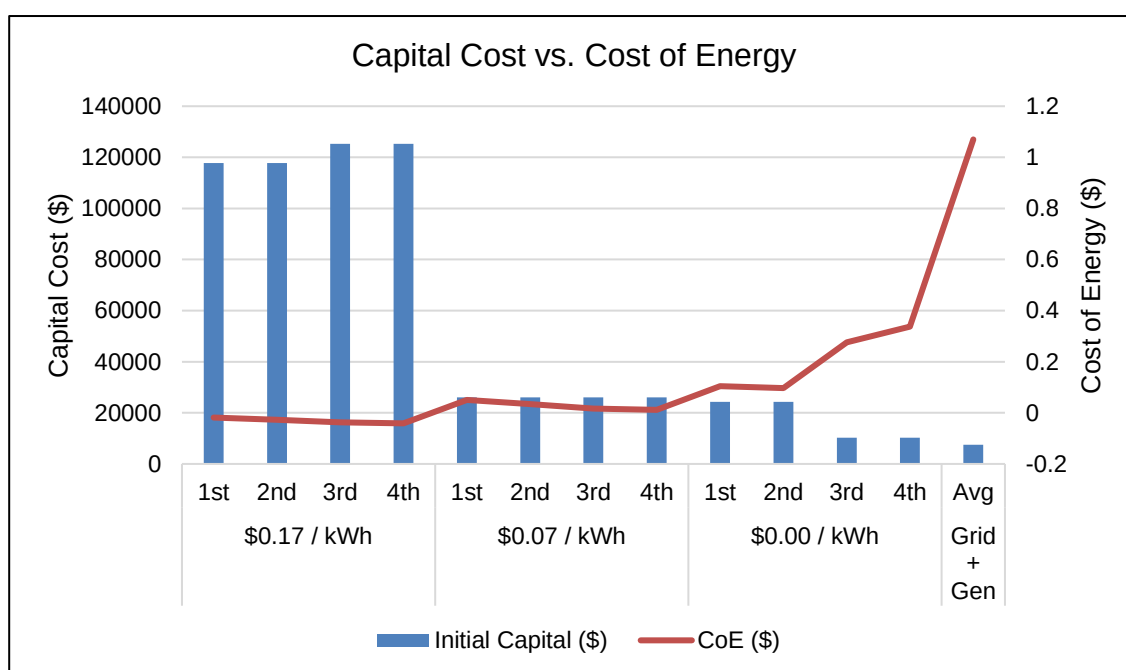


Figure 6-4: Capital cost vs CoE for system configurations in Ibadan

The costs of energy across the zero FiT regime are much higher than the CoE for the other FiT regimes due to the lack of renewable energy components especially

in the 3rd and 4th systems. These two systems have CoEs that are 1,583% and 2,891% higher than those of the \$0.07/kWh FiT regime. However, the capital costs under the zero FiT regime are not much lower than those under the \$0.07/kWh FiT regime – capital cost of 1st and 2nd systems are 6.7% less in the zero FiT regime. The 1st and 2nd Therefore, the systems under the \$0.07/kWh FiT regime present the best capital cost to cost of energy ratio. The \$0.07/kWh FiT regime also represents the most likely situation an electric power generating plant will face, that is selling back excess energy at the same rate as the grid.

Overall, the 4th load profile system under this regime gives the best capital cost to cost of energy ratio. However, the system will power only the most critical devices. The facility can choose to operate the 1st load profile since the same components are required but with higher operating costs than the other systems under the same regime.

When compared with the conventional power system containing only grid and genset components, all the optimised systems presented higher capital costs. The lowest optimal system capital cost is \$10,250 for the 3rd and 4th load profile systems under the zero FiT regime. Whereas, the grid and generator system have almost 27% less capital cost of \$7,500 which represents the cost of the genset. However, the cost of energy for the grid and genset system for each load profile is much higher than the corresponding optimal system.

The average CoE for all the load profiles powered by the conventional systems is plotted in Figure 6-4. Although the conventional systems presented lower initial capital cost, they have higher operating costs due to the longer periods of generator operation making the CoE much more expensive than the DER systems. The lowest CoE of all the conventional systems, that is \$0.488 per kWh for the 1st load profile, is approximately 31% higher than the highest CoE for the optimal DER systems, that is \$0.338 per kWh for the 4th load profile under the \$0.00/kWh FiT regime.

6.2.2 System and Emission Factors of Optimal System Configurations for Ibadan

Table 6-6 below shows the technical and emissions results of optimised system configurations for the four load profiles under different FiT regimes in the city of

Ibadan. The *Component* column shows the power producing components in each system while the *Ren Fraction (%)* column lists the percentage renewable energy in the total electrical energy produced by the system. *Energy Produced* column indicates the total annual electrical energy output of all the components in the system including electricity purchased from the grid and losses in the storage and converter. Whereas, the *Energy Sold* column shows the total quantity of excess electrical energy available for sale. The *Energy used by Loads* column depicts the component of useful energy that is used up by the loads in the facility. The addition of energy sold, and energy used by loads represent useful energy in the system. The remaining energy from energy produced, after energy sold and energy used by loads are removed, is lost in the system.

The CO_2 column indicates the amount of carbon dioxide emitted by each system. This will be discussed along with the other pollutant emissions under each FiT regime, and later for the other cities. It is included under technical analysis to show how systems containing larger percentages of renewable resources offset the amount of CO_2 emissions from the grid and ICE diesel generator. Negative quantities of CO_2 emissions do not mean a system is removing carbon dioxide from the atmosphere. They indicate the difference between CO_2 emissions saved using renewable energy sources and CO_2 emissions from other energy sources such as the grid and generator.

In short, the CO_2 column indicates the net energy purchased (energy purchased from grid minus energy sold). Instances where the CO_2 emission figure is negative indicate that more energy is generated from renewable sources than non-renewable sources including the energy purchased from the grid.

Under the comparisons between optimal systems and conventional systems, the actual CO_2 emissions from the DER systems are used instead of net emissions. Net CO_2 emission figures include carbon dioxide emissions saved due to use of renewable sources. Using net CO_2 emission figures in the comparisons between optimal and conventional systems will significantly skew emission figures in favour of the optimal systems. Hence, actual CO_2 emissions from the optimal DER systems are used.

6.2.2.1 Systems under Ibadan's \$0.17/kWh FiT regime

As shown in Table 6-6, every system under this category includes PV cells, a bank of five 1kW batteries and the 20kW hydrokinetic turbine. The 3rd and 4th systems include an additional generator. A clear majority, from 97% to 99%, of the electrical energy generated by the systems under this FiT regime come from renewable sources. Although this will result in high capital costs, the high feed-in-tariff makes the generation and sale of excess energy attractive from the extra renewable energy components. The energy produced is more than 51,000 kWh/year on the average for all the load profiles considered.

Table 6-6: Technical factors for system configurations in Ibadan

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	97	52,384	31,059	7,556	-18,901
	2nd	14.30	PV, Battery x 5, Grid, HydroK	98	51,935	32,621	5,056	-20,171
	3rd	7.31	PV, Gen10, Battery x 5, Grid, HydroK	99	51,764	34,292	2,668	-21,460
	4th	4.82	PV, Gen10, Battery x 5, Grid, HydroK	99	51,611	34,872	1,759	-21,900
\$0.07 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	80	26,514	10,063	7,859	-4,535
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	86	25,211	11,136	5,216	-5,825
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	92	24,079	12,276	2,668	-7,042
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	95	23,665	12,681	1,760	-7,530
\$0.00 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	75	26,511	6,642	7,858	-2,375
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	82	25,208	7,715	5,216	-3,665
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
	4th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

When compared, the differences between the amounts of energy produced by the systems simulated under the \$0.17 /kWh FiT regime are negligible in contrast to the considerable differences between the energy demand of each system. This happens because there is a lot of potential revenue generation from the excess electricity produced when sold back to the grid. HOMER selects optimal systems based on the best net present cost and the revenue from excess energy sold lowers the NPC of each system. But this is assuming that the FiT system in Nigeria is fully operational and revenue can be recovered.

The energy sold, and energy used by the loads help in understanding the amount of energy wasted in the system. Energy produced less the addition of energy sold and energy used by loads gives the amount of energy wasted due to losses during transmission, in the storage and converter. Overall, it is important to note that the energy used by similar load profiles are almost the same across all the profile groupings as shown in Table 6-6. All the simulated load profiles produced systems with excess energy to sell. However, the 3rd and 4th energy profiles under the zero FiT regime produces no excess energy because of the lack of renewable energy components. Adding renewable energy components to these profiles is not cost effective.

The fuel consumption and consequential pollutant emissions readings for all the systems considered under the \$0.17 /kWh FiT regime are shown in Table 6-7. The reading for the normal grid and generator system is included for comparison. It is important to note that the difference between the CO₂ emissions presented in Table 6-6 and Table 6-7 are different for systems in the \$0.17 /kWh FiT regime. Table 6-6 shows the net CO₂ emissions of each system by adding the carbon dioxide emissions from grid generation and from system components. HOMER assigns negative CO₂ emissions for renewable energy components according to the amounts of CO₂ they save compared to if they were conventional sources. For example, HOMER will record the CO₂ emission of a 20kW PV system as - 1,000kg/year (negative 1,000kg/year) although, it technically emits zero carbon dioxide, because a conventional power generation plant of the same rating will produce 1000kg of CO₂ per year.

On the other hand, Table 6-7 shows the actual total emission figures of all energy producing components. This difference in CO₂ emissions calculation is evident in the CO₂ emission figures for the 2nd and 3rd load profile in both tables. Table 6-6 showed that the 3rd load profile has a lower CO₂ emission than the 2nd load profile. This is reasonable because the 2nd profile has more electrical loads to power. However, Table 6-7 shows that the 3rd load profile has more CO₂ emission of 459kg/year) than the 2nd profile.

The net CO₂ of all the systems in Table 6-6 is negative which indicates that every system saves more carbon dioxide than they emit. CO₂ savings increase as the electrical load profile reduces ranging between 18,900 and 21,700 kg/year for the largest and smallest loads respectively. However, the actual emissions produced by the systems in Table 6-7 indicate that the 1st load profile is the largest pollutant emitter, in line with its size, followed by the 3rd load, 2nd load and the 4th load respectively. The 3rd load profile has a slightly higher CO₂ emission than the bigger 2nd load profile because a diesel generator is included in its mix of components whereas, the only source of CO₂ in the 2nd profile is the grid.

Table 6-7: \$0.17 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	729	445	459	339	10,134
Carbon Monoxide	0	0	1.87	1.51	48.1
Unburned Hydrocarbons	0	0	0.068	0.0551	1.75
Particulate Matter	0	0	0.113	0.0916	2.92
Sulphur Dioxide	3.16	1.93	1.42	1.01	29.2
Nitrogen Oxides	1.55	0.944	2.57	2.01	62.7
Fuel Consumption (L/yr)	0	0	94.4	76.5	2,435

There are no carbon monoxide (CO), unburned hydrocarbons and particulate matter for the 1st and 2nd profiles because these pollutants are associated with

combustion engines as discussed in Chapter 5 (Section 0) and there are no electricity generators in their systems. Optimal systems for the 3rd and 4th load profiles register these pollutants in quantities that correlate with their sizes. Sulphur dioxide (SO₂) and nitrogen oxides (NO_x) emissions are considered for electricity from both grid and on-site generator. SO₂ emission measures for the 1st and 2nd profiles are larger than for the 3rd and 4th profiles despite not having generators mainly because some of the SO₂ produced by generators are emitted as particulate matter. The NO_x emission figures reflect the sizes of the loads and the systems containing ICE generators.

The last column in Table 6-7 shows the pollutant emission figures for the most common electric power supply scenario for most buildings and facilities in Nigeria. The emissions results for the optimal systems simulated present much less pollutant emissions. The DER system with the highest emissions figures is not close to the grid in pollutant emissions by any reasonable measure.

Meanwhile, the data maps (Dmaps) in Figure 6-5 below show the daily distribution of the generator power output in an entire year for the 3rd and 4th energy demand profiles. Generator outputs for these profiles are shown because they each have a generator in their optimal systems while the other two do not. In both Dmaps, the generators show more activity during the first and last six hours of the days in the months of January to March and October to December. Generator activity is frequent during the early and late hours of the day mainly because solar resource is minimal during these hours resulting in less power from the PV array in the systems. Furthermore, Ibadan experiences less precipitation during the months of January to March and October to December resulting in less power output from the hydrokinetic turbine. The generator is inactive during daytime hours and during months in the rainy season in Ibadan. Both solar and hydro resources are discussed in Chapter 4.

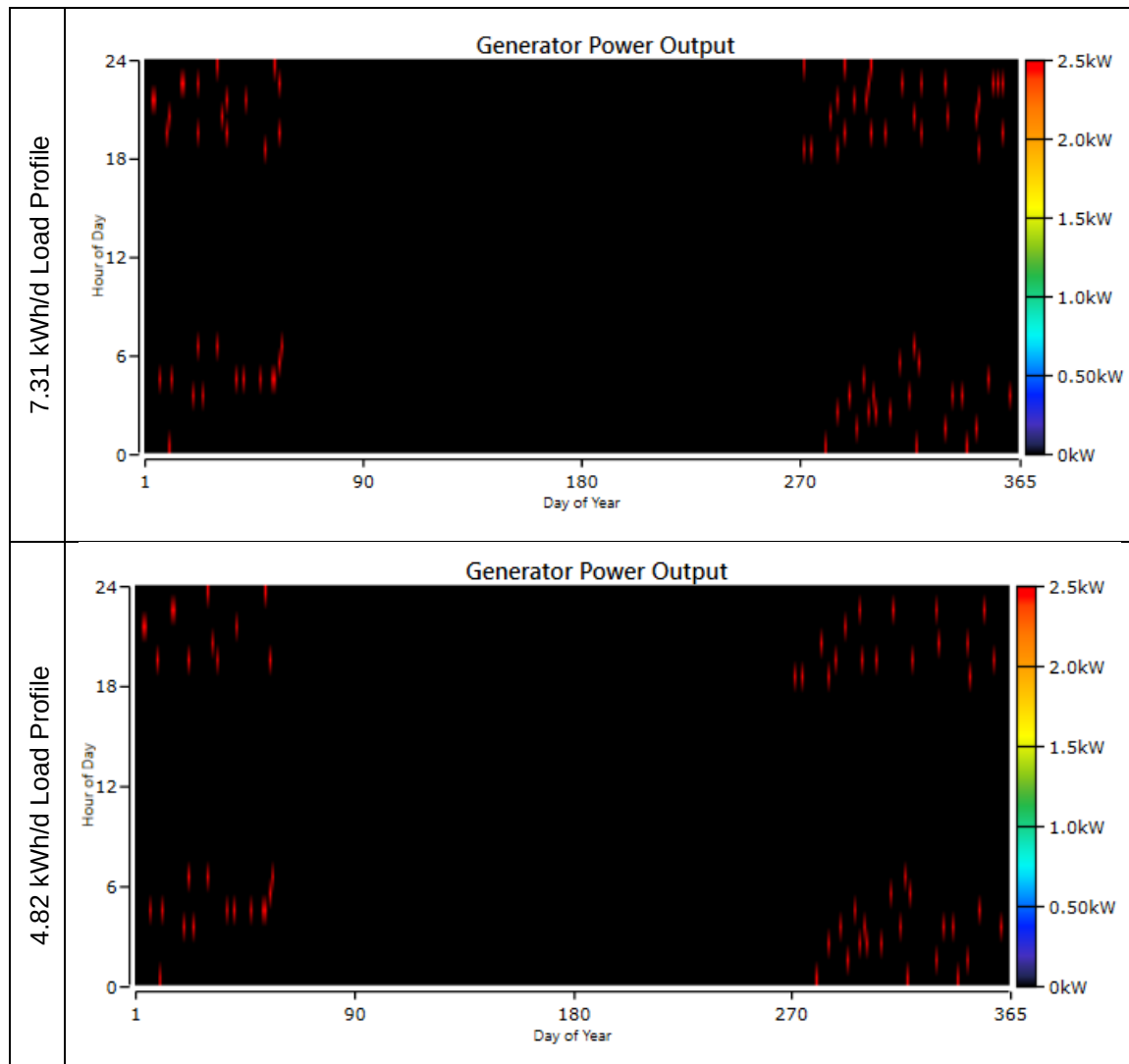


Figure 6-5: Generator outputs under \$0.17/kWh FiT regime

Night hours experience more energy demand than the early hours and therefore show more generator activity compared with the early hours during the active generator months (see Chapter 3 for daily energy distribution). Moreover, generator activity in the optimal system for the 7.31 kWh/day (3rd) load profile is more than in the 4.82 kWh/day (4th) load profile due to its larger total energy demand. It is important to observe from Figure 6-5 that the 10kW generators in both optimal systems are not operating near their rated power due to the abundance of renewable energy alternatives. They operate mostly at a mean electrical output of 2.5kW as shown in the figure. It is therefore up to facility managers to opt for generators rated closer to 2.5kW to reduce expenses. However, the ability of the power system to supply the entire facility in busy or emergency situations will be diminished as a trade-off.

6.2.2.2 Systems under Ibadan's \$0.07/kWh FiT regime

Table 6-8 shows that every optimal system under the \$0.07/kWh FiT regime contain the same type and quantity of components in addition to grid connection. These are: 10kW generator, bank of five 1kW batteries, and a 20kW hydrokinetic turbine. Only the hydrokinetic turbine provides renewable energy. The renewable energy fraction of the energy production of each system ranges from 79.7% for the largest load profile to 94.5% for the smallest load profile. Despite having the same capital costs, the higher operating costs of the larger load profiles ensure higher CoEs and NPCs that the smaller load profiles as shown in Table 6-6. The implication of this is that the diesel generator, usually responsible for high operating costs, operates more with heavier loads. Furthermore, the quantities of energy sold by the smaller load profiles are more than those sold by the larger load profile.

Table 6-8: Technical factors associated with \$0.07/kWh FiT regime in Ibadan

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Gen10, Battery x 5, Grid, HydroK	79.70	26,514	10,063	7,859	-4,535
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	85.70	25,211	11,136	5,216	-5,825
3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	91.90	24,079	12,276	2,668	-7,042
4 th	4.82	Gen10, Battery x 5, Grid, HydroK	94.50	23,665	12,681	1,760	-7,530

Since the feed-in-tariff considered for these systems, that is \$0.07/kWh, is the same as the current grid tariff in Nigeria, there is less incentive to generate substantial additional energy to generate additional revenue. The energy generated by the systems range from 26,514 to 23,665 kWh/year compared with an average of 51,000 kWh/year under the \$0.17/kWh FiT regime. The differences between the quantities of energy produced by the systems simulated under the \$0.07/kWh FiT regime are more varied than those under the \$0.17/kWh FiT

regime. Again, this is due to the comparatively lower incentive to generate additional sellable energy.

Under this FiT regime, all system results correlate with the load sizes. However, there are more energy losses in systems for the smaller loads because of the sizing of the components. A facility may decide to reduce the power rating of some of the components as trade-off for higher renewable fraction in energy produced and the ability of the power supply system to power all the devices in the facility during busy emergency periods.

Like the readings under the \$0.17 /kWh FiT regime, the net CO₂ emission savings under \$0.07 /kWh FiT scenario in Ibadan increase as the loads reduce (see Table 6-8). On the other hand, the actual carbon dioxide emissions due to the operation of the DER system reduces as the loads reduce in size (see Table 6-9). The considerable difference between the CO₂ savings and emissions between the \$0.17/kWh and \$0.07/kWh FiT regimes indicates how much a facility's environment can benefit from higher level renewable energy investments.

Table 6-9: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	2,581	1,636	795	515	10,134
Carbon Monoxide	5.72	3.20	0.595	0.227	48.1
Unburned Hydrocarbons	0.208	0.116	0.0217	0.00826	1.75
Particulate Matter	0.347	0.194	0.0361	0.0137	2.92
Sulphur Dioxide	9.44	6.11	3.26	2.16	29.2
Nitrogen Oxides	10.4	6.21	2.19	1.29	62.7
Fuel Consumption (L/yr)	290	162	30.1	11.5	2,435

Again, the sizes of the load profiles correlate positively with actual pollutant emissions quantities. Nevertheless, there seem to be a load size threshold where

pollutant emissions increase sharply. It can be observed that the heavier load profiles present higher proportions of emissions in relation to load size compared with emissions for the two lighter load profiles. This is likely due to the heavier loads resulting in higher intensity of generator operation and increased rate of fuel consumption.

Generally, the emissions figures for the 1st and 2nd optimal systems under the \$0.17/kWh FiT regime are better for the facility's environment than the emissions for systems under parallel profiles in the \$0.07/kWh FiT regime. This is because the 1st and 2nd systems under the \$0.07/kWh FiT regime contain a diesel generator while the systems in the other FiT scheme does not. On the other hand, the 3rd and 4th systems under the \$0.07/kWh FiT regime present fairer pollutant emissions figures than the 3rd and 4th systems under the \$0.17/kWh FiT regime. In these cases, the systems under both FiT regimes contain ICE generators but the generators under the \$0.17/kWh FiT regimes operated for longer periods.

Comparisons between emissions values for the optimised DER systems under the \$0.07/kWh FiT regime and those under current grid and generator power systems (see Table 6-9) show that DERs under this regime still provide much fairer emissions results despite having lower renewable energy fraction than the previous FiT regime. This is further evidence that hybridisation of DERs, even with minimal renewable energy components, and conventional power supply systems can provide not only reliable and less expensive power supply, but a low pollutant emission footprint per unit of energy produced. In the current power supply industry in Nigeria, conventional systems are proven to be chronically unreliable and become expensive and highly polluting when backed up with on-site generator(s).

Nevertheless, HOMER still presents feasible optimal systems comprised of only the grid and generator because they guarantee regular power supply despite their high financial costs. Renewable energy sources by themselves are too intermittent to be relied upon and therefore, no optimal system generated presented renewable sources by themselves. The grid is a constant in every optimal solution due to its low cost of energy and the generator appears in about 65% of all the possible systems generated for each load profile due to its reliability.

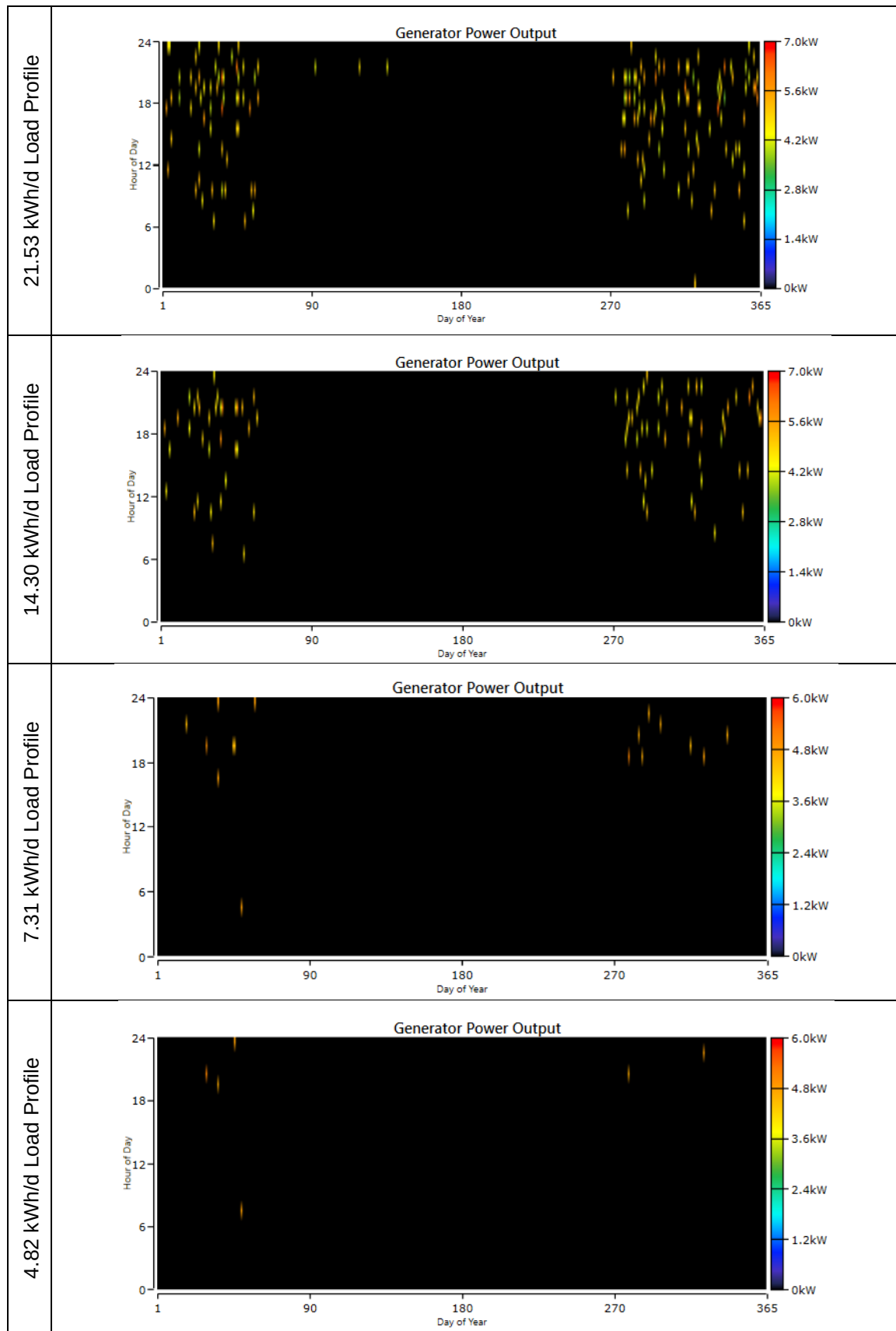


Figure 6-6: Generator outputs under \$0.07/kWh FiT regime

In Figure 6-6 above, the Dmaps present the distribution of daily power output of the 10kW generator in the optimal systems under the \$0.07/kWh FiT regime. All four electric load profiles contain a generator under this FiT regime unlike two in the previous regime. Since all the optimal systems under each FiT regime contain the same components, the frequency of generator activity reduces as the energy demand drops.

The pattern of generator activity under this regime indicate more afternoon and evening activity than in the morning unlike more morning and evening activity in the previous FiT regime. This is due in part to the absence of solar PV in the system components paving the way for the hydrokinetic turbine as the only renewable component which can produce power optimally throughout the day. The other factor responsible for this pattern of generator activity is that day and night times are the periods when energy demand is highest, and the system requires the generator to provide the additional power required to support the hydrokinetic turbine and unreliable grid.

Furthermore, during the months of March and October, there is little to no generator activity across the optimal systems under different load profiles. This is due to the abundance of precipitation during this period in Ibadan resulting in strong river flow velocities that help drive the hydrokinetic turbine. The robust battery system provides the buffer for when there is excess power generated by the turbine during heavy rainfalls and when power drops due to lower river flow velocities.

6.2.2.3 Systems under Ibadan's \$0.00/kWh FiT regime

Table 6-10 below shows that the 1st and 2nd systems contain the same set of components and the 3rd and 4th systems contain a different set of the same components in their simulated optimal systems. The 1st and 2nd systems have approximately 75% and 82% renewable energy fraction in their systems made up of the 10kW generator, 5 Li-Ion batteries and the hydrokinetic turbine as the only renewable source of energy. Whereas, the 3rd and 4th profiles contain the 10kW

generator and 5 Li-Ion batteries but no renewable energy components in their optimal systems.

Table 6-10: Technical factors associated with \$0.00/kWh FiT regime in Ibadan

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Gen10, Battery x 5, Grid, HydroK	74.90	26,511	6,642	7,858	-2,375
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	81.90	25,208	7,715	5,216	-3,665
3 rd	7.31	Gen10, Battery x 5, Grid	0.00	2,951	-	2,668	1,737
4 th	4.82	Gen10, Battery x 5, Grid	0.00	1,951	-	1,759	1,208

The lack of significant renewable energy sources under this FiT regime is mainly due to the lack of financial incentives. Both the 1st and 2nd profiles produced systems with excess energy to sell, hence their negative net CO₂ emissions. These two systems have more loads to power. Therefore, the addition of the hydrokinetic turbine allows for these loads to be covered by the system while generating excess electrical energy in the process. This excess will go to waste as there is no provision for it to be sold. Hence, the actual emission figures are more representative of the emissions scenarios under this FiT regime.

However, the 3rd and 4th energy profiles under the zero FiT regime produce no excess energy because they lack renewable energy components. Adding renewable energy components to these profiles is not cost effective because the loads are not large enough to justify the required investment to add renewable components to the systems. Furthermore, any excess energy generated due to the addition of a renewable component will be wasted since they cannot be sold to generate income.

It can be observed that the net (see Table 6-10) and actual (see Table 6-11) CO₂ emission figures for the 3rd and 4th loads under this FiT regime are similar. Whereas, the corresponding figures for the 1st and 2nd systems are significantly

different. This is due to the presence of renewable energy components in the 1st and 2nd systems helping to create negative net CO₂ emissions. On the other hand, the 3rd and 4th profiles have no renewable energy components and had figures close to their actual emissions presented under their net emissions. The difference between the net and actual CO₂ emission figures for the 3rd and 4th systems is caused by the net emission not taking CO₂ from energy losses into consideration (uses only energy purchased minus energy sold) while actual emission figures do.

Table 6-11: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	2,579	1,633	1,940	1,248	10,134
Carbon Monoxide	5.72	3.20	1.54	0.301	48.1
Unburned Hydrocarbons	0.208	0.116	0.056	0.011	1.75
Particulate Matter	0.347	0.194	0.0932	0.0183	2.92
Sulphur Dioxide	9.43	6.10	7.94	5.32	29.2
Nitrogen Oxides	10.4	6.20	5.43	2.9	62.7
Fuel Consumption (L/yr)	290	162	77.8	15.2	2,435

However, emissions relating to both the grid and generator components are not well correlated with load sizes due to the renewable energy components in the 1st and 2nd systems. This allows the 1st and 2nd systems to produce a lower ratio of emissions to load size than the 3rd and 4th systems. Furthermore, although the ratio of fuel consumption to load size is relatively high for the 1st and 2nd systems, their renewable energy components contributes pollutant emissions savings which bring down their overall emissions figures.

Like the other FiT regimes, the emissions figures for the optimised DER systems under the zero FiT regime are better than those under the grid and generator only system. Carbon dioxide emission under the 1st and largest load profile is 3 times

less than in grid and generator only systems while carbon monoxide and unburned hydrocarbons are 8 times less. The addition of batteries alone to the grid and generator in the 3rd and 4th systems significantly reduced the ratio of emissions to load size compared with the grid and generator only system.

The DMaps in Figure 6-7 show similar generator activities in the 1st and 2nd systems under the zero FiT regime than under the \$0.07/kWh FiT regime (Figure 6-6). Both systems under the two FiT regimes contain the same components. However, the 3rd and 4th systems under the zero FiT regime present more generator activity than the corresponding systems under the \$0.07/kWh FiT regime. This occurred because the former systems have no renewable energy component in their configuration.

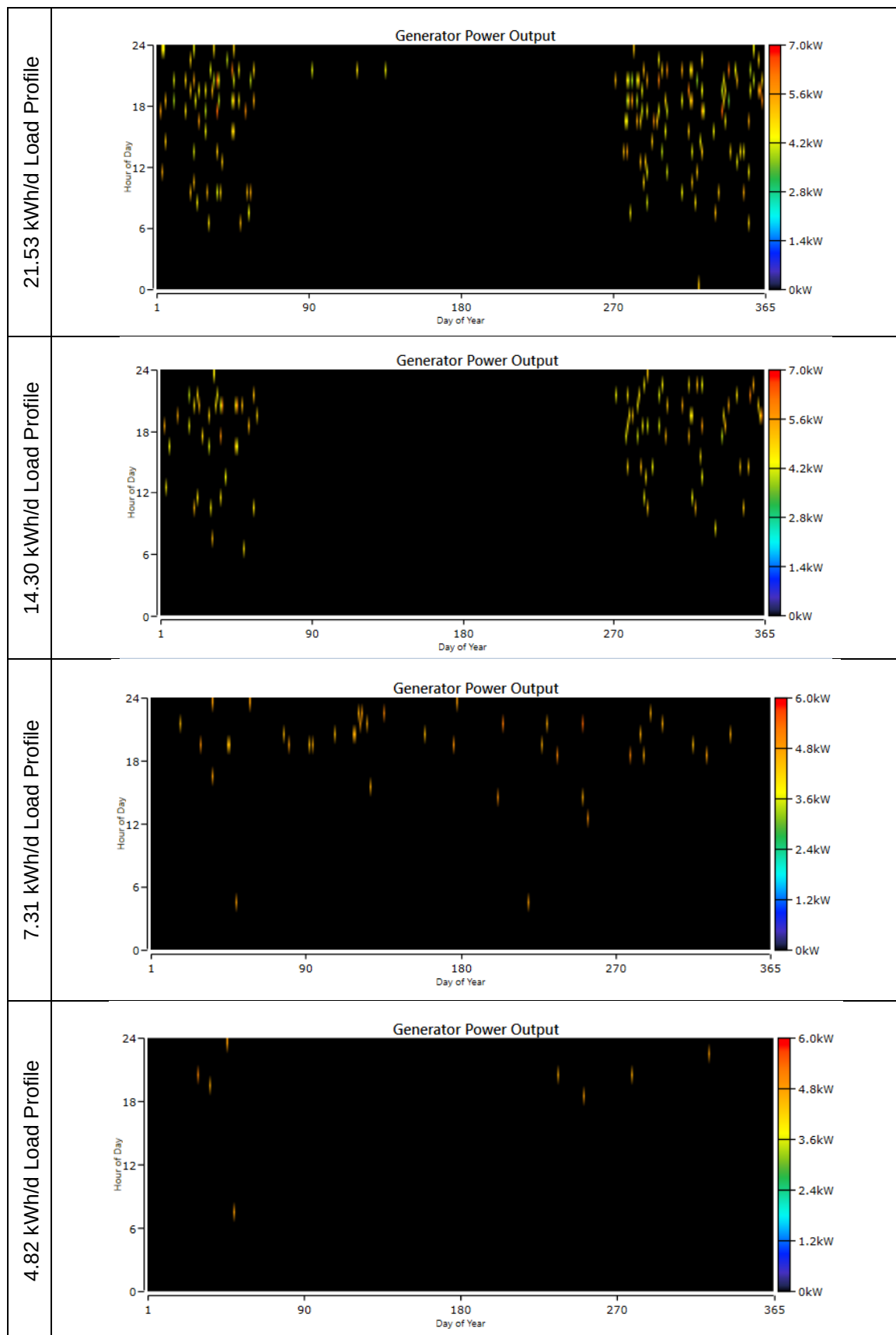


Figure 6-7: Generator outputs under \$0.00/kWh FiT regime

6.2.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Ibadan Systems

Figure 6-8 presents a comparison of actual carbon dioxide and particulate matter emissions between all the systems modelled for the city of Ibadan including a grid and generator only conventional system. Except for the 1st system, emissions generally reduce with reduction in load sizes despite the use of similarly sized power generation components. On the other hand, quantities of emissions also increased with reduction in feed-in-tariffs for the optimised DER systems. This indicates that the reduction or removal of financial incentives in the form of feed-in-tariffs makes renewable energy components less attractive investments.

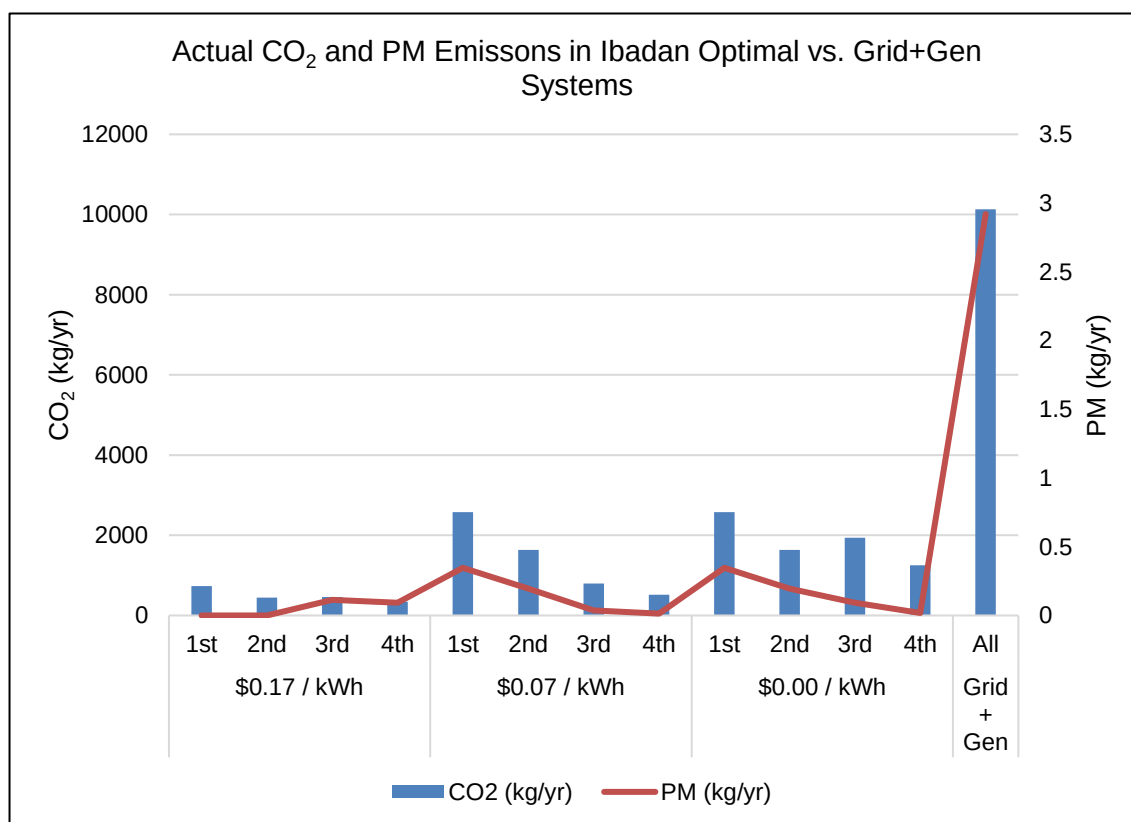


Figure 6-8: CO₂ vs. PM emissions for system configurations in Ibadan

Despite the removal or reduction of FiT in some of the optimised DER systems, they all presented considerably lower emissions figures compared with the current conventional power supply system. The conventional system has 8 times more PM and 4 times more CO₂ emissions than the optimised systems have.

Depending on the prevailing FiT system in an area, facility managers can therefore choose between powering all the facility's devices and having high overall pollutant

emissions or trade off constant optimum operations for lower emissions foot print. However, it is important to note that some systems that presented higher carbon dioxide emissions had comparably lower particulate matter emissions in the 1st and 2nd systems under the \$0.17/kWh FiT regime. This underlines the importance of designing and running models of different electricity demand and supply scenarios before making final decisions.

6.3 Port Harcourt (SS Nigeria) Results and Discussions

Other location specific data such as, clearness index, daily radiation and, wind speeds used in building DER models in HOMER are presented in Section 4.2.

12,032 solutions were modelled for each FiT regime sensitivity. Under the \$0.17/kWh FiT regime, 8,564 of these were feasible while 3,468 were infeasible due to capacity shortage constraint. 9,192 solutions were feasible and 2,840 were infeasible under the \$0.07/kWh FiT regime. The \$0.00/kWh FiT regime generated 9,964 feasible and 2,068 infeasible solutions.

6.3.1 Costs of Optimal System Configurations for Port Harcourt

Table 6-12 below shows the costs associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Port Harcourt, Nigeria.

Table 6-12: Cost factors for system configurations in Port Harcourt

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load /System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1 st	21.53	PV, Battery x 5, Grid, HydroK	-0.1095	-315,619	88,700	1,126	73,295
	2 nd	14.29	PV, Battery x 5, Grid, HydroK	-0.1146	-326,757	88,700	715	74,897
	3 rd	7.31	PV, Gen10, Battery x 5, Grid, HydroK	-0.1199	-338,794	96,200	334	76,554
	4 th	4.82	PV, Grid, HydroK	-0.1273	-357,688	87,700	230	77,141
\$0.07 /kWh	1 st	21.53	Battery x 5, Grid, HydroK	-0.0377	-90,836	22,700	3,098	60,026
	2 nd	14.29	Gen10, Battery x 5, Grid, HydroK	-0.0413	-97,749	30,200	1,958	61,198
	3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	-0.0468	-108,481	30,200	1,156	62,330
	4 th	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0484	-111,314	30,200	785	62,730
\$0.00 /kWh	1 st	21.53	Battery x 5, Grid, HydroK	0.0574	48,058	16,750	3,095	15,993
	2 nd	14.29	Gen10, Battery x 5, Grid, HydroK	0.0553	44,107	24,250	1,954	17,164
	3 rd	7.31	Gen10, Battery x 5, Grid	0.2763	26,285	10,250	2,748	0
	4 th	4.82	Gen10, Battery x 5, Grid	0.3376	21,178	10,250	1,911	0

6.3.1.1 Costs under Port Harcourt's \$0.17/kWh FiT regime

Port Harcourt presents the lowest cost of energy under this FiT regime amongst all the systems modelled (see Appendix H for figures across all cities) with an average CoE of -\$0.1178/kWh. At -\$0.1095 per kWh cost of energy used, the system modelled for the 21.53 kWh/day load profile earns \$0.1095 for every kWh of energy consumed by the loads. This is due to the high amount of energy produced and sold back to the grid by the energy system. Port Harcourt, a coastal city, experiences a comparatively high annual precipitation. This ensures that the potential excess energy from the hydrokinetic turbine in the city is higher than in any other city studied. The 1st and 4th systems present the highest and lowest CoEs respectively with Port Harcourt's 4th profile presenting a system CoE that is 3 times less (or earns 3 times more income) than its counterpart under Ibadan.

The Net Present Costs under this FiT regime indicate a significant potential for income from energy generation from renewables in Port Harcourt. The city presented the highest net present values (the direct opposite of NPC in sign) across all load profiles simulated among all the cities studied. Over a 25-year operation period, the Port Harcourt systems presented NPVs of above \$300,000 for all the systems modelled. This is approximately 7 times better, on the average, than the NPVs presented in Ibadan's systems. By generating comparably large amounts of excess energy from renewable sources, a DER system in Port Harcourt is able to generate a lot of income over its lifetime compared to an Ibadan system.

Under the \$0.17/kWh FiT regime, Port Harcourt also presented some of the lowest initial capital costs after Awka. Port Harcourt's 1st 2nd and 4th systems are \$88,700 each, these are approximately 25% less than the 1st and 2nd systems and 29% less than the 4th system in Ibadan. Port Harcourt's 3rd system is 23% less than its Ibadan counterpart under this FiT regime. The cost of PV components proved to be the main reason for high capital costs of systems across the cities. Since Port Harcourt has significantly more hydro potential than solar, less solar components were included in the models under the city resulting in an overall less capital cost across systems.

Figure 6-9 shows the plot of Port Harcourt's CoE against capital cost across the systems modelled under the \$0.17/kWh FiT regime. Unlike Ibadan where there is a

directly inverse relationship between the capital cost and cost of energy, Port Harcourt's results under the \$0.17/kWh FiT regime presented a different CoE versus capital cost profile. This is due to the 4th load profile not having any battery storage in its system. Therefore, the 4th load profile under the \$0.17/kWh FiT regime presents the best value for capital invested by having the lowest capital requirement and the lowest cost of energy or highest income generated for every kWh of energy consumed.

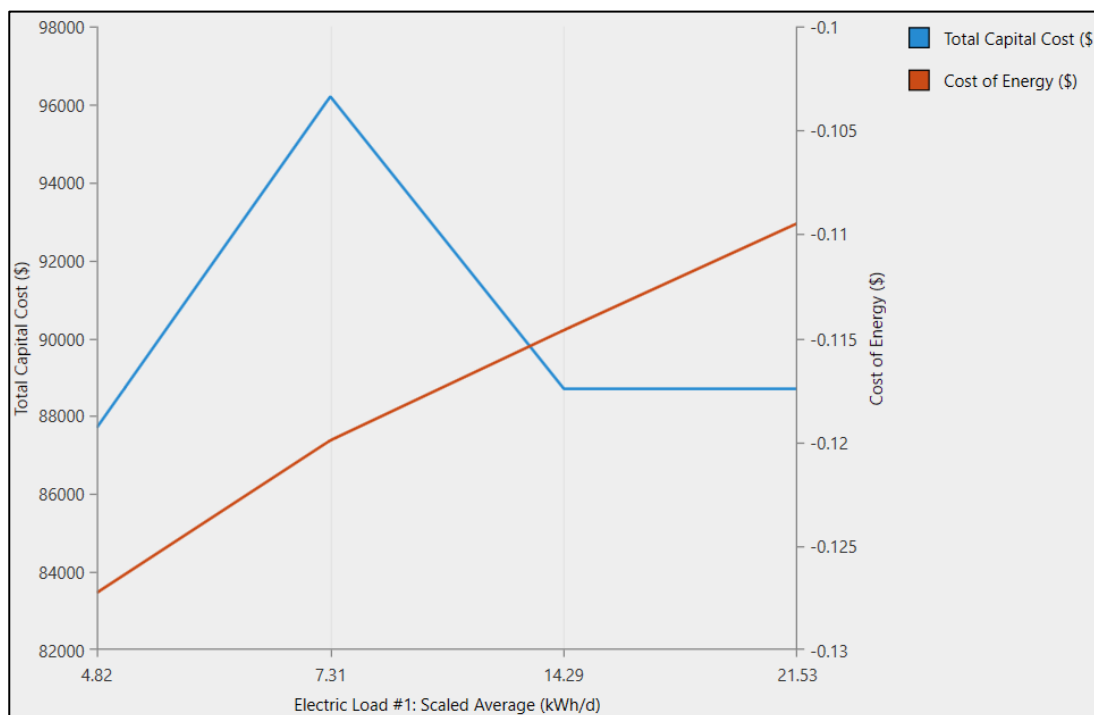


Figure 6-9: Capital cost vs. Cost of energy under \$0.17 FiT regime

Besides the 4th and lowest system, the other systems under this FiT regime in Port Harcourt have a similar inverse relationship between capital cost and CoE to that of Ibadan. The 2nd (14.29 kWh/day) load profile presents the next best CoE value for capital invested after the 4th load profile in Port Harcourt. Decision makers can choose the 4th load profile and trade off the ability to store some of excess energy produced to use during emergencies for higher income generation from excess energy sales. Otherwise, the 2nd load profile presents a good CoE to capital cost ratio while allowing for more equipment to be powered at any time with a larger capacity and more resilient system.

6.3.1.2 Costs under Port Harcourt's \$0.07/kWh FiT regime

Similar to the results under the \$0.07/kWh FiT regime for Ibadan, the cost of energy and NPC for the \$0.07 FiT regime under Port Harcourt indicate net income per kWh energy consumed with an average CoE of -\$0.0436/kWh. This is despite the cost of energy remaining the same as the official national electricity rate. The cost of energy is still comparatively low under this FiT regime. Ibadan's 1st, 2nd, 3rd and 4th system CoEs are 175%, 221%, 385% and 528% higher than their equivalents in Port Harcourt. It is important to note that only Port Harcourt and Awka presented negative CoEs under the \$0.07/kWh FiT regime among the cities. The two cities have the largest hydro potential due to their high annual precipitation as shown in Figure 4-14. This shows that the hydro power potential in Nigeria, if harnessed, presents higher returns on investment than solar PV potential.

As expected, the load profile with the largest energy demand has the highest CoE and vice versa. However, the capital cost for the 1st and largest energy demand profile is the lowest. This is due to lack of a backup diesel generator in the 1st load profile's system. Omitting the generator helps to bring down the capital cost. This will expose the system to incidences of unmet loads during emergencies. Nevertheless, the battery bank in the 1st load profile's system should provide a reasonably adequate power backup but resulting in the need to change batteries more frequently.

Table 6-13: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	-0.0377	-90,836	22,700	3,098	60,026
	14.29	-0.0413	-97,749	30,200	1,958	61,198
	7.31	-0.0468	-108,481	30,200	1,156	62,330
	4.82	-0.0484	-111,314	30,200	785	62,730

Figure 6-10 below shows that there is little relationship between capital cost and cost of energy across the systems under the \$0.07/kWh FiT regime. All the systems, except for the 1st system with the largest load profile, presented the same capital cost of \$30,200. The 1st system has a lower capital cost than the other

systems because the benefit of not having an additional power generating component, a diesel generator, is offset by the higher cost of energy over the 25 year lifetime of the system. The CoE for the 1st system is higher than the 2nd, 3rd and 4th systems by 9%, 24% and 28% respectively.

Although Ibadan and Yola presented a lower capital cost for the optimal systems presented under the \$0.07/kWh FiT regime, Port Harcourt presents lower CoE than in all the other cities. Port Harcourt's 1st system is 232%, 24%, 178%, 187% and 352% less than Ibadan, Awka, Abuja, Kano and Yola's 1st systems respectively. Similarly, Port Harcourt's 4th system is 123%, 13%, 93%, 119% and 795% lower CoE in Ibadan, Awka, Abuja, Kano and Yola's 4th systems respectively. This is also due to Port Harcourt's ability to comparably higher hydro energy generation potentials.

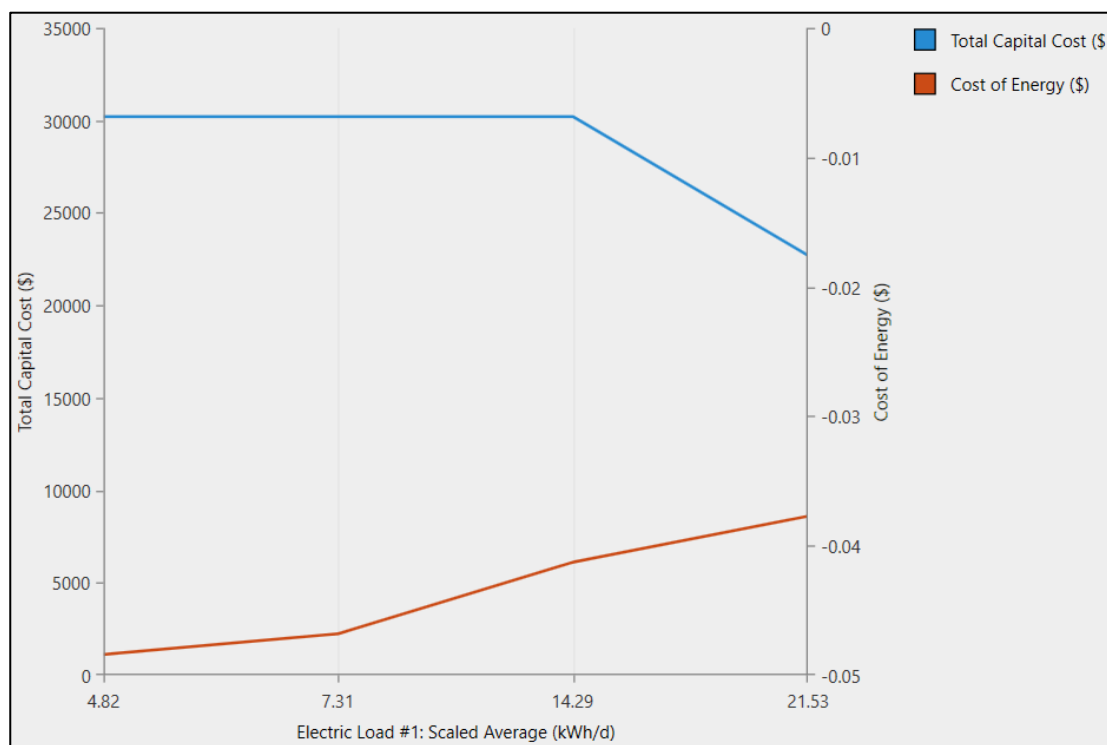


Figure 6-10: Capital cost vs. Cost of energy under \$0.07 FiT regime

Under this FiT regime, Port Harcourt and Ibadan have the same energy generating components, except for their 1st systems. However, Port Harcourt presents an overall higher capital cost than Ibadan under the \$0.07/kWh FiT regime. This is because the Port Harcourt system generates a significant proportion of energy from the hydrokinetic turbine with a DC power output. This requires the system to

have a larger capacity converter of 22 kW to convert the additional DC output to AC power required by the devices compared with Ibadan that has a 10 kW converter since a bigger portion of its energy generation comes from the AC power producing diesel generator.

As presented in Table 6-14 below, there are significant differences of \$0.5257, \$227,468, and \$6,805 between the cost of unit energy, net present cost over 25 years, and annual operating cost respectively of the optimal system for the 1st load profile under the \$0.07 FiT regime and under a conventional system in Port Harcourt. This represents 107.7% reduction in CoE, 166.5% reduction in NPC and 187.9% reduction in annual operating costs.

The optimal system presented these cost advantages over a conventional system under the 1st load profile while only costing \$15,200 (202.7%) more in capital cost than a conventional power system. Two years and three months' cost savings from lower operations costs for the optimal system under this FiT regime covers the additional capital cost of installing the DER components. These cost advantages are available despite the lower amount of income from selling excess energy at the same rate as the grid instead of the higher feed-in-tariff rate of \$0.17/kWh.

Table 6-14: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Port Harcourt (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	-0.0377	0.488	-90,836	136,632	-3,184	3,621	22,700	7,500
14.3	-0.0413	0.7	-97,749	130,171	-3,588	3,440	30,200	7,500
7.31	-0.0468	1.3	-108,481	123,944	-3,889	3,265	30,200	7,500
4.82	-0.0484	1.94	-111,314	121,722	-3,968	3,203	30,200	7,500

6.3.1.3 Costs under Port Harcourt's \$0.00/kWh FiT regime

As shown in Table 6-15, the cost of energy and net present cost results under the \$0.00/kWh FiT regime are presented as positive costs. This reflects the zero potential for income from excess energy sales. Because of this removal of incentive to generate excess energy, the optimal systems for all the load profiles under the zero FiT regime present lower capital costs compared to the capital costs

of systems modelled under the other feed-in-tariff regimes. Meanwhile, there are no energy sales in the systems for the 3rd and 4th systems. This is because of the omission of renewable energy components from both systems due to lack of financial incentives to generate excess electrical energy.

Table 6-15: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.00/kWh	21.53	0.0574	48,058	16,750	3,095	15,993
	14.29	0.0553	44,107	24,250	1,954	17,164
	7.31	0.2763	26,285	10,250	2,748	0
	4.82	0.3376	21,178	10,250	1,911	0

Nevertheless, Port Harcourt presented overall lower costs than the other cities under the zero FiT regime with an average CoE of \$0.18 /kWh and average capital cost of \$15,375, except for Awka. Awka presented the same cost results as Port Harcourt under this FiT regime. This is because Awka's level of annual precipitation and overall climatic conditions are closest in characteristics to Port Harcourt's. Therefore, they both have the same components installed in the optimal systems considered in their models.

Like the capital cost versus cost of energy comparison under the zero FiT regime in Ibadan, the relationship between the two variables are inversely proportional as shown in Figure 6-11. The 2nd load profile of 14.30 kWh/day presents the lowest CoE but has the highest capital cost. The optimal system for the 3rd load profile of 7.31 kWh/day presents an attractive option because it has one of the least capital costs (137% lower than the highest) and only the second highest CoE (22% lower than the highest CoE). Nevertheless, the 4th profile with the highest CoE presents a longer term benefit of having the lowest NPC over the lifetime of the system.

It is important to note that, unlike the norm in other two FiT regimes, the system cost of energy under the zero FiT regime increases as the system load size reduces. This is due to the advantage of economies of scale enjoyed by the larger load profiles. However, in the long term, the NPC for the smaller system loads are

lower over the 25-year lifetime of the systems just like in the systems modelled under the other FiT regimes.

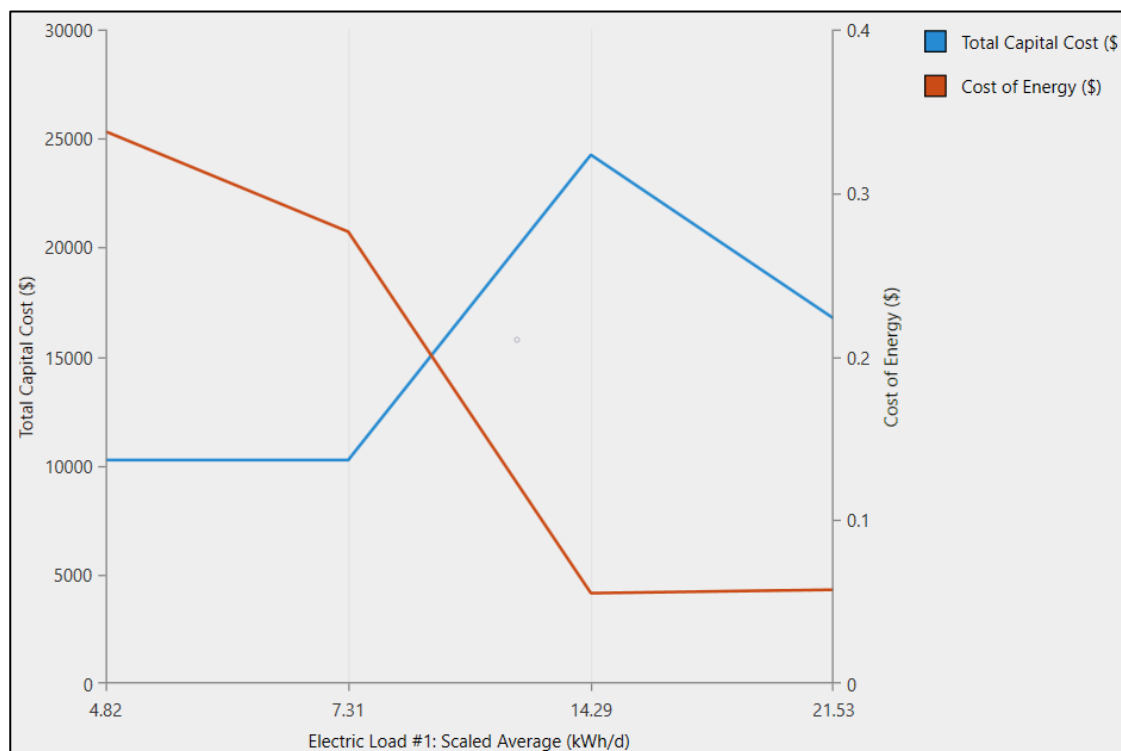


Figure 6-11: Capital cost vs. Cost of energy under \$0.00 FiT regime

Table 6-16 shows that when compared with a conventional power system of grid and a diesel generator, the optimal DER system for the 1st load profile under the zero FiT regime presents lower costs of \$0.4306 (750% less), \$88,574 (184% less) and \$2,743 (312% less) respectively for unit cost of energy, net present cost and annual operating cost. The optimal DER system's capital cost is only \$9,250 (123%) more than that of the conventional system. This equates to 3 years and 4 month's savings on the operating cost from the DER system.

Figures from the other load profiles' systems are similar with the less energy demand profiles presenting much lower capital cost differences with the conventional system. These cost savings are not as attractive as the other FiT regimes that pay out for excess energy generated. Nevertheless, the costs associated with the DER systems under the zero FiT regime are still considerably lower, both in the short and long term, than those associated with conventional sources of electrical power.

Table 6-16: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Port Harcourt (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0574	0.488	48,058	136,632	878	3,621	16,750	7,500
14.3	0.0553	0.7	44,107	130,171	557	3,440	24,250	7,500
7.31	0.2763	1.3	26,285	123,944	450	3,265	10,250	7,500
4.82	0.3376	1.94	21,178	121,722	306	3,203	10,250	7,500

6.3.1.4 Capital Cost and Cost of Energy Comparison between all Port Harcourt Systems

Figure 6-11 shows that systems under the \$0.07/kWh FiT regime present the most balanced capital cost to cost of energy ratio. The \$0.17/kWh FiT regime requires considerably higher capital costs to achieve slightly lower costs of energy. On the other hand, the zero FiT regime presents slightly lower capital costs to produce positive costs of energy compared with negative CoEs (due to income from excess energy) under the \$0.07/kWh FiT regime. Average costs are charted for the conventional systems across all the systems modelled. The chart shows that CoE for conventional systems are significantly higher than DER systems with comparable capital costs (e.g. 371% and 475% higher conventional CoEs in 3rd and 4th systems respectively).

Furthermore, when Port Harcourt's optimal systems are compared with those of the other cities, they generally present much lower cost of energy per capital invested. For example, Port Harcourt's first system under this regime is 14%, 33%, 66% and 40% lower than its equivalents in Ibadan, Abuja, Kano and Yola respectively. Port Harcourt and Awka's systems have similar capital costs. This shows the impact of higher rainfall, an important natural energy resource for hydrokinetic power, in the renewable energy potential of a city.

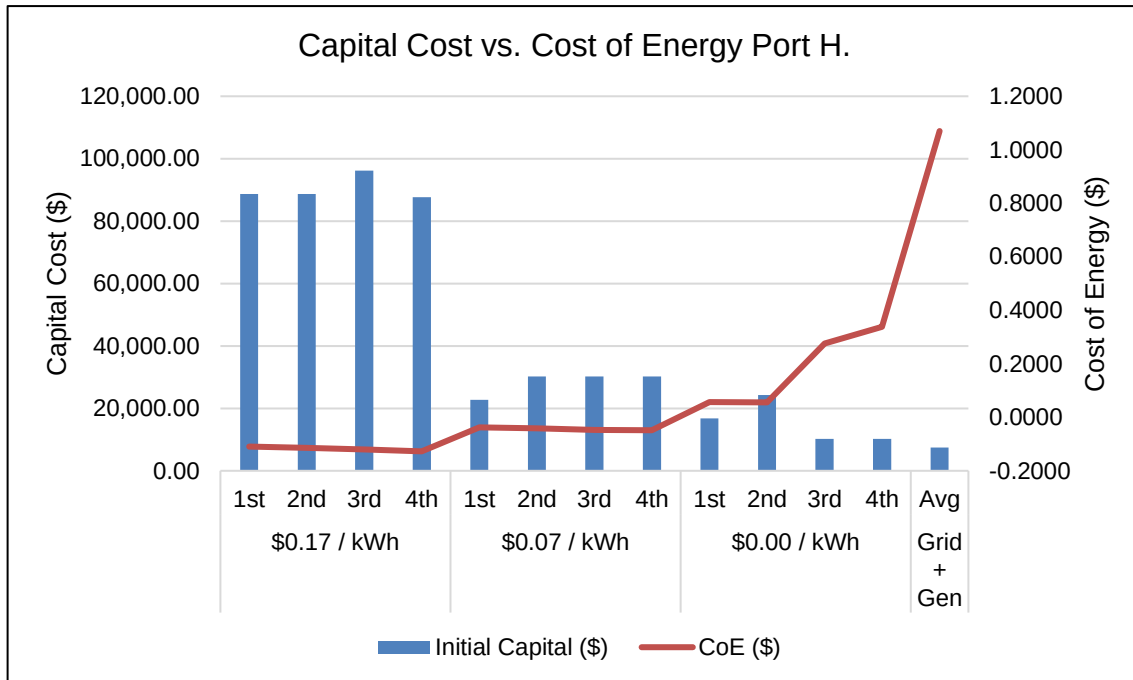


Figure 6-12: Capital cost vs CoE for system configurations in Port Harcourt

6.3.2 System and Emission Factors of Optimal System Configurations for Port Harcourt

Table 6-17 below shows the technical variables associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Port Harcourt.

Table 6-17: Technical factors for system configurations in Port Harcourt

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	99	119,422	73,295	7,549	-45,611
	2nd	14.30	PV, Battery x 5, Grid, HydroK	99	119,012	74,897	5,045	-46,883
	3rd	7.31	PV, Gen10, Battery x 5, Grid, HydroK	99	118,856	76,554	2,668	-48,171
	4th	4.82	PV, Grid, HydroK	100	118,527	77,141	1,681	-48,607
\$0.07 /kWh	1st	21.53	Battery x 5, Grid, HydroK	95	95,725	60,026	7,501	-35,979
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	96	94,995	61,198	5,216	-37,440
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	98	93,857	62,330	2,668	-38,662
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	99	93,436	62,730	1,759	-39,149
\$0.00 /kWh	1st	21.53	Battery x 5, Grid, HydroK	87	95,722	15,993	7,500	-8,151
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	89	94,991	17,164	5,216	-9,612
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
	4th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

6.3.2.1 Systems under Port Harcourt's \$0.17/kWh FiT regime

Table 6-17 shows that PV components appear only in optimal systems under the \$0.17/kWh FiT regime. Whereas, only two systems do not have a hydrokinetic turbine out of twelve optimised systems. This is testament to Port Harcourt having more hydro potential than solar. It should be noted that the optimal systems present emission figures proportional to their load sizes except for the 3rd system. Only the 3rd system under this FiT regime contains an ICE generator. This ensures that energy for onsite consumption is secure while the energy generated by the renewable sources is prioritised for grid sale with less reliability requirements. The 3rd system will produce higher amounts of pollutant emissions than the others.

All the systems under Port Harcourt's \$0.17/kWh FiT regime present high net CO₂ emission savings, the highest in all the system results. However, the actual CO₂ emission figures are second lowest behind Awka's. This is due to the optimisation algorithm prioritising renewable power generation for high value FiT sale while allowing the loads to be powered by the cheaper utility as often as possible.

Table 6-18: \$0.17 FiT optimal systems vs. grid + gen system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	711	452	492	145	10,134
Carbon Monoxide	0	0	2.13	0	48.1
Unburned Hydrocarbons	0	0	0.0774	0	1.75
Particulate Matter	0	0	0.129	0	2.92
Sulphur Dioxide	3.08	1.96	1.48	0.630	29.2
Nitrogen Oxides	1.51	0.958	2.86	0.308	62.7
Fuel Consumption (L/yr)	0	0	108	0	2,435

Figure 6-13 contains the DMap of system 3's generator activity, a confirmation that only the 3rd system has a diesel generator. Table 6-18 shows the larger proportion of pollutant emissions produced by the 3rd optimal system, while the other systems

did not produce generator related emissions. When compared with its Ibadan counterpart in Figure 6-5, Port Harcourt's 3rd system has more generator activity during the middle of the year. This is an indication of the limited solar resource in Port Harcourt during this period of rainy season because of cloud cover. Nevertheless, Port Harcourt presents only one system with a generator while Ibadan presented two. This is an indication of the strength of Port Harcourt's hydro potential to compensate for its lower solar resource. Furthermore, all the optimal systems in Port Harcourt under the \$0.17/kWh FiT regime present significantly better emissions figures compared with the conventional system option.

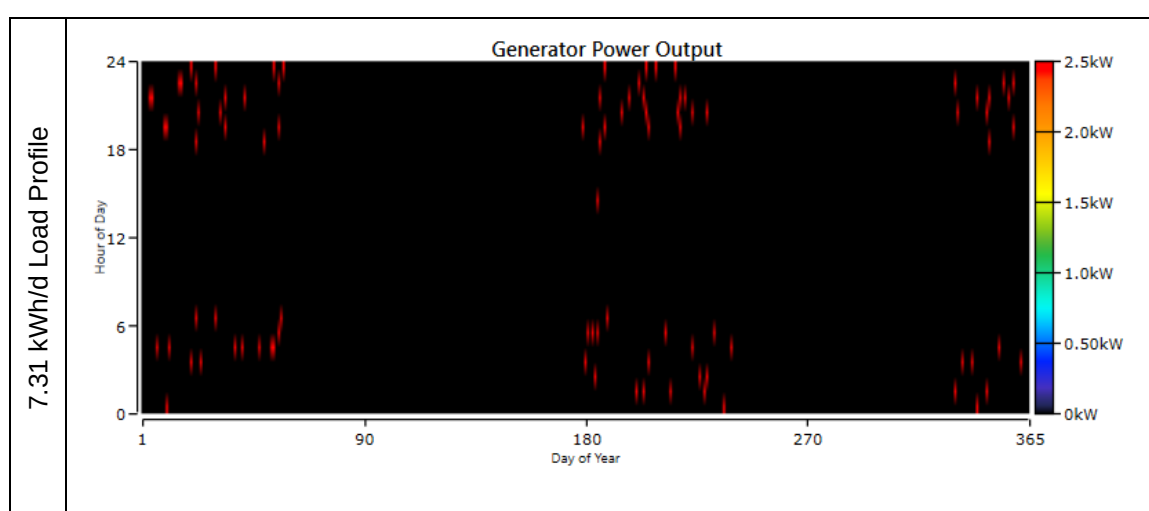


Figure 6-13: Generator outputs under \$0.17/kWh FiT regime

6.3.2.2 Systems under Port Harcourt's \$0.07/kWh FiT regime

Under the \$0.07/kWh FiT regime, the renewable fraction in the total energy produced generally reduces compared with the systems under the \$0.17/kWh FiT regime. Every system under the \$0.07/kWh FiT regime has a hydrokinetic turbine and no PV module, further proof of Port Harcourt's relatively more abundant hydro potential. Only the 1st system lacks a diesel generator, resulting in a lower renewable fraction than the other systems under this FiT regime as shown in Table 6-19. Nevertheless, the 1st system presents the lowest pollutant emissions in proportion to its load. Furthermore, it does not emit any of the generator-related pollutants such as carbon monoxide, unburned hydrocarbons and particulate matter as shown in Table 6-20.

Table 6-19: Technical factors associated with \$0.07/kWh FiT regime in PH

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net tCO ₂ (kg/yr)
1 st	21.53	Battery x 5, Grid, HydroK	95	95,725	60,026	7,501	-35,979
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	96	94,995	61,198	5,216	-37,440
3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	98	93,857	62,330	2,668	-38,662
4 th	4.82	Gen10, Battery x 5, Grid, HydroK	99	93,436	62,730	1,759	-39,149

Compared with the \$0.17/kWh FiT regime, systems under the \$0.07/kWh FiT regime are generally more polluting but still present significantly less pollutant emissions figures than a conventional system. It can be observed that the 2nd system under this FiT regime produces disproportionately larger amounts of pollutants compared with the 3rd and 4th systems. This is because its ICE generator is much more active (see Figure 6-14) to maximise the sale of renewable power despite the reduced FiT.

Table 6-20: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,958	1,645	805	521	10,134
Carbon Monoxide	0	3.09	0.564	0.189	48.1
Unburned Hydrocarbons	0	0.112	0.0206	0.00688	1.75
Particulate Matter	0	0.187	0.0342	0.0114	2.92
Sulphur Dioxide	8.49	6.19	3.32	2.20	29.2
Nitrogen Oxides	4.15	6.13	2.19	1.27	62.7
Fuel Consumption (L/yr)	0	156	28.6	9.55	2,435

The DMaps in Figure 6-14 show the generator activity for Port Harcourt's optimal systems under the \$0.07/kWh FiT regime. The generator activity heat maps indicate a directly proportional relationship between the load sizes and generator usage. This indicates that renewable energy systems, even when situated in areas with high energy resources, require some form of back up to ensure reliability. Although it must be pointed out that, where there are more mixes of renewable energy components, such as under Port Harcourt's \$0.17/kWh FiT regime, the need for fossil fuel-based backups are reduced.

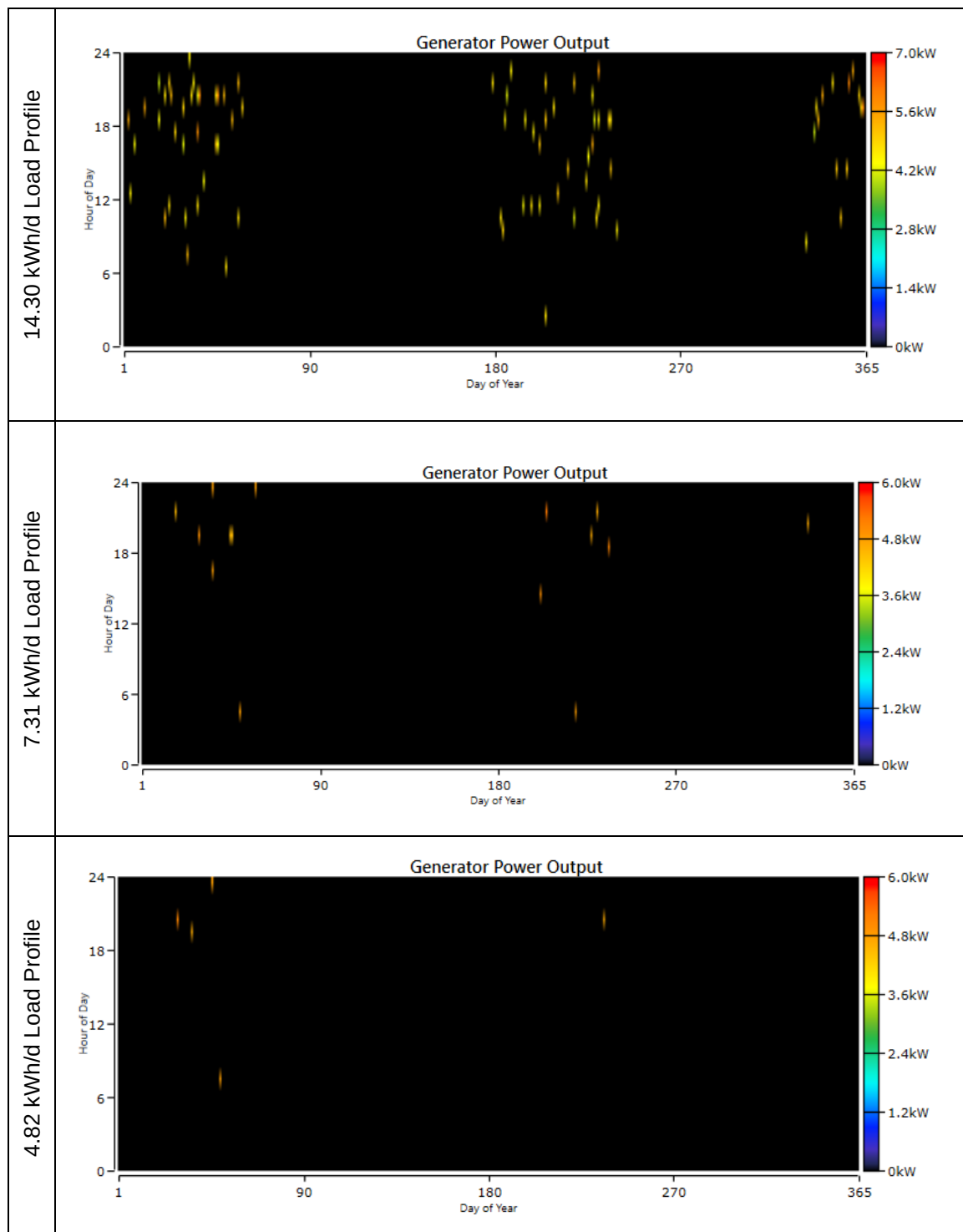


Figure 6-14: Generator outputs under \$0.07/kWh FiT regime

6.3.2.3 Systems under Port Harcourt's \$0.00/kWh FiT regime

Table 6-21 shows that Port Harcourt's 3rd and 4th optimal systems under the \$0.00/kWh FiT regime have the same mix of components. Whereas, the 1st system has a generator less than the 2nd system. Although the 1st system has no fossil fuel-based component, its renewable energy fraction is less, and its CO₂ emission profile is more than that of the 2nd system. This is because it supplies a larger load using the grid. Furthermore, the 1st system, like most other optimal systems with wholly renewable energy components, experiences instances of unmet loads when there are extended periods of grid power outage.

Table 6-21: Technical factors associated with \$0.07/kWh FiT regime in PH

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Battery x 5, Grid, HydroK	87	95,722	15,993	7,500	-8,151
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	89	94,991	17,164	5,216	-9,612
3 rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
4 th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

Nevertheless, the overall emissions profile of the 1st system, as shown in Table 6-22 show an absence of generator-related emissions. This means that the facility running the 1st system will offer the most pollutant-free environment. The other systems present pollutant emissions in proportion to their load sizes. However, the 2nd system presents a lower CO₂ emission profile due to the presence of a renewable energy component (hydrokinetic turbine) in its mix. As seen in Ibadan's zero FiT regime, optimal systems still present much lower emission factors compared with a conventional system as shown in Table 6-22.

Table 6-22: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1st	2nd	3rd	4th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,956	1,643	1,940	1,248	10,134
Carbon Monoxide	0	3.09	1.54	0.301	48.1
Unburned Hydrocarbons	0	0.112	0.0560	0.0110	1.75
Particulate Matter	0	0.187	0.0932	0.0183	2.92
Sulphur Dioxide	8.48	6.18	7.94	5.32	29.2
Nitrogen Oxides	4.15	6.13	5.43	2.90	62.7
Fuel Consumption (L/yr)	0	156	77.8	15.2	2,435

The generator activities shown in Figure 6-15 indicate that generator activity is commensurate with load size. However, the generator activity under the 2nd system indicate a level of intermittency not observable in the other two systems. This is caused by the presence of the hydrokinetic turbine in the 2nd system. The turbine provides most of the energy required during periods of heavy rainfall, the periods showing as blank in the data map for the 14.30 kWh/d profile. Overall, the 4th system presents the least generator activity due to its smaller load.

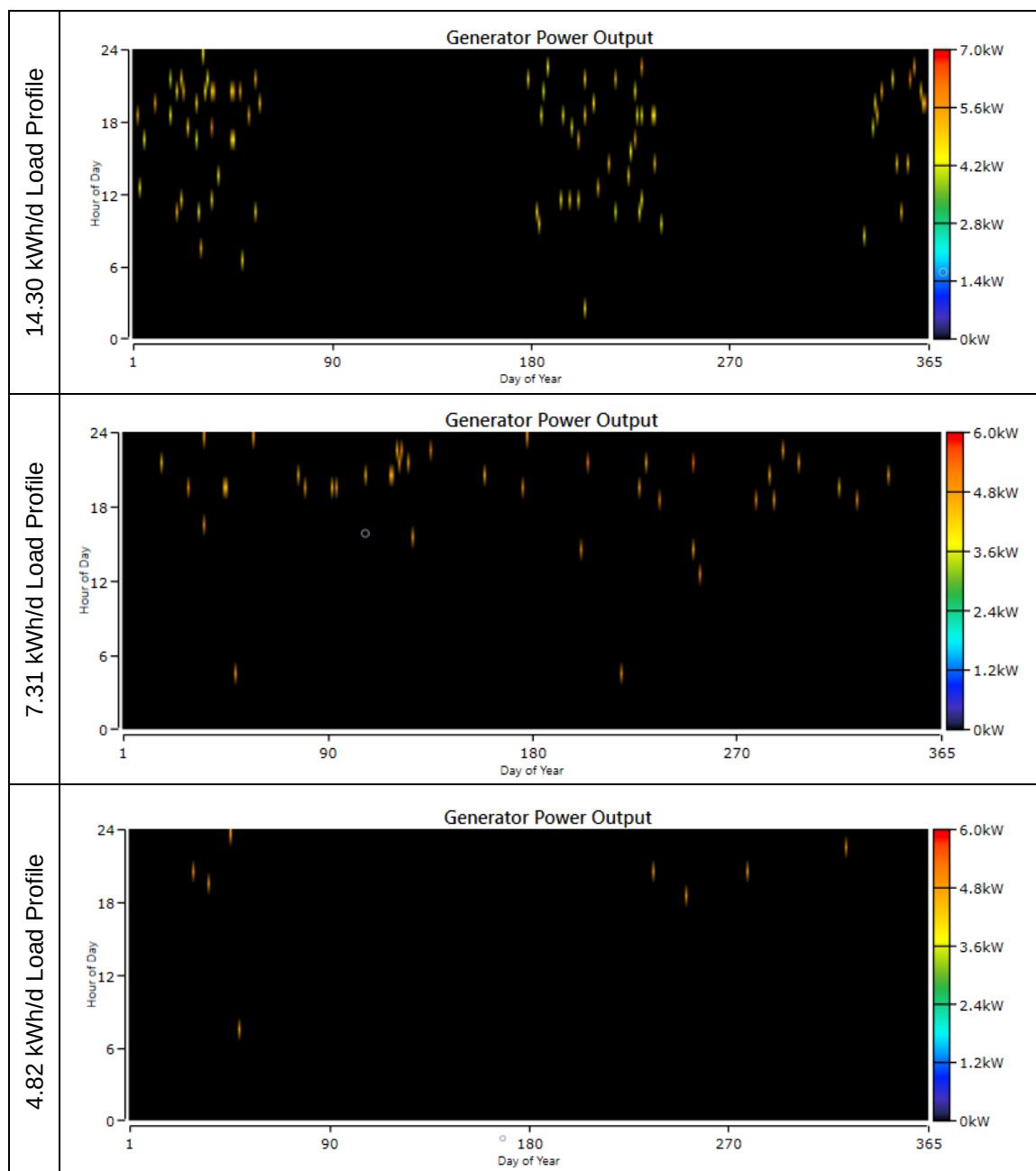


Figure 6-15: Generator outputs under \$0.00/kWh FiT regime

6.3.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Port Harcourt Systems

In Port Harcourt systems, CO₂ emissions are directly proportional load sizes and the amount of feed-in-tariff. However, unlike in Ibadan, the 1st systems with the heaviest loads present the lowest particulate matter emissions along with the 4th systems. This is because the systems are mainly cost-optimised and therefore the heavy 1st systems contain no diesel generators which are mainly responsible for PM emissions.

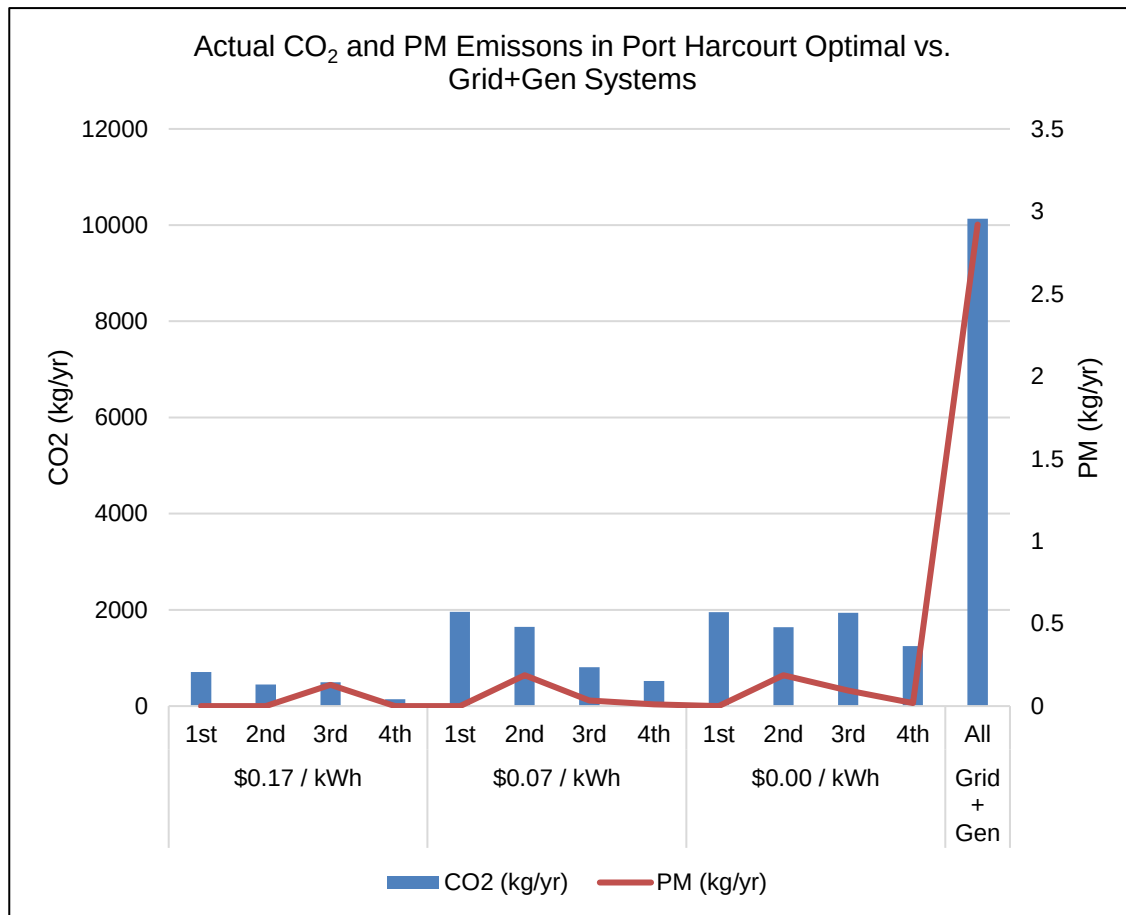


Figure 6-16: CO₂ vs. PM emissions for system configurations in Port Harcourt

Generally, emissions from the optimised systems are considerably lower than those from a conventional system as shown in Figure 6-16. The conventional system has more than 15 times the amount of PM and 5 times CO₂ emissions than the highest optimal system in Port Harcourt.

6.4 Awka (SE Nigeria) Results and Discussions

Location-specific data used in HOMER simulations for Awka such as its clearness index, daily radiation and, wind speeds are presented in Section 4.2.

For each FiT sensitivity figure modelled, 12,032 solutions were simulated. Under the \$0.17/kWh FiT regime, 9,040 were feasible while 2,992 were not. 9,596 solutions were feasible while 2,436 were infeasible under the \$0.07/kWh FiT regime. The \$0.00/kWh FiT regime produced 10,216 feasible and 1,816 infeasible solutions.

6.4.1 Costs of Optimal System Configurations for Awka

Table 6-23 below shows the costs associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Awka.

Table 6-23: Cost factors for system configurations in Awka

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1 st	21.53	PV, Grid, HydroK	-0.0882	-211,004	116,740	931	59,524
	2 nd	14.29	PV, Grid, HydroK	-0.1124	-230,752	64,900	616	52,584
	3 rd	7.31	PV, Grid, HydroK	-0.1289	-241,916	43,300	313	50,062
	4 th	4.82	PV, Grid, HydroK	-0.1317	-245,855	43,300	200	50,639
\$0.07 /kWh	1 st	21.53	Battery x 5, Grid, HydroK	-0.0284	-51,682	22,700	2,489	43,481
	2 nd	14.29	Gen10, Battery x 5, Grid, HydroK	-0.0337	-60,073	30,200	1,535	44,783
	3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	-0.0401	-69,625	30,200	907	46,079
	4 th	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0419	-72,115	30,200	606	46,539
\$0.00 /kWh	1 st	21.53	Battery x 5, Grid, HydroK	0.0581	45,911	16,750	2,486	14,572
	2 nd	14.29	Gen10, Battery x 5, Grid, HydroK	0.0543	40,807	24,250	1,532	15,873
	3 rd	7.31	Gen10, Battery x 5, Grid	0.2763	26,285	10,250	2,748	0
	4 th	4.82	Gen10, Battery x 5, Grid	0.3376	21,178	10,250	1,911	0

6.4.1.1 Costs under Awka's \$0.17/kWh FiT regime

The cost of energy for DER systems simulated under the city of Awka are the second lowest out of the six cities studied behind Port Harcourt's systems with an average system CoE of -\$0.1153 per kWh energy consumed. Awka, like Port Harcourt, enjoys a relatively high amount of precipitation annually. Like every other system modelled under the \$0.17/kWh FiT regime in every city, the CoE is negative indicating that there is a net income for every unit of energy consumed. This is due to the sale of excess energy generated. Like in every city studied under this FiT regime, the system cost of energy increases as the load sizes increase.

As shown in Table 6-23, the Net Present Cost of each system under the \$0.17/kWh FiT regime is negative over the 25-year system lifetime. This indicates a positive net present value of above \$200,000 for every system modelled for Awka over each system's lifetime. These figures are higher than in the other cities except for DER systems in Port Harcourt.

Overall, Awka presented the lowest capital costs across the DER systems modelled for the different load profiles in every city under this FiT regime except for capital cost of its 1st load profile. Under this \$0.17/kWh FiT regime, Awka's 2nd, 3rd and 4th systems' capital costs are 37%, 122% and 102% less than their respective counterparts in Port Harcourt, the other city with low system capital costs. This is largely due to the exclusion of batteries from the DER systems in Awka under \$0.17/kWh FiT regime. Since Awka does not have as high a hydro potential as Port Harcourt to provide additional energy for charging, batteries were excluded in the optimised DER systems to prevent diminishing returns of the systems due to redundant components. This inherently resulted in Awka's systems under the \$0.17 FiT regime having an average energy sold of 53,202 kWh/year compared with an average of 75,472 kWh/year across Port Harcourt's systems.

Furthermore, while all the system results for Port Harcourt under this FiT regime include 22 kW PV cells, only the 1st system in Awka has a 22 kW PV cell. The optimised DER systems for the 2nd, 3rd and 4th load profiles contain 10 kW, 5 kW and 5 kW PV cells respectively hence, contributing to the lower capital costs of these systems. These are evidences of HOMER's cost optimisation objectives.

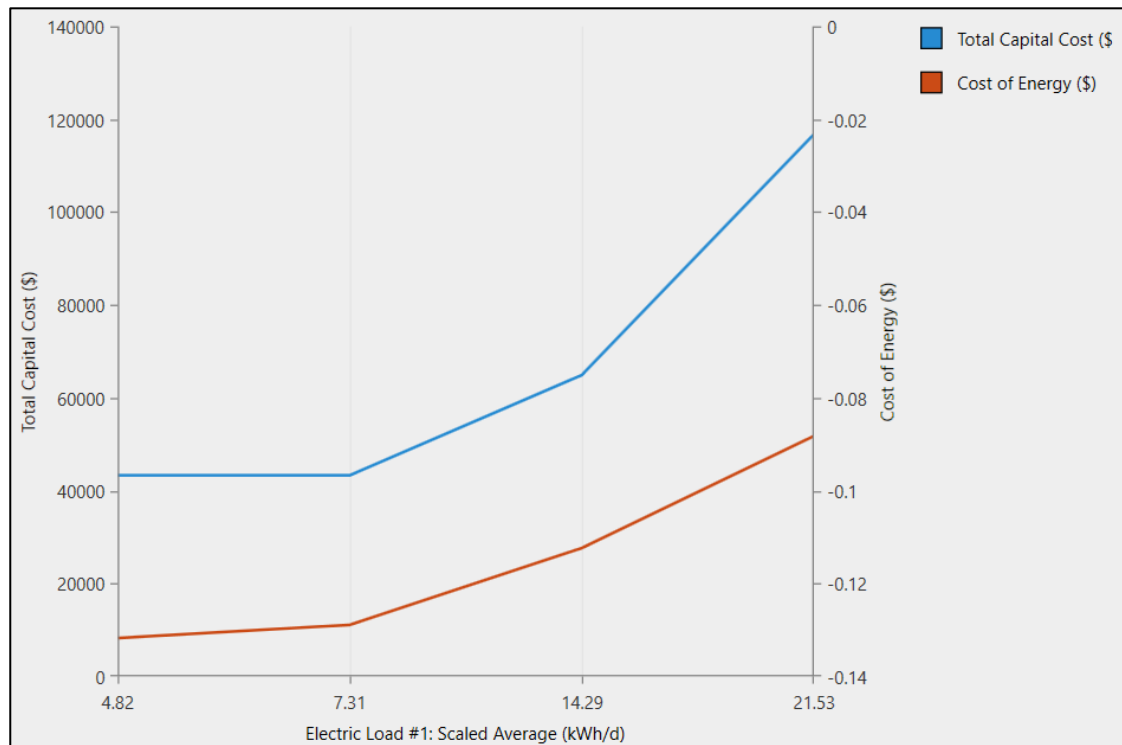


Figure 6-17: Capital cost vs. Cost of energy under \$0.17 FiT regime

Figure 6-19 shows the direct relationship between capital cost and cost of energy across all the optimised systems considered for Awka under the \$0.17 FiT regime. This is unlike the mostly inverse relationships observed between the two variables under the Ibadan and Port Harcourt systems. The obvious reason for the direct relationship between capital cost and cost of energy in Awka's optimised systems is the fact that all the systems have the same components. The only differences, as explained in the fourth paragraph above, are the sizes of the PV components in the systems for each load profile. As the sizes of the load profiles increase, the sizing of the PV modules increases and thus resulting in a direct increase in the capital cost of the systems.

6.4.1.2 Costs under Awka's \$0.07/kWh FiT regime

The general pattern of system cost figures under the \$0.07 FiT regime presented for Awka are similar to those presented for Port Harcourt. One of the differences is that the CoE for the 1st, 2nd, 3rd and 4th systems under this FiT regime are respectively higher by 33%, 22%, 17% and 16% in Awka than in Port Harcourt. Another difference is that the net present values are lower in Awka than in Port

Harcourt by 76%, 63%, 56% and 54% for the systems respectively. Average CoE in Awka's optimised systems under this FiT regime is -\$0.036/kWh compared with Port Harcourt's average of -\$0.0436/kWh of energy used. The capital costs for all the systems modelled for both Awka and Port Harcourt are the same under the \$0.07/kWh FiT regime.

Table 6-24: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	-0.0284	-51,682	22,700	2,489	43,481
	14.29	-0.0337	-60,073	30,200	1,535	44,783
	7.31	-0.0401	-69,625	30,200	907	46,079
	4.82	-0.0419	-72,115	30,200	606	46,539

It is important to note that, Awka's systems are optimised more for local energy consumption than Port Harcourt's systems which seem to be optimised more for energy sales. This is demonstrated by the larger quantities of energy purchased from the grid under Port Harcourt's systems (see Table 6-13) despite the generation and sale of more energy than the equivalent Awka systems as shown in Table 6-24 above.

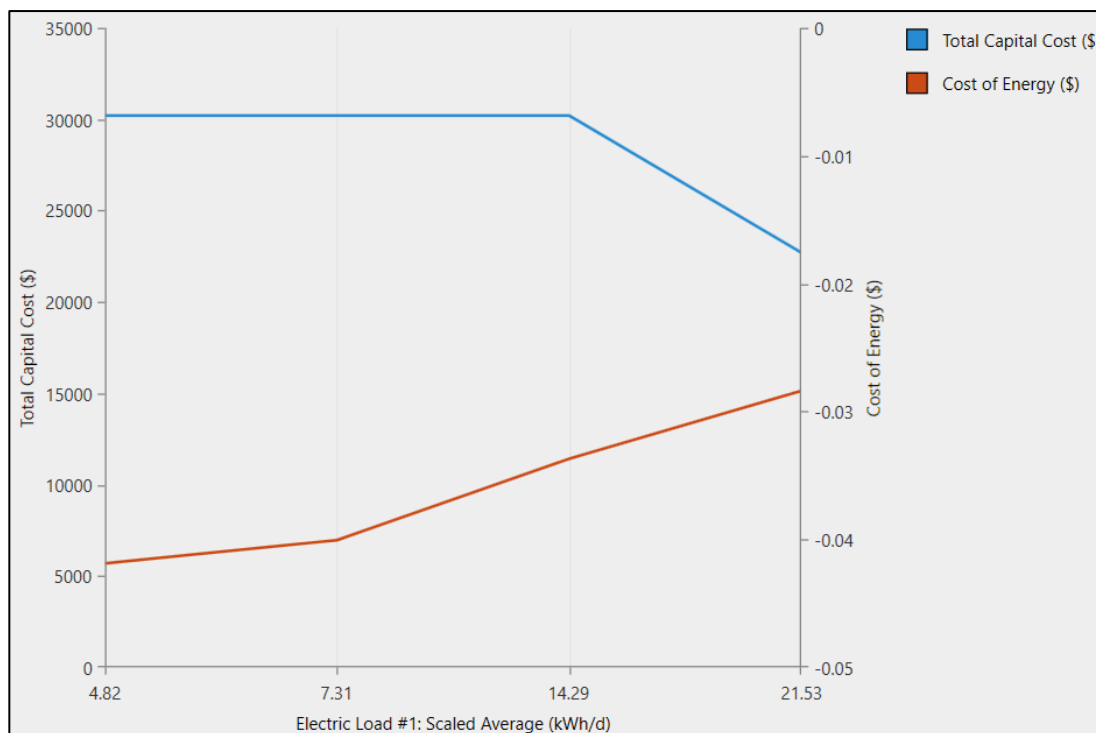


Figure 6-18: Capital cost vs. Cost of energy under \$0.07 FiT regime

Due to the inclusion of solar PV, the capital costs of the 1st, 2nd, 3rd and 4th optimised systems under the \$0.17/kWh FiT regime are 414%, 114%, 43% and 43% higher than corresponding systems under the \$0.07/kWh FiT regime in Awka. But they present higher cost of energy across all systems modelled and lower net present values than the \$0.17/kWh FiT regime systems. As shown in Figure 6-20, the system capital cost versus cost of energy analysis for Awka's \$0.07/kWh FiT regime is similar to that of Port Harcourt's \$0.07/kWh FiT regime (Figure 6-10) except for Awka's higher costs of energy for each of the optimal systems.

Table 6-25: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Awka (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	-0.0284	0.488	-51,682	136,632	-2,086	3,621	22,700	7,500
14.3	-0.0337	0.7	-60,073	130,171	-2,531	3,440	30,200	7,500
7.31	-0.0401	1.3	-69,625	123,944	-2,799	3,265	30,200	7,500
4.82	-0.0419	1.94	-72,115	121,722	-2,869	3,203	30,200	7,500

The analysis of figures from Table 6-25 reveals that the optimal system for the 1st load profile under the \$0.07/kWh FiT regime presented cost savings of \$0.5164/kWh (1,818%), \$188,314 (364%), and \$5,707 (274%) on the cost of energy, net present cost and annual operating cost respectively over a conventional system for the same load profile. These savings are achieved with additional capital cost of \$15,200 over the conventional system which, can be recovered from operating cost savings of 2 years and 8 months.

6.4.1.3 Costs under Awka's \$0.00/kWh FiT regime

The costs associated with optimised systems modelled under the \$0.00/kWh FiT regime for Awka are similar to the ones generated under the same FiT regime for Port Harcourt. These have been discussed under Section 6.3.1.3 above. The few differences between the results for both cities are discussed in this section.

The CoE for systems optimised for the 3rd and 4th load profiles for both cities are the same. CoE figures for the 1st and 2nd systems for Port Harcourt and Awka are different by a few thousandths of a dollar per kWh as shown in Table 6-15 and Table 6-26 respectively. This trend is also found in the NPC figures. However, the capital costs for systems under the zero FiT regime for both cities are the same.

Table 6-26: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.00/kWh	21.53	0.0581	45,911	16,750	2,486	14,572
	14.29	0.0543	40,807	24,250	1,532	15,873
	7.31	0.2763	26,285	10,250	2,748	0
	4.82	0.3376	21,178	10,250	1,911	0

Another set of differences between Awka and Port Harcourt model results under the \$0.00/kWh FiT regime is the energy purchased-energy sold element. As mentioned under Section 6.4.1.2 Costs under Awka's \$0.07/kWh FiT regime, Port Harcourt systems are optimised mainly to promote excess energy generation for sale while Awka systems are optimised mainly to satisfy local energy demand. This is also reflected in the 1st and 2nd systems under the zero FiT regime where Awka presents less amount of electrical energy purchased from the grid and sold (or

wasted in this case since FiT is zero) compared with Port Harcourt systems (see Table 6-15).

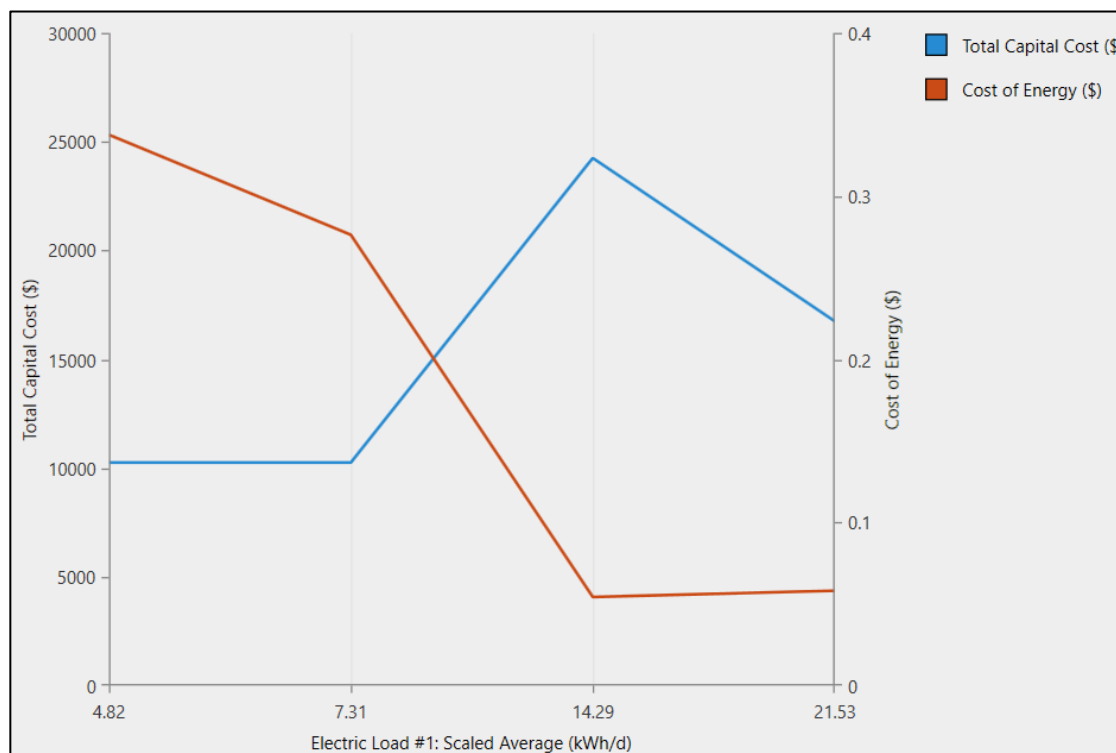


Figure 6-19: Capital cost vs. Cost of energy under \$0.00 FiT regime

Figure 6-19 shows the charting of capital costs versus costs of energy for optimised systems under the zero FiT regime in Awka. This is almost identical to the corresponding chart for Port Harcourt with the indiscernible differences only in the position of the CoE lines for the 1st and 2nd systems.

Table 6-27: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Awka (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0581	0.488	45,911	136,632	818	3,621	16,750	7,500
14.3	0.0543	0.7	40,807	130,171	464	3,440	24,250	7,500
7.31	0.2763	1.3	26,285	123,944	450	3,265	10,250	7,500
4.82	0.3376	1.94	21,178	121,722	306	3,203	10,250	7,500

Table 6-27 shows that an optimised system for the 1st load profile under the \$0.00/kWh FiT regime present cost advantages over a conventional system as

follows: \$0.4299/kWh (740%) less cost of energy; \$90,721 (198%) less NPC; and \$2,803 (343%) less annual operating cost. Whereas, the capital cost of the conventional system is only a \$9,250 (55%) decrease of the 1st optimal system. Nevertheless, it is important to note that this additional capital cost can be prohibitive in many resource-constrained settings around the world. These figures are similar to those obtained for Port Harcourt under the same FiT regime.

6.4.1.4 Capital Cost and Cost of Energy Comparison between all Awka Systems

The systems under the \$0.07/kWh FiT regime and \$0.00/kWh FiT regime for both Port Harcourt (see Figure 6-11) and Awka (see Figure 6-20 below) presented similar figures and trends in the analysis of their capital cost versus cost of energy. However, the optimised systems under \$0.17/kWh FiT regime in Awka present generally more attractive capital costs (average of \$67,070) than those in Port Harcourt (average of \$90,325) for slightly higher cost of energy (difference of \$0.0025/kWh). Although it is important to point out that, spread over a 25-year period, these slightly higher cost of unit energy add up to make the Port Harcourt systems have lower net present costs or higher net present values.

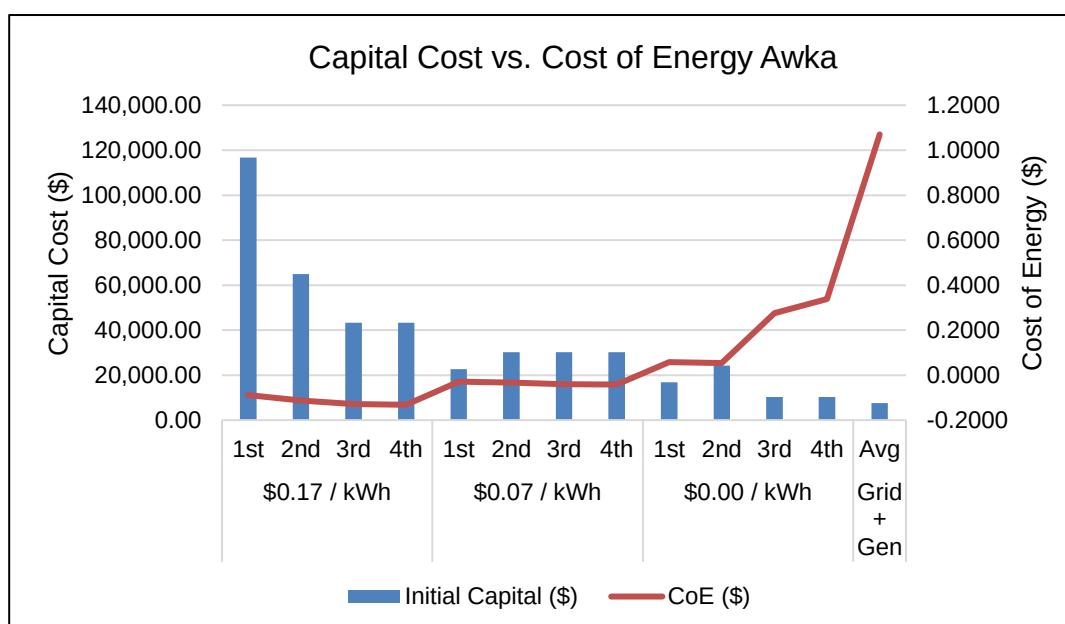


Figure 6-20: Capital cost vs CoE for system configurations in Awka

6.4.2 System and Emission Factors of Optimal System Configurations for Awka

Table 6-28 below shows the technical variables associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Awka.

Table 6-28: Technical factors for system configurations in Awka

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Grid, HydroK	99	96,760	59,524	7,539	-37,031
	2nd	14.30	PV, Grid, HydroK	99	81,802	52,584	5,006	-32,844
	3rd	7.31	PV, Grid, HydroK	99	75,397	50,062	2,561	-31,441
	4th	4.82	PV, Grid, HydroK	100	75,284	50,639	1,691	-31,878
\$0.07 /kWh	1st	21.53	Battery x 5, Grid, HydroK	95	71,472	43,481	7,582	-25,907
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	96	70,836	44,783	5,216	-27,333
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	98	69,943	46,079	2,668	-28,549
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	99	69,614	46,539	1,759	-29,030
\$0.00 /kWh	1st	21.53	Battery x 5, Grid, HydroK	89	71,469	14,572	7,582	-7,638
	2nd	14.30	Gen10, Battery x 5, Grid, HydroK	91	70,833	15,873	5,216	-9,064
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
	4th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

6.4.2.1 Systems under Awka's \$0.17/kWh FiT regime

Awka's optimised systems under the \$0.17/kWh FiT regime contain the same mix of DERs. This is responsible for the similar percentages of renewable fraction in the energy produced by each system as shown in Table 6-28. It is also important to note that the absence of a diesel generator in any of Awka's systems is responsible for zero emissions under fossil fuel-based pollutants shown in Table 6-29. All actual emissions presented are directly proportional to the amount of electrical load in each system. Awka's net CO₂ emission savings of between 31,878 and 37,031 kg/year are the second highest of all the optimised system solutions simulated (see Section 4.4.3 for CO₂ emission savings description).

Table 6-29: \$0.17 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	588	389	198	126	10,134
Carbon Monoxide	0	0	0	0	48.1
Unburned Hydrocarbons	0	0	0	0	1.75
Particulate Matter	0	0	0	0	2.92
Sulphur Dioxide	2.55	1.69	0.858	0.547	29.2
Nitrogen Oxides	1.25	0.826	0.419	0.267	62.7
Fuel Consumption (L/yr)	0	0	0	0	2,435

Table 6-29 shows that no fuel was consumed in any of the Awka systems generated under the \$0.17/kWh FiT regime. The lack of fuel-associated emissions adds to the benefits of having a microgrid in Awka over deploying a conventional system of grid power and a diesel generator. The emissions figures presented under the optimal systems are emissions associated with grid power used by the loads in the systems.

6.4.2.2 Systems under Awka's \$0.07/kWh FiT regime

Except for the 1st system, every optimal system under the \$0.07/kWh FiT regime in Awka contains a 10 kWh ICE generator, a bank of five 1 kWh batteries and a hydrokinetic turbine. The composition of each system under Awka's \$0.07/kWh FiT regime is the same as its counterpart under Port Harcourt's \$0.07/kWh FiT regime. The only difference between optimised system solutions in Awka and Port Harcourt is that the hydrokinetic turbines in Port Harcourt's systems produce more energy per year. This is because of the city's higher hydro potential than Awka.

Table 6-30: Technical factors associated with \$0.07/kWh FiT regime in Awka

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Battery x 5, Grid, HydroK	95	71,472	43,481	7,582	-25,907
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	96	70,836	44,783	5,216	-27,333
3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	98	69,943	46,079	2,668	-28,549
4 th	4.82	Gen10, Battery x 5, Grid, HydroK	99	69,614	46,539	1,759	-29,030

Nevertheless, Awka systems under this FiT regime generally produce less emissions because they generate less energy overall than Port Harcourt systems. Port Harcourt's systems prioritise energy sale when a feed-in-tariff is available. Consequently, the responsibility of charging the energy storage system (batteries) is left mostly with the grid, and the generator where present. The nature of Awka systems' emission figures (Table 6-31) in relation to each other are similar to those in Port Harcourt (Table 6-20). However, there are differences in the operations of the generators in both cities

Table 6-31: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,573	1,286	627	408	10,134
Carbon Monoxide	0	2.39	0.408	0.190	48.1
Unburned Hydrocarbons	0	0.0871	0.0149	0.00693	1.75
Particulate Matter	0	0.145	0.0247	0.0115	2.92
Sulphur Dioxide	6.82	4.84	2.59	1.71	29.2
Nitrogen Oxides	3.34	4.77	1.68	1.03	62.7
Fuel Consumption (L/yr)	0	121	20.6	9.62	2,435

Comparing the generator output figures under Awka with Port Harcourt systems show that the generators in Port Harcourt (see Figure 6-14) are more active. The DMaps in Figure 6-21 show less generator activity during mid-year months for Awka than for Port Harcourt. This is because Awka systems are less prioritised for excess energy sales. Therefore, the renewable energy generated is used mostly onsite, reducing the need to depend on the ICE generator when the grid is offline.

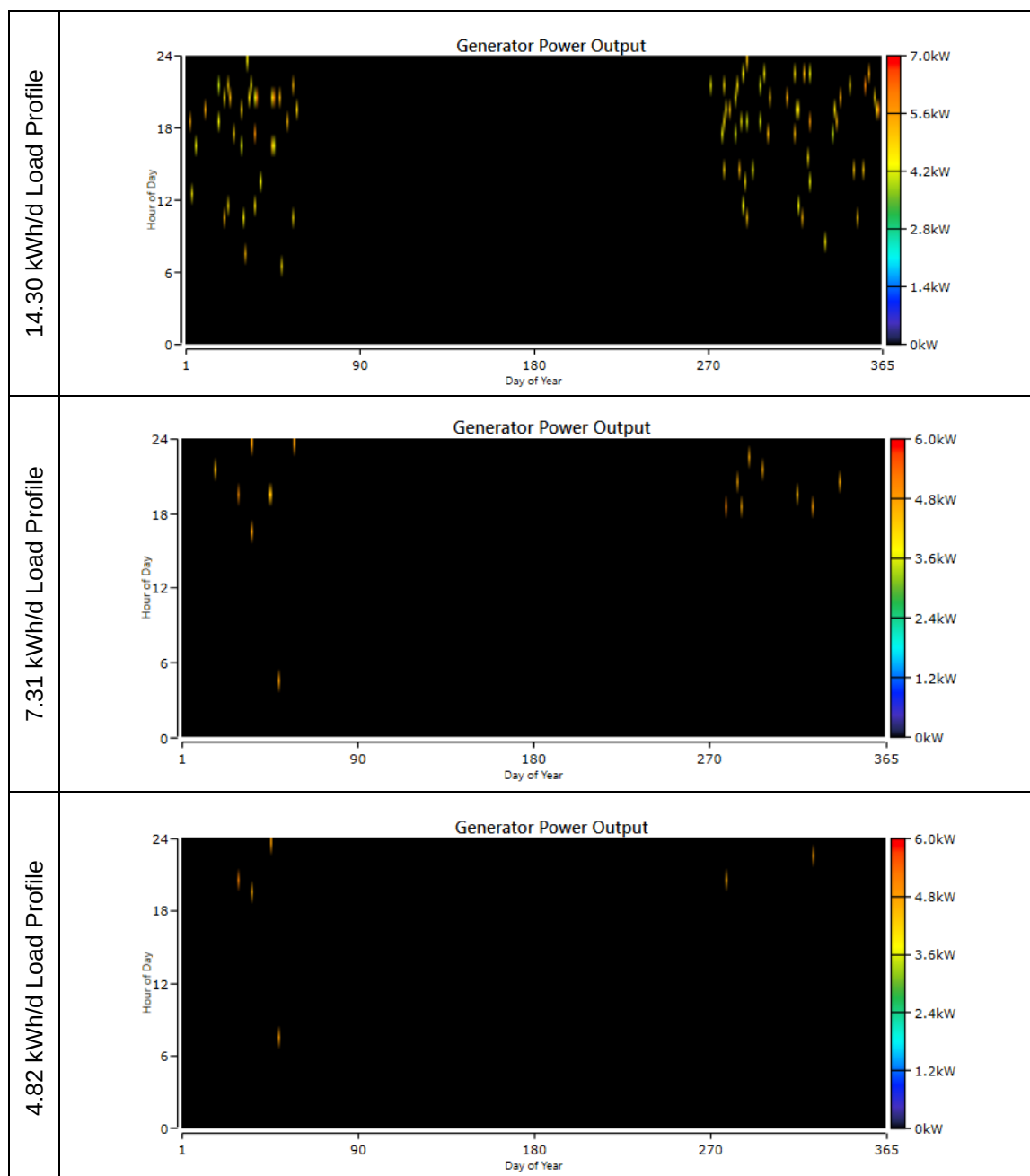


Figure 6-21: Generator outputs under \$0.07/kWh FiT regime

6.4.2.3 Systems under Awka's \$0.00/kWh FiT regime

Like the Port Harcourt systems under this FiT regime, the 3rd and 4th Awka optimal systems have the same units of power generation components. The 1st Awka system is also a generator less than the components in the city's 2nd system, same as in Port Harcourt. The effect of these is that, the systems under Awka present similar characteristics with the earlier discussed Port Harcourt systems in Section 6.3.2.3.

Table 6-32: Technical factors associated with \$0.00/kWh FiT regime in Awka

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Battery x 5, Grid, HydroK	89	71,469	14,572	7,582	-7,638
2 nd	14.30	Gen10, Battery x 5, Grid, HydroK	91	70,833	15,873	5,216	-9,064
3 rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
4 th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

Despite the similarities between optimised DER systems in Awka and Port Harcourt, it is important to note the few differences they present. First, the 1st and 2nd systems under the zero FiT regimes present different emission figures with the Port Harcourt systems producing more emissions. Although it is worth noting that the 3rd and 4th systems in the two cities under present the same emissions figures throughout.

Table 6-33: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,571	1,284	1,940	1,248	10,134
Carbon Monoxide	0	2.39	1.54	0.301	48.1
Unburned Hydrocarbons	0	0.0871	0.0560	0.0110	1.75
Particulate Matter	0	0.145	0.0932	0.0183	2.92
Sulphur Dioxide	6.81	4.84	7.94	5.32	29.2
Nitrogen Oxides	3.33	4.77	5.43	2.90	62.7
Fuel Consumption (L/yr)	0	121	77.8	15.2	2,435

The second difference between the modelled systems under the zero FiT regime for Awka and Port Harcourt is the lower generator operation in Awka's 2nd system (see Figure 6-22 for Awka and Figure 6-15 for Port Harcourt). This is responsible for Awka's 2nd system presenting less pollutant emissions than in Port Harcourt.

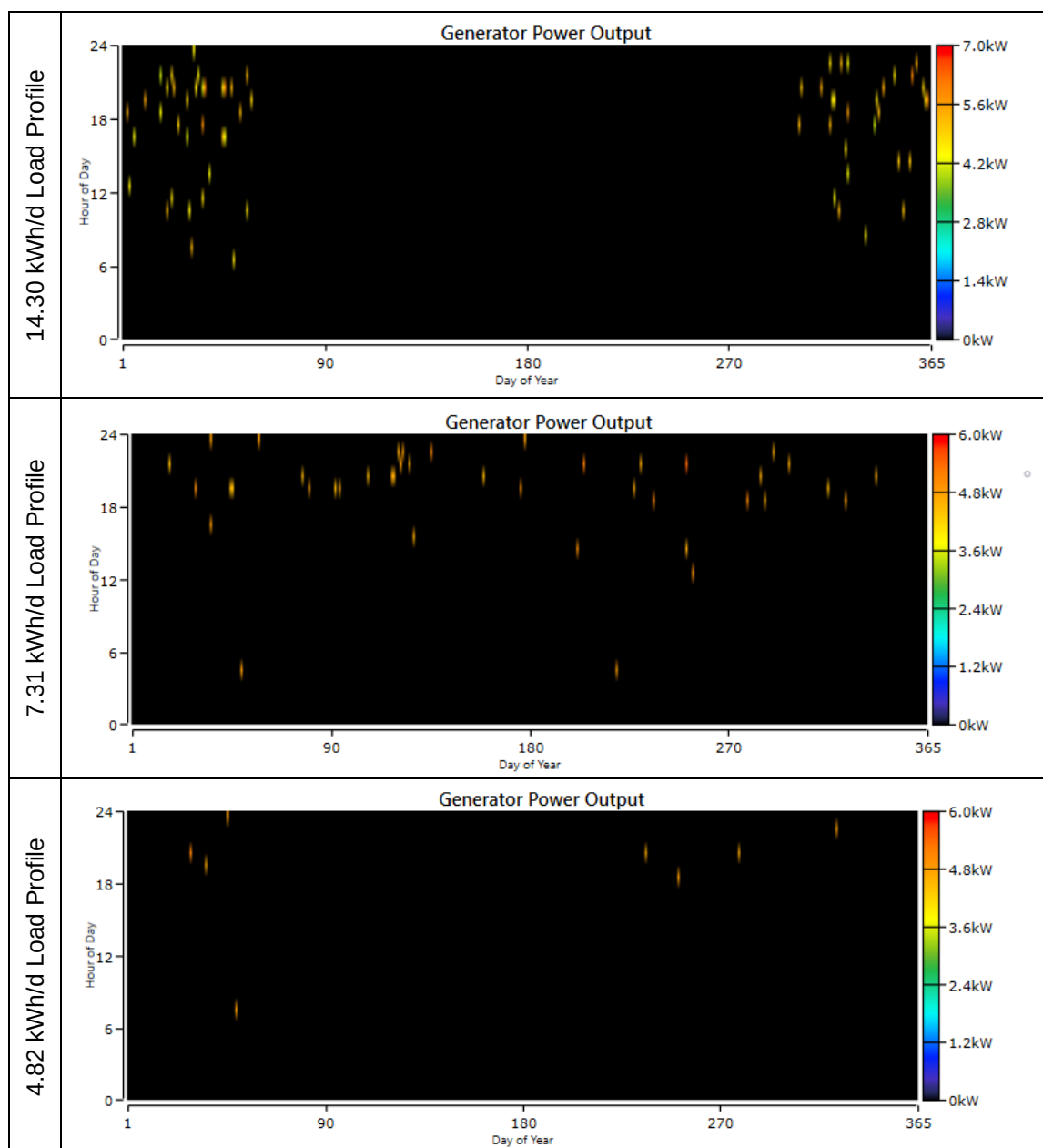


Figure 6-22: Generator outputs under \$0.00/kWh FiT regime

6.4.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Awka Systems

CO₂ emissions are generally directly proportional to load sizes under Awka's optimal systems. For particulate matter emissions, the 2nd systems under the \$0.07/kWh and \$0.00/kWh FiT regimes presented higher levels of PM emissions

than their heavier-load-bearing 1st systems as shown in Figure 6-23. This is because the 2nd systems under the two FiT regimes contain diesel generator components whereas, the 1st systems do not. The 3rd and 4th Awka systems present similar pollutant emission figures to their Port Harcourt counterparts under the zero FiT regime.

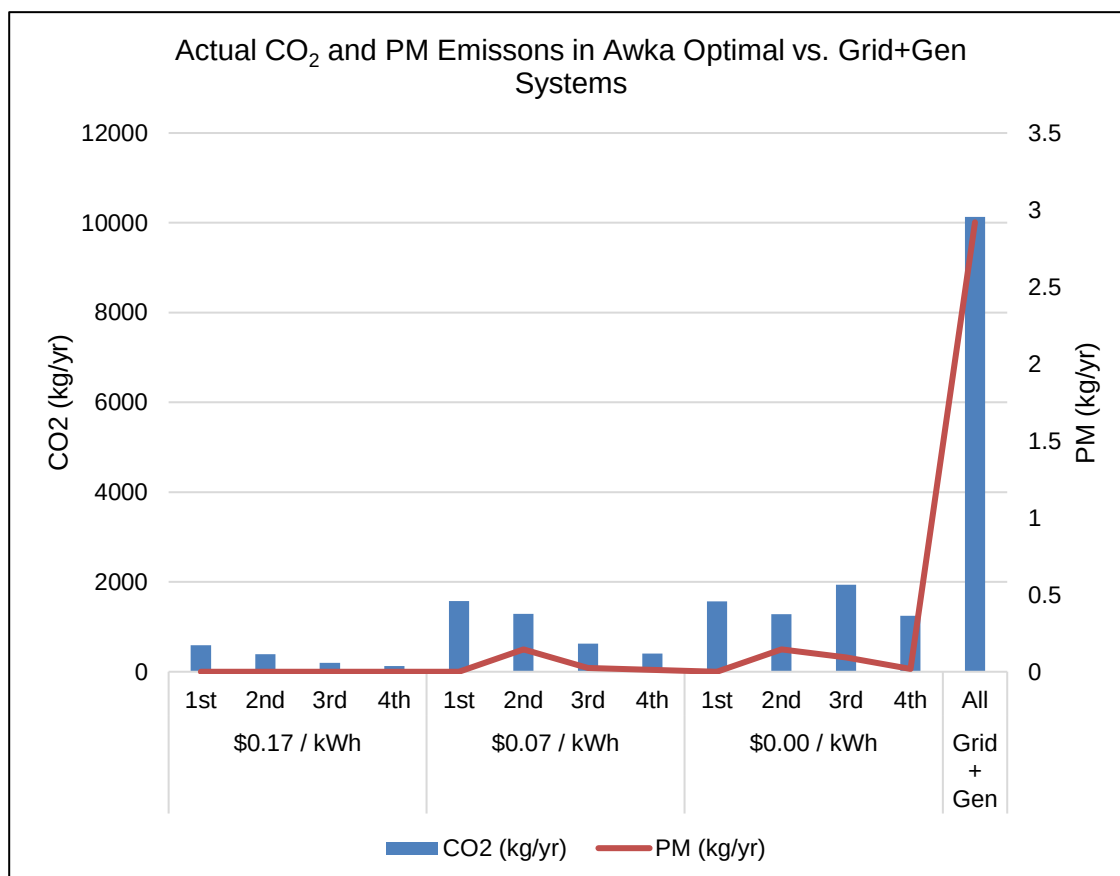


Figure 6-23: CO₂ vs. PM emissions for system configurations in Awka

Like in the other city systems, the optimal system's levels of emissions in Awka present more environment-friendly results than those of a conventional system.

6.5 Abuja (NC Nigeria) Results and Discussions

Like the other cities, 12,032 solutions in total were modelled for each FiT regime sensitivity for Abuja. Under the \$0.17/kWh FiT regime, 8,088 of these were feasible while 3,944 were infeasible due to capacity shortage constraint. For the \$0.07/kWh FiT regime, 8,840 solutions were feasible while 3,192 were infeasible. Whereas, the \$0.00/kWh FiT regime produced 9,772 feasible and 2,260 infeasible solutions. It is important to note that differences in feasibility of solutions presented for each city are caused by variations in each city's weather conditions and ability to produce natural energy resources.

6.5.1 Costs of Optimal System Configurations for Abuja

Table 6-34 shows the costs associated with the optimised system configurations for the four load profiles under the three FiT regimes considered in the city of Abuja, Nigeria.

Table 6-34: Cost factors for system configurations in Abuja

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	-0.0330	-57,109	117,740	6,288	40,999
	2nd	14.29	PV, Battery x 5, Grid, HydroK	-0.0484	-76,924	117,740	1,031	39,628
	3rd	7.31	PV, Battery x 5, Grid, HydroK	-0.0564	-87,913	117,740	506	41,105
	4th	4.82	PV, Battery x 5, Grid, HydroK	-0.0594	-91,725	117,740	329	41,633
\$0.07 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	0.0294	26,985	30,200	4,076	17,875
	2nd	14.29	Battery x 5, Grid, HydroK	0.0165	13,916	22,700	3,070	18,657
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	0.0021	1,664	30,200	1,576	19,471
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0030	-2,315	30,200	1,112	19,764
\$0.00 /kWh	1st	21.53	Battery x 10, Grid	0.2224	59,820	3,750	8,208	0
	2nd	14.29	Gen10, Battery x 5, Grid	0.2394	44,532	10,250	4,737	0
	3rd	7.31	Gen10, Battery x 5, Grid	0.2813	26,764	10,250	2,689	0
	4th	4.82	Gen10, Battery x 5, Grid	0.3324	20,851	10,250	1,915	0

6.5.1.1 Costs under Abuja's \$0.17/kWh FiT regime

Model results for Abuja under the \$0.17/kWh FiT regime show that the same type, number and sizing of energy producing components are included in each of the DER system modelled for all the load profiles. Kano also produced the same number and sizing of components. It is noteworthy that the optimal systems for Ibadan's 1st and 2nd load profiles under the \$0.17/kWh FiT regime contain the same type, quantity and sizing of components as all of Abuja's systems under the same FiT regime.

However, Abuja's optimised systems produced lower net present costs than in Ibadan that is, 56%, 53%, 44% and 41% reductions across 1st, 2nd, 3rd and 4th systems respectively. Abuja also presented an average CoE of -\$0.0493/kWh while Ibadan has an average CoE of -\$ 0.0309/kWh of energy used. This is largely due to Abuja's clearer skies than Ibadan. This allows for a greater solar potential in Abuja than in Ibadan despite the latter city enjoying higher average monthly temperatures. Clearer skies allow Abuja, like the other northern cities, to enjoy an overall high clearness index resulting in higher solar global horizontal irradiance which is more useful for solar electricity generation than heat (see Section 4.2.2 Resources).

Solar components in Abuja's systems under the \$0.17/kWh FiT regime produced an average of 32,600 kWh/year, the second highest after Kano's (see Appendix H for PV outputs). Although, Yola has a higher solar potential than Abuja, it must be pointed out that Abuja's optimised systems achieved a slightly higher PV output than Yola's because they had more PV modules with Abuja's PV capital cost at \$95,040 for each system and Yola costing \$66,000 for each system. Abuja presents the fourth best overall CoE, better than Yola and Ibadan but bested by Port Harcourt, Awka and Kano. Abuja enjoys a better hydro and solar potential than Ibadan, but Yola and Kano have better solar potentials. Whereas, Port Harcourt and Awka present much better hydro potential than Abuja.

Figure 6-27 shows the relationship between capital cost and cost of energy for Abuja's systems under the \$0.17/kWh FiT regime. The capital cost is constant while the CoE is directly proportional to the load size, that is, the cost of energy increases as the load increases. This is because the bigger the load size, the less

energy is available to sell off to subsidise the cost of energy consumed by the loads. Like the CoE results presented in the other cities under the \$0.17/kWh FiT regime, Abuja experiences a negative NPC indicating net income for every unit energy used by the facility due to the feed-in-tariff paid for excess energy generated.

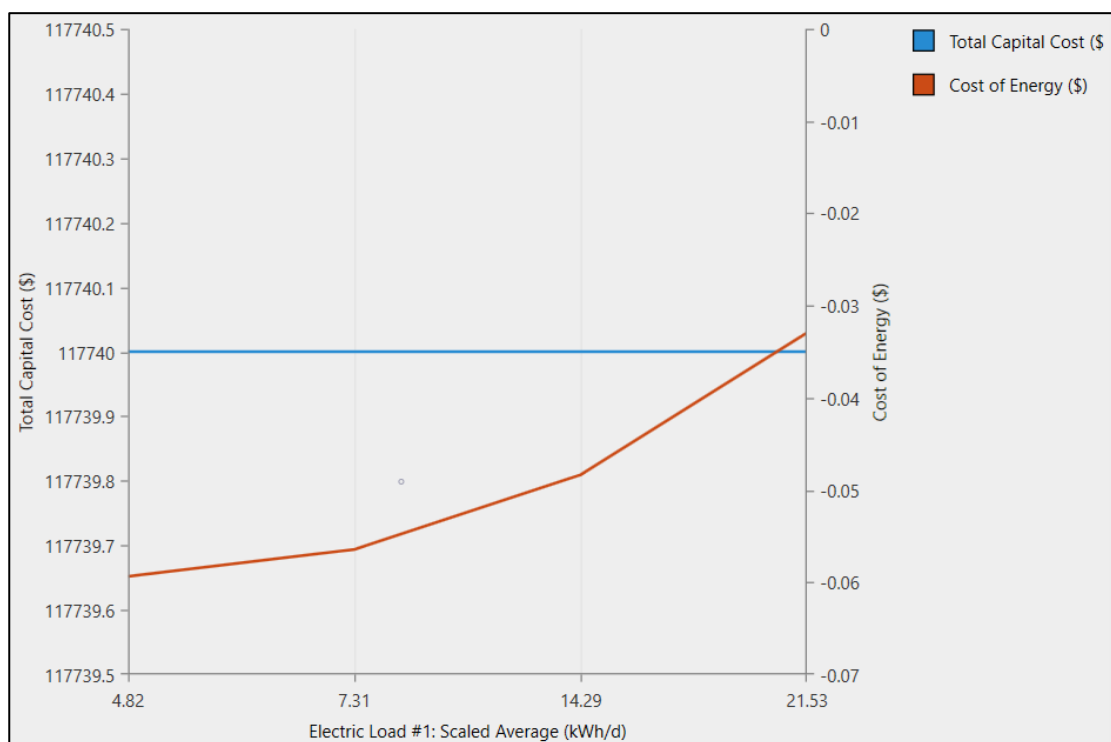


Figure 6-24: Capital cost vs. Cost of energy under \$0.17 FiT regime

The uniformity of components and their capital cost in Abuja's systems under the \$0.17/kWh FiT regime will make the job of decision makers easier by providing the opportunity to choose a system entirely based on long-term financial considerations. All the modelled systems can provide all the power required to run the entire suite of devices in the health facility. Only the potential for income will be affected based on the amount of electrical power used by the facility.

6.5.1.2 Costs under Abuja's \$0.07/kWh FiT regime

Only the optimised system for the 4th load profile under Abuja's \$0.07/kWh FiT regime produced a negative net present cost. Unlike all the southern Nigerian cities that produced income generating optimal systems under the \$0.07/kWh FiT regime, all the optimised systems for northern cities presented positive net present costs except the system for the 4th load profile in Abuja. The obvious reason for

this is the much lower level of precipitation found in northern Nigeria compared with the south.

Nevertheless, Abuja, a central northern city in Nigeria, experiences higher precipitation levels than many other northern cities as shown in Figure 4-14. This is the reason for the 4th and lowest load profile in Abuja presenting a system with negative NPC under the \$0.07/kWh FiT regime. It is important to note that the hydrokinetic turbine outputs for the northern cities are zero in the first and last quarter of the year due to low water flow speeds caused by reduced rainfall. This is a case of forced redundancy in the hydrokinetic turbine component of the systems for half of the year in the northern cities.

Table 6-35: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	0.0294	26,985	30,200	4,076	17,875
	14.29	0.0165	13,916	22,700	3,070	18,657
	7.31	0.0021	1,664	30,200	1,576	19,471
	4.82	-0.0030	-2,315	30,200	1,112	19,764

As shown in Table 6-35, the capital cost of optimised systems in Abuja under this FiT regime are similar to those of Port Harcourt (Table 6-13) and Awka (Table 6-24). The main difference between Abuja and the other two cities is that the capital cost and component composition of the systems in Abuja's 1st and 2nd systems have been swapped over compared with those in Port Harcourt and Awka (see the *Components* columns in Table 6-12, Table 6-23, and Table 6-34). Consequently the diesel generator is omitted from Abuja's 2nd system, driving down its capital cost, instead of the 1st load profile's system in the other two cities.

Figure 6-36 shows a mixed relationship between capital cost and cost of energy in the systems generated for the load profiles considered for Abuja under the \$0.07/kWh FiT regime. The CoE for the systems are generally above zero except for the 1st load profile. Also, capital costs are the same at \$30,200 for all power systems except for the system for the 2nd load profile. Overall, the cost of energy tends to rise as the load sizes increase. The generator was exempted from the 2nd

load profile's system to reduce capital and operating costs. This makes the 2nd system relatively attractive both in the short and long term. However, this will result in some minor unmet loads during the dry season in Abuja when the hydrokinetic turbine is no longer able to generate power and there are extended power outages.

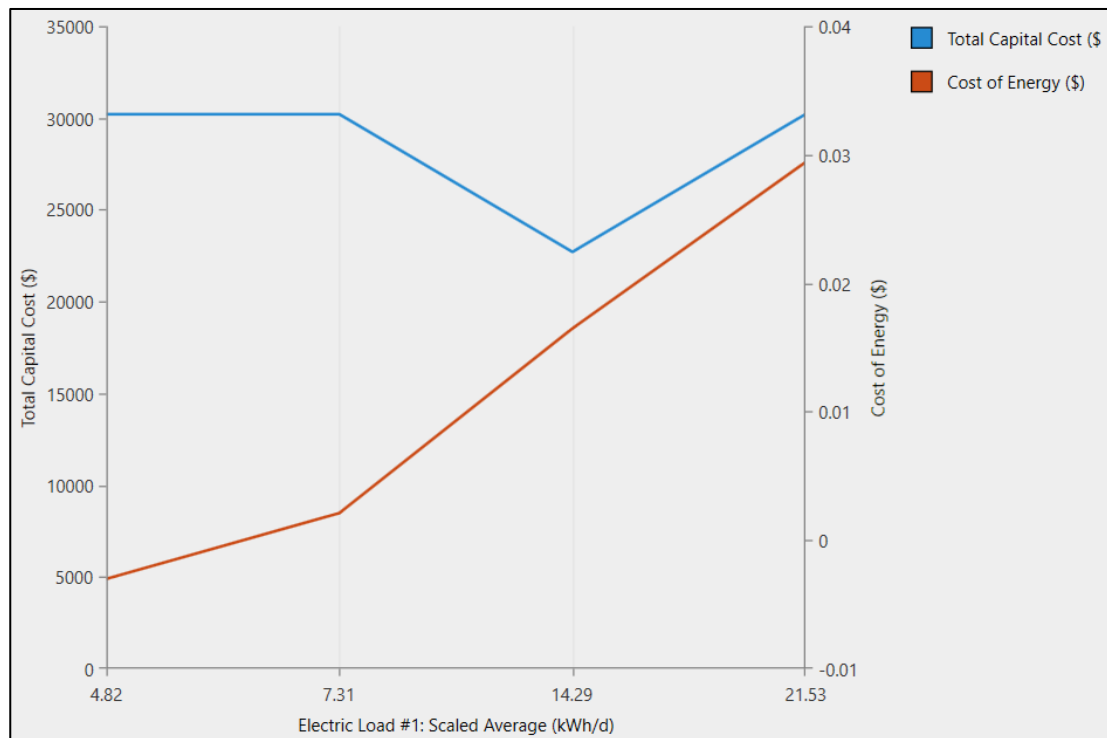


Figure 6-25: Capital cost vs. Cost of energy under \$0.07 FiT regime

The analysis of the differences between the costs associated with the optimised system and conventional system for the 1st load profile, presented in Table 6-36, shows that the optimised system is better by \$0.4586 per kWh in cost of energy, \$109,647 in net present cost and \$3,711 in annual operating cost. The overall average CoE of optimised systems is \$0.0112/kWh while the average CoE for the conventional systems is \$1.107/kWh under this FiT regime.

However, the conventional system presented a capital cost that is lower by \$22,700. It is noteworthy to point out that these figures, including the capital cost, are even better when comparing the conventional system with the 2nd load profile's optimised system. Furthermore, the 4th and the least load profile presents the only scenario where income is generated from excess energy produced.

Table 6-36: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Awka (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0294	0.488	26,985	136,632	-90	3,621	30,200	7,500
14.3	0.0165	0.7	13,916	130,171	-246	3,440	22,700	7,500
7.31	0.0021	1.3	1,664	123,944	-800	3,265	30,200	7,500
4.82	-0.0030	1.94	-2,315	121,722	-912	3,203	30,200	7,500

6.5.1.3 Costs under Abuja's \$0.00/kWh FiT regime

All the systems produced for Abuja under the zero FiT regime present positive CoEs and NPCs, like in the other cities under the same FiT regime. The removal of financial incentive in the form of feed-in-tariff to generate onsite energy for income means none of the systems under this FiT regime contains a renewable energy component. Hence, there is no excess energy produced by the systems under the *Energy Sold* column in Table 6-37 for all the systems modelled under the zero FiT regime in Abuja.

Table 6-37: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.00/kWh	21.53	0.2224	59,820	3,750	8,208	0
	14.29	0.2394	44,532	10,250	4,737	0
	7.31	0.2813	26,764	10,250	2,689	0
	4.82	0.3324	20,851	10,250	1,915	0

Unlike the systems under the zero FiT regime from other cities, Abuja's optimised systems show a trend of increasing cost of energy as the load sizes reduce as shown in Figure 6-29. This is largely due to capacity wastages from additional energy produced by the ICE generators for the smaller sized loads. Nevertheless, the smaller loads present lower annual operating costs and less NPC over the lifetime of the systems. It is important to note that the optimised system for the 1st load profile under this FiT regime is the only system across all the cities that

contains only one DER component, a bank of ten batteries, in addition to the grid (see Table 6-34).

Every other system under the zero FiT regime for Abuja has an additional ICE generator but, with a bank of only five batteries each. This is the cause of the uniform capital cost for the 2nd, 3rd and 4th systems. The 1st load profile's system for Abuja under the \$0.00/kWh FiT regime has the least capital cost, at \$3,750 only, of all the systems modelled in this study. However, it also has the highest net present cost, at \$59,820, over the 25-year lifetime of the systems. This is because of the need to regularly maintain and change the bank of ten batteries every 3 years or less, due to the total reliance on the batteries for power when there are grid outages. Furthermore, the system is prone to instances of unmet loads during extended grid outages.

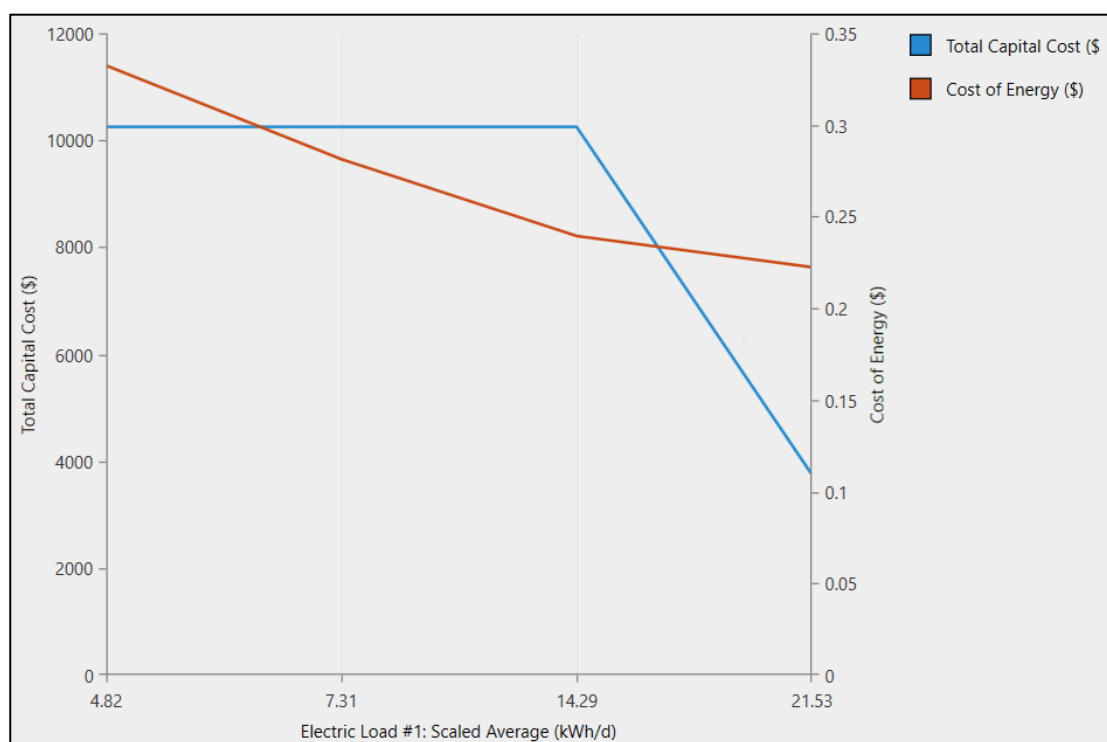


Figure 6-26: Capital cost vs. Cost of energy under \$0.00 FiT regime

Table 6-38 shows the comparisons between the costs associated with optimal systems and conventional systems for the different load profiles in Abuja under the \$0.00/kWh FiT regime. The optimised system for the 1st load profile presented cost advantages over the corresponding conventional system as follows: CoE is less by \$0.2656/kWh; NPC is less by \$76,812 over 25 years; annual operating cost is reduced by \$2,049; and even the capital cost is less by \$3,750. It is imperative to

point out that only the 1st load profile presented a lower capital cost than its corresponding conventional system. Each of the other systems presented a capital cost that is higher by \$2,750 than the capital cost of its corresponding conventional system.

Table 6-38: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Awka (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.2224	0.488	59,820	136,632	1,572	3,621	3,750	7,500
14.3	0.2394	0.7	44,532	130,171	961	3,440	10,250	7,500
7.31	0.2813	1.3	26,764	123,944	463	3,265	10,250	7,500
4.82	0.3324	1.94	20,851	121,722	297	3,203	10,250	7,500

6.5.1.4 Capital Cost and Cost of Energy Comparison between all Abuja Systems

The analysis presented in Figure 6-27 indicate that, like in the systems under the other FiT regimes, the systems under the \$0.07/kWh FiT regime present the most balanced relationship between capital cost of systems and the cost of energy used. It is noteworthy that Abuja's optimised systems under the \$0.00/kWh FiT regime present the lowest overall capital costs across all the systems produced but have the overall highest CoE for each profile.

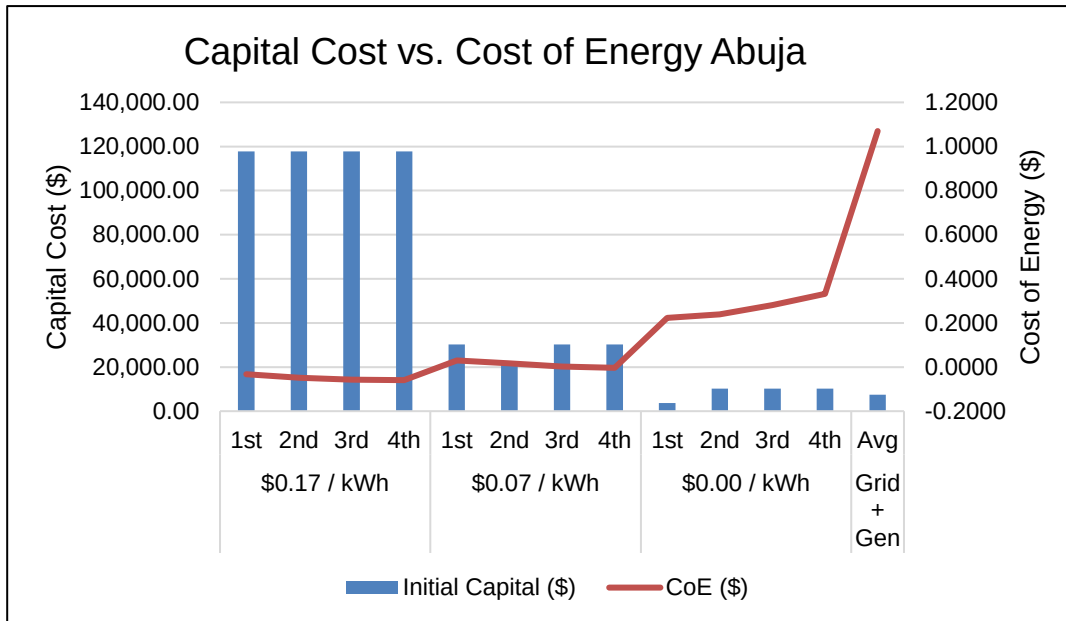


Figure 6-27: Capital cost vs CoE for system configurations in Abuja

While the capital costs of optimised systems under the zero FiT regime are close to the cost of the conventional system, their costs of energy are significantly less. On the other hand, the capital costs of the optimised systems under the \$0.17/kWh FiT regime are high while their CoEs do not seem to be much lower than those of the \$0.07/kWh FiT regime. Nevertheless, the cost of energy savings over the 25-year lifetime of the systems do add up to give significantly less net present costs.

6.5.2 System and Emission Factors of Optimal System Configurations for Abuja

Table 6-39 below shows the technical variables associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Abuja.

Table 6-39: Technical factors for system configurations in Abuja

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	87	68,451	40,999	7,580	-21,937
	2nd	14.30	PV, Battery x 5, Grid, HydroK	98	63,194	39,628	4,986	-24,394
	3rd	7.31	PV, Battery x 5, Grid, HydroK	99	62,669	41,105	2,572	-25,659
	4th	4.82	PV, Battery x 5, Grid, HydroK	99	62,492	41,633	1,698	-26,104
\$0.07 /kWh	1st	21.53	Gen10, Battery x 5, Grid, HydroK	81	34,562	17,875	7,858	-8,721
	2nd	14.30	Battery x 5, Grid, HydroK	87	32,633	18,657	5,035	-9,851
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	92	31,260	19,471	2,668	-11,310
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	95	30,685	19,764	1,759	-11,788
\$0.00 /kWh	1st	21.53	Battery x 10, Grid	0	8,208	0	7,542	5,187
	2nd	14.30	Gen10, Battery x 5, Grid	0	5,680	0	5,216	3,934
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,933	0	2,668	1,943
	4th	4.82	Gen10, Battery x 5, Grid	0	1,940	0	1,759	1,235

6.5.2.1 Systems under Abuja's \$0.17/kWh FiT regime

As shown in Table 6-39, Abuja's optimised systems contain the same set of DER components across all load profiles explored under the \$0.17/kWh FiT regime. Each microgrid system contains a 22 kW PV array, a bank of five 1 kW Li-ion batteries, and a 20 kW Guinard-P154 hydrokinetic turbine. These wholly renewable energy components result in the 1st, 2nd, 3rd and 4th systems having 87%, 98%, 99%, and 99% renewable energy fraction in the power used by the loads in the systems. The 1st system presents a noticeably lower renewable energy fraction because it draws more power from the grid to power its bigger electric load.

Nevertheless, the 1st DER system produced the largest amount of energy and sold more power to the grid than the 2nd system with less electric load. It is important to remember that, a grid-connected DER system will prioritise renewable energy produced for sale to the grid, if FiT is available, while relying on the grid to power system loads and charge batteries. This is especially the case when the feed-in-tariff is higher than grid tariff.

Table 6-40: \$0.17 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	3,974	652	320	208	10,134
Carbon Monoxide	0	0	0	0	48.1
Unburned Hydrocarbons	0	0	0	0	1.75
Particulate Matter	0	0	0	0	2.92
Sulphur Dioxide	17.2	2.82	1.39	0.900	29.2
Nitrogen Oxides	8.43	1.38	0.677	0.440	62.7
Fuel Consumption (L/yr)	0	0	0	0	2,435

The net CO₂ emission figures from the systems, shown in Table 6-39, indicate that there is a steady increase in the amount of CO₂ emission savings as the load sizes reduce. On the other hand, the actual CO₂ and other pollutant emissions from

Table 6-40 show a disproportionate increase in the emission for the 1st system relative to its electric load size compared with the other systems. This is due to the relatively large amount of energy purchased from the grid in the 1st system.

Figures of energy purchased from the grid are 6,288 kWh, 1,031 kWh, 506 kWh, and 329 kWh for the 1st, 2nd, 3rd, and 4th systems respectively (see Abuja data table in Appendix H). This is expected because the 1st system, with the largest load profile, contains the same quantity and size of components with the other systems. No generator activity charts are presented under the \$0.17/kWh FiT regime because none of the systems has a generator. Consequently, these systems will be prone to experiencing power shortages in periods of prolonged grid outages.

6.5.2.2 Systems under Abuja's \$0.07/kWh FiT regime

Except for the 2nd optimal system, the systems generated for Abuja under the \$0.07/kWh FiT regime contain the same DER components. The 2nd system misses a diesel generator in a common mix containing the generator, a bank of five batteries and a hydrokinetic turbine as shown in Table 6-41. The renewable energy fraction of energy produced increases as the load sizes increase. The net CO₂ emission savings also increases proportionally to load size reduction as shown in Table 6-42.

Table 6-41: Technical factors associated with \$0.07/kWh FiT regime in Abuja

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Gen10, Battery x 5, Grid, HydroK	81	34,562	17,875	7,858	-8,721
2 nd	14.30	Battery x 5, Grid, HydroK	87	32,633	18,657	5,035	-9,851
3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	92	31,260	19,471	2,668	-11,310
4 th	4.82	Gen10, Battery x 5, Grid, HydroK	95	30,685	19,764	1,759	-11,788

The zero fuel-related emissions figures presented in Table 6-42 under the 2nd optimal system highlight the benefit of not having a diesel generator in its

component mix. The other systems present emission figures relative to the amount of electrical load they power. As in other FiT regimes and cities, the pollutant emission figures of optimised systems are more environment-friendly than those of the conventional power system.

Table 6-42: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	3,495	1,940	1,116	713	10,134
Carbon Monoxide	6.95	0	0.910	0.0743	48.1
Unburned Hydrocarbons	0.253	0	0.0332	0.00271	1.75
Particulate Matter	0.422	0	0.0552	0.00451	2.92
Sulphur Dioxide	13.0	8.41	4.56	3.07	29.2
Nitrogen Oxides	13.4	4.11	3.15	1.58	62.7
Fuel Consumption (L/yr)	352	0	46.0	3.76	2,435

In Figure 6-28, the generator activity under the 1st system reflects the need to have additional backup to renewable energy infrastructure in systems that power fairly large loads (20 kWh/day and above). The dark areas in the DMaps represent periods when renewable energy resources are sufficient to power the loads in the systems. The 1st system presents a large portion of the year when the ICE generator is required to be operational. Whereas, the 4th system hardly requires the operation of the generator. To avoid redundancies in the system, operating almost has of all the equipment in the facility, as shown under the 3rd system presents a balanced use of all the components in the system.

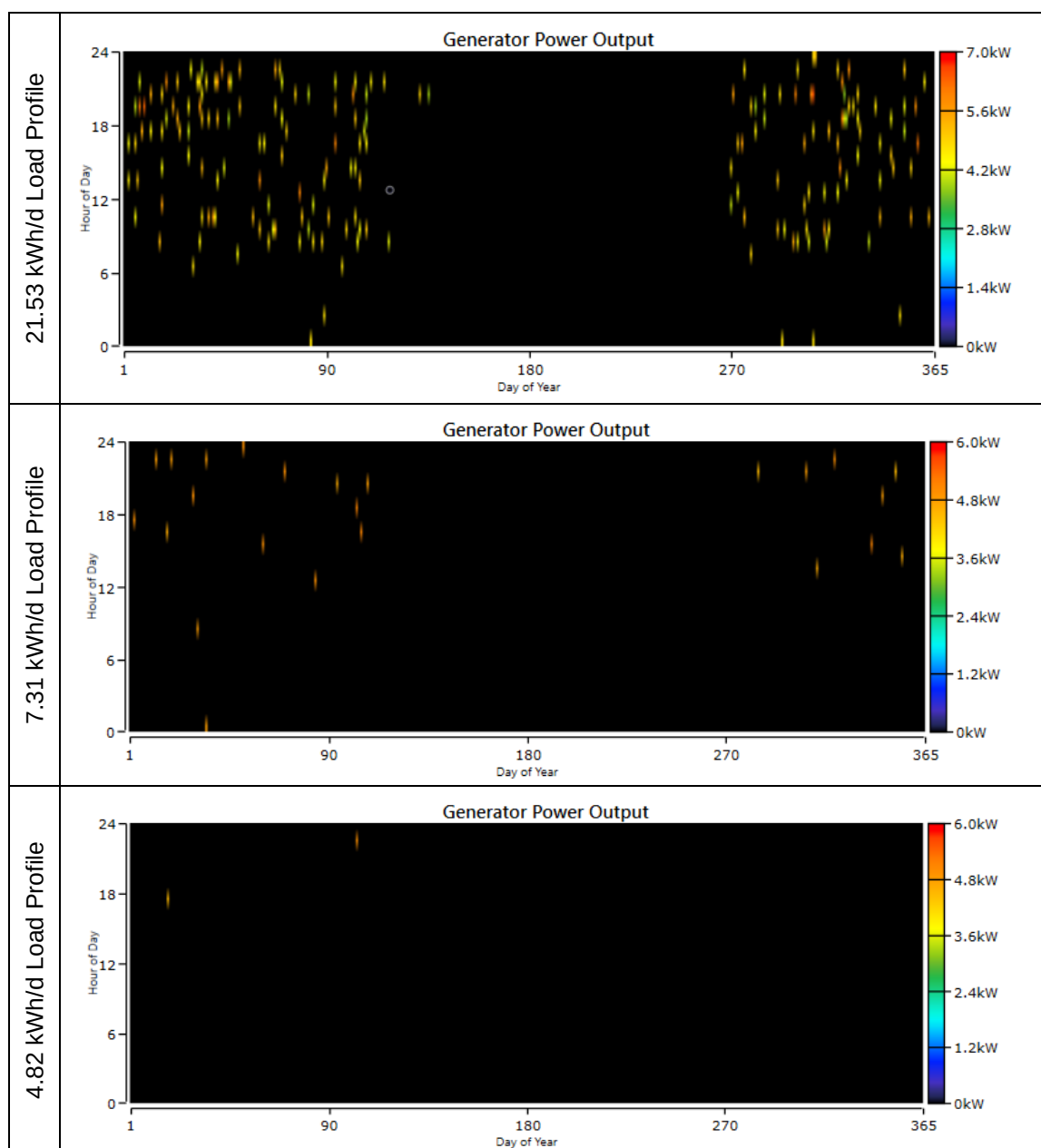


Figure 6-28: Generator outputs under \$0.07/kWh FiT regime

6.5.2.3 Systems under Abuja's \$0.00/kWh FiT regime

The 2nd, 3rd and 4th systems under Abuja's zero FiT regime present the same DER component profile. The 1st system lacks an ICE generator while the other systems have a bank of batteries in addition to the generator as shown in Table 6-43. None of the systems contain a renewable energy component. This, as described in Section 6.5.1.3, is because of the removal of financial incentives to generate energy locally. Consequently, there is zero renewable energy fraction in the energy produced column for each system. Moreover, the net CO₂ emissions figures are

positive, indicating that there are no emission savings under this FiT regime for Abuja.

Table 6-43: Technical factors associated with \$0.00/kWh FiT regime in Abuja

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	Battery x 10, Grid	0	8,208	0	7,542	5,187
2 nd	14.30	Gen10, Battery x 5, Grid	0	5,680	0	5,216	2,994
3 rd	7.31	Gen10, Battery x 5, Grid	0	2,933	0	2,668	1,699
4 th	4.82	Gen10, Battery x 5, Grid	0	1,940	0	1,759	1,210

The actual CO₂ emission figures presented in Table 6-44 are higher than the net CO₂ emissions in Table 6-43. This shows that grid supply of all the electricity demand of the facility under each load profile presents lower CO₂ emissions than the optimised systems (description of net and actual CO₂ emissions can be found in Section 4.4.3). Still, the optimised systems present better emission figures compared with a grid and generator conventional system as shown in Table 6-44. Current grid conditions in Nigeria do not allow for facilities to be reliably powered wholly by the national grid. Therefore, the optimised systems are more environment-friendly options compared with the current conventional means of supplying power reliably in Nigeria.

Table 6-44: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1st	2nd	3rd	4th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	5,187	3,934	1,943	1,235	10,134
Carbon Monoxide	0	7.11	1.85	0.188	48.1
Unburned Hydrocarbons	0	0.259	0.0672	0.00685	1.75
Particulate Matter	0	0.431	0.112	0.0114	2.92
Sulphur Dioxide	22.5	14.9	7.86	5.30	29.2
Nitrogen Oxides	11.0	14.4	5.70	2.78	62.7
Fuel Consumption (L/yr)	0	360	93.4	9.51	2,435

The generator outputs represented in the DMaps in Figure 6-29 show that the diesel generator in each of the 2nd and 3rd systems are actively deployed while the one in the 4th system is less so. This is because of the lack of a renewable energy component in the systems caused by a combination of zero financial incentive and inadequate renewable energy resources in Abuja to compensate. The absence of an ICE generator in the 1st system is possible because it has a deeper bank of ten batteries compared with five in the others. Nevertheless, the 1st system is more vulnerable to long periods of power outages.

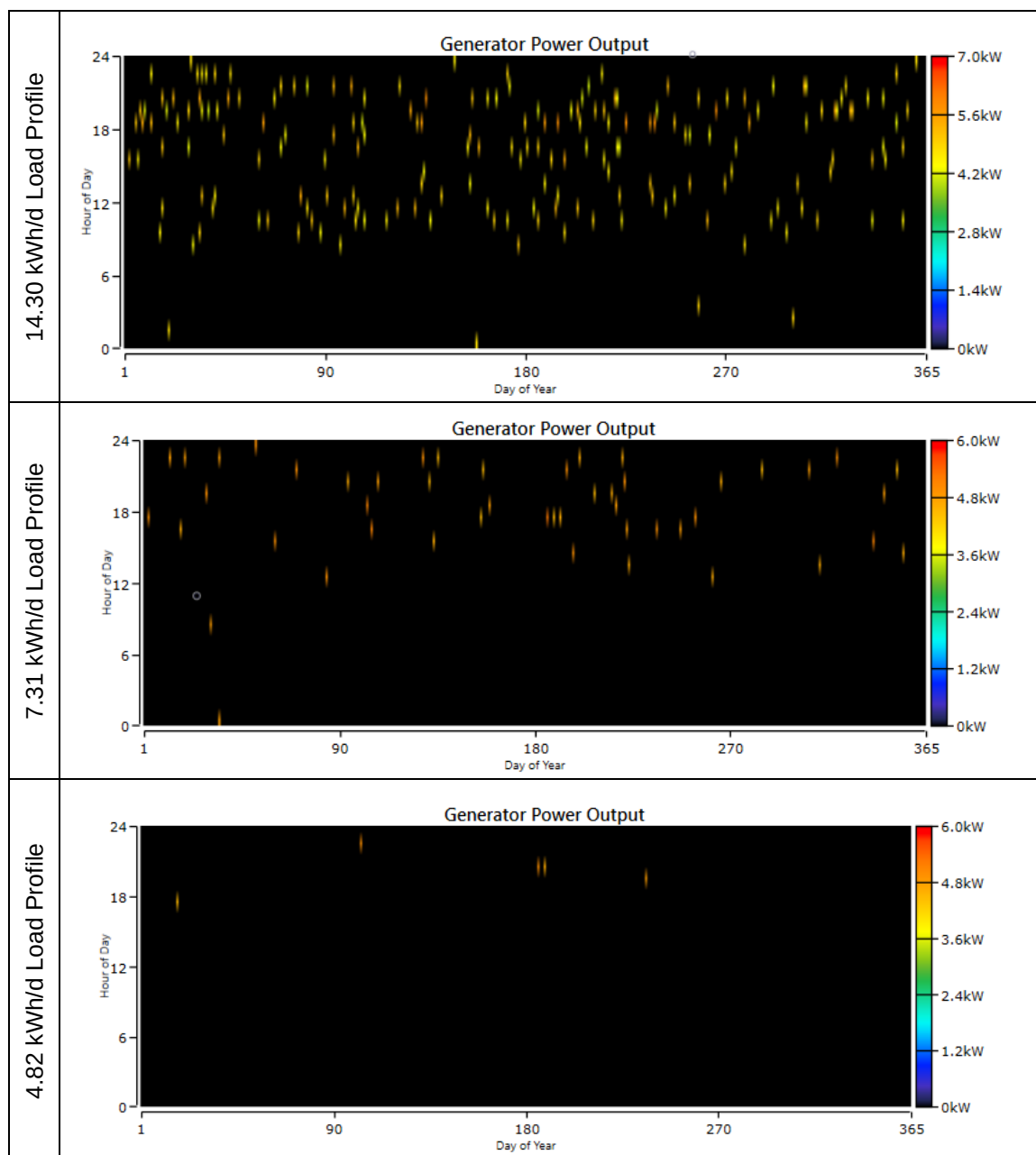


Figure 6-29: Generator outputs under \$0.00/kWh FiT regime

6.5.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Abuja Systems

Generally, CO₂ emission figures under Abuja are higher than any of the southern Nigerian cities studied. Nevertheless, the 3rd and 4th systems under each FiT regime present competitive emission figures. This indicates that prioritisation of critical applications is more important, especially for pollutant emission considerations, in Abuja's facilities than in the southern cities. Nevertheless, emissions figures for optimised systems in Abuja are more favourable to the environment than those presented by the current conventional system

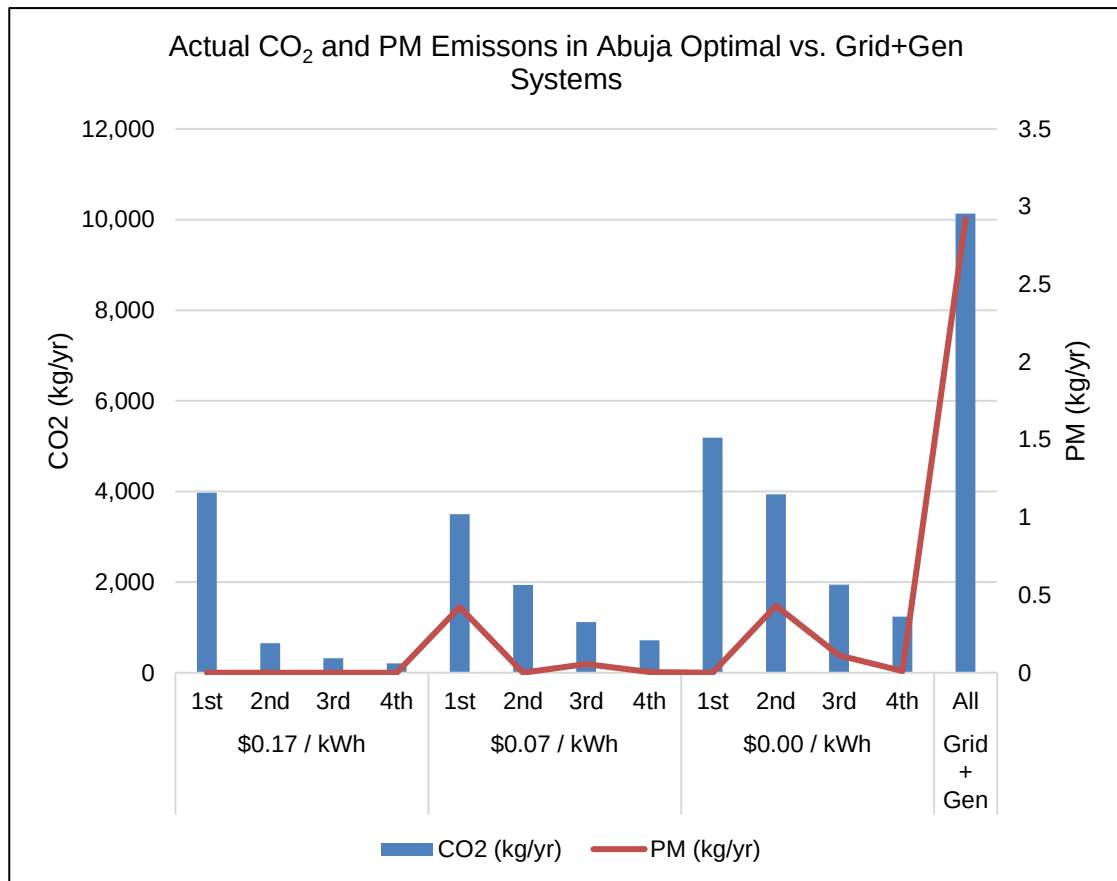


Figure 6-30: CO₂ vs. PM emissions for system configurations in Abuja

6.6 Kano (NW Nigeria) Results and Discussions

Models generated for Kano produced 12,032 solutions for each FiT regime sensitivity. Of these, 8,368 were feasible while 3,664 were infeasible due to capacity shortage constraint under the \$0.17/kWh FiT regime. Under the \$0.07/kWh FiT regime, 9,9024 solutions were feasible and 3,008 were infeasible. The \$0.00/kWh FiT regime generated 9,964 feasible and 2,068 infeasible solutions.

6.6.1 Costs of Optimal System Configurations for Kano

Table 6-45 shows the costs associated with the optimised system configurations for the four load profiles under the three FiT regimes considered in the city of Kano, Nigeria.

Table 6-45: Cost factors for system configurations in Kano

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	-0.0510	-86,547	88,700	6,801	40,125
	2nd	14.29	PV, Battery x 10, Grid, HydroK	-0.0644	-101,061	89,700	1,102	39,044
	3rd	7.31	PV, Battery x 5, Grid, HydroK	-0.0770	-116,428	88,700	550	39,857
	4th	4.82	PV, Battery x 5, Grid, HydroK	-0.0802	-120,412	88,700	357	40,387
\$0.07 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	0.0329	30,771	37,700	2,586	18,674
	2nd	14.29	PV, Gen10, Battery x 5, Grid, HydroK	0.0240	21,523	45,200	1,484	19,929
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	0.0158	9,389	26,000	1,817	13,983
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	0.0093	5,326	26,000	1,267	14,217
\$0.00 /kWh	1st	21.53	PV, Gen10, Battery x 5, Grid	0.1527	57,106	25,250	3,542	2,631
	2nd	14.29	PV, Battery x 10, Grid	0.1883	44,876	18,750	306	1,554
	3rd	7.31	Gen10, Battery x 5, Grid	0.2763	26,285	10,250	2,748	0
	4th	4.82	Gen10, Battery x 5, Grid	0.3376	21,178	10,250	1,911	0

6.6.1.1 Costs under Kano's \$0.17/kWh FiT regime

All the systems produced under the \$0.17/kWh FiT regime in Kano present the same sets of electrical energy generating components. Only the 2nd system contains a bank of ten batteries compared to five in the other three systems as shown in Table 6-45. Therefore, the capital cost of the 2nd system is \$1,000 higher than the others as shown in Figure 6-31.

Like in all other system modelled under the \$0.17/kWh FiT regime, the CoE for each Kano system present negative CoE and NPC. This indicates earnings per energy used and a positive net present value over the lifetime of the systems. The components in all the Kano systems under this FiT regime are closest in composition and capital cost value to those of Yola and Port Harcourt in the same FiT regime.

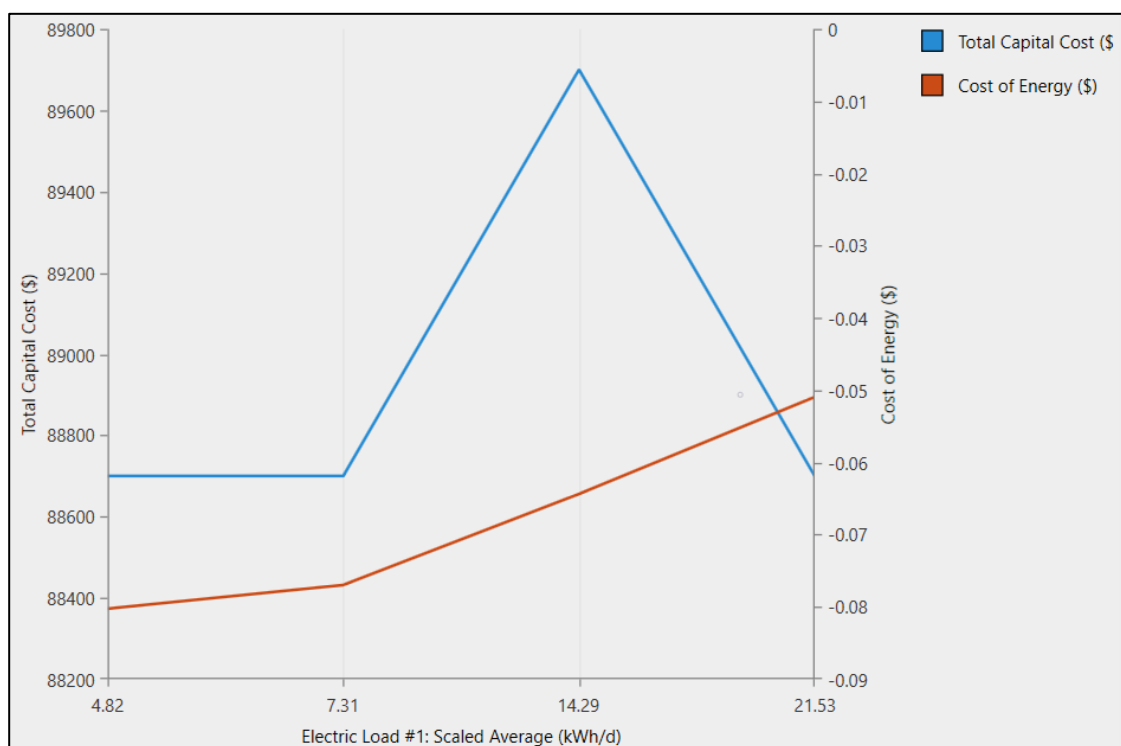


Figure 6-31: Capital cost vs. Cost of energy under \$0.17 FiT regime

However, Kano, a north western Nigerian city, enjoys more solar irradiance than any other city studied due to its comparatively higher monthly clearness index (see Section 4.2.2 Resources). Therefore, Kano has more PV modules on the average in its systems than the other cities. Each system under this FiT regime produces a solar PV output of 34,480 kWh/year, the highest of any city. Kano is followed by

Abuja and Yola with PV outputs of 32,600 kWh/year and 32,106 kWh/year respectively. These three northern Nigerian cities are the cities with the highest solar potential out of the six cities studied.

Decision makers can choose a system based on long term financial considerations rather than short term because the capital costs across the optimised systems shown in Figure 6-31 are almost the same. Nevertheless, the optimised system for the 2nd load profile presents an attractive choice for having a more resilient set of components due to the additional batteries.

6.6.1.2 Costs under Kano's \$0.07/kWh FiT regime

Only Kano and Yola have no system with negative CoE and NPC under the \$0.07/kWh FiT regime. This is largely due to the cities' long dry season preventing the hydrokinetic component in the systems from generating electrical power for six to seven months in the year. Although the northern cities have high solar potential all year round, the southern cities can also generate solar power all year round albeit at lower intensities. It is also worth noting that the PV capacities have been reduced under the \$0.07/kWh FiT regime due to less prospect of income from excess energy generation.

Table 6-46: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	0.0329	30,771	37,700	2,586	18,674
	14.29	0.0240	21,523	45,200	1,484	19,929
	7.31	0.0158	9,389	26,000	1,817	13,983
	4.82	0.0093	5,326	26,000	1,267	14,217

The composition and capital cost of components for optimised Kano systems under the \$0.07/kWh FiT regime are similar to those of Port Harcourt and Awka under the same FiT regime. However, the higher amount of precipitation in Port Harcourt and Awka allows their systems to present negative costs of energy and NPCs compared with Kano's positive costs. Nevertheless, the excess energy sold provided enough income to cover operating costs with some extra to spare, making

the operating costs under this regime negative costs (see *Operating Costs* in Appendix H).

The CoE across the systems modelled present a near straight-line direct proportionality with the load sizes as shown in Figure 6-32. However, the capital costs are the same for the two lesser loads while the 2nd load profile got an optimised system that is more expensive than the larger 1st load profile. This is caused by the additional generator in the 2nd system allowing for a more resilient system while presenting a lower CoE than the 1st system.

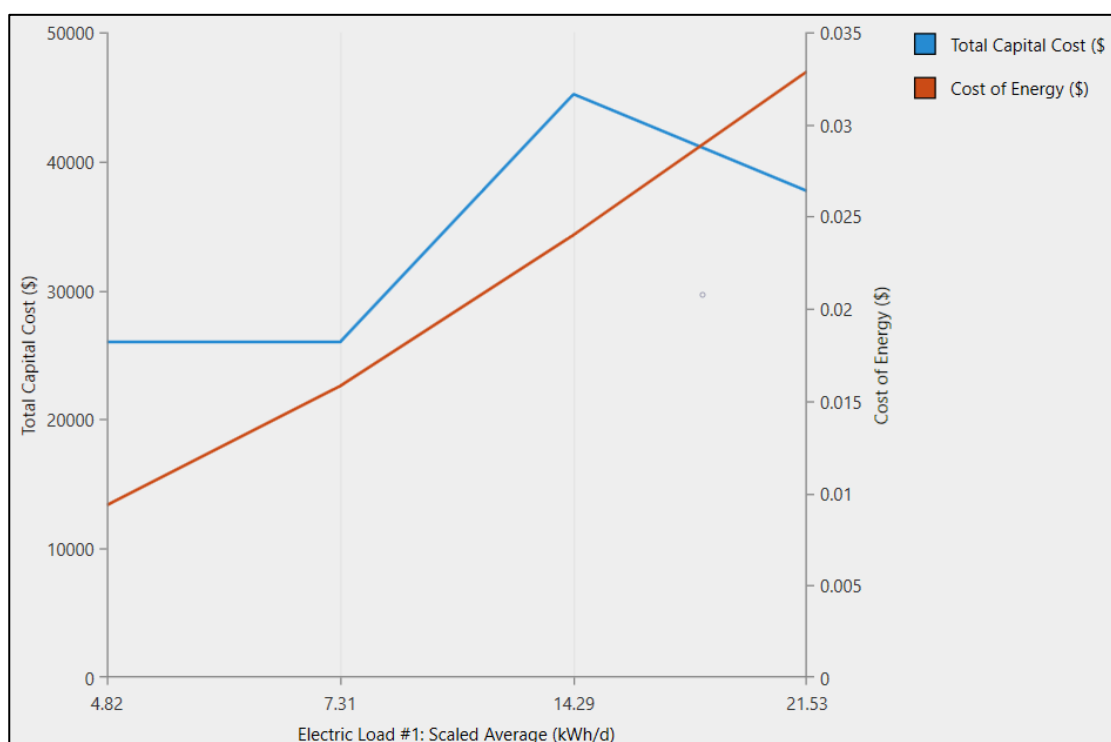


Figure 6-32: Capital cost vs. Cost of energy under \$0.07 FiT regime

As shown in the Table 6-47, optimised DER systems present considerable cost advantages over the conventional grid and ICE generator power systems. The optimised 1st system under the \$0.07/kWh FiT regime presents the following cost advantages over a corresponding conventional system: CoE is \$0.4551 less; NPC is \$105,861 less over 25 years; and annual operating cost is \$3,815 less. However, the capital cost of the 1st system is \$30,200 more costly than a conventional system to set up. Decision makers will have to choose between long and short term benefits and based on available financial resources.

Table 6-47: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Kano (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0329	0.488	30,771	136,632	-194	3,621	37,700	7,500
14.3	0.0240	0.7	21,523	130,171	-664	3,440	45,200	7,500
7.31	0.0158	1.3	9,389	123,944	-466	3,265	26,000	7,500
4.82	0.0093	1.94	5,326	121,722	-580	3,203	26,000	7,500

6.6.1.3 Costs under Kano's \$0.00/kWh FiT regime

Optimised Kano systems under the zero FiT regime present positive costs overall as shown in Table 6-48. This is common to all the cities studied due to the absence of sale outlet for excess energy produced by the renewable power components. Nevertheless, the 1st and 2nd systems have PV modules in their optimised systems same as in Yola's optimised systems under the zero FiT regime. This highlights the abundance of solar potential in the northern cities compared with the southern Nigerian cities having hydrokinetic turbines as the only renewable energy components in their systems under the zero FiT regime.

Table 6-48: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.00/kWh	21.53	0.1527	57,106	25,250	3,542	2,631
	14.29	0.1883	44,876	18,750	306	1,554
	7.31	0.2763	26,285	10,250	2,748	0
	4.82	0.3376	21,178	10,250	1,911	0

There is an inversely proportional relationship between capital costs and cost of energy across the optimised systems as shown in Figure 6-33. This is a common trend within all the systems under the zero FiT regime for all the cities studied. CoE also reduces as the load sizes increase. This is either due to HOMER optimising for economies of scale in the larger load profiles or because of redundancies in the systems for the smaller loads.

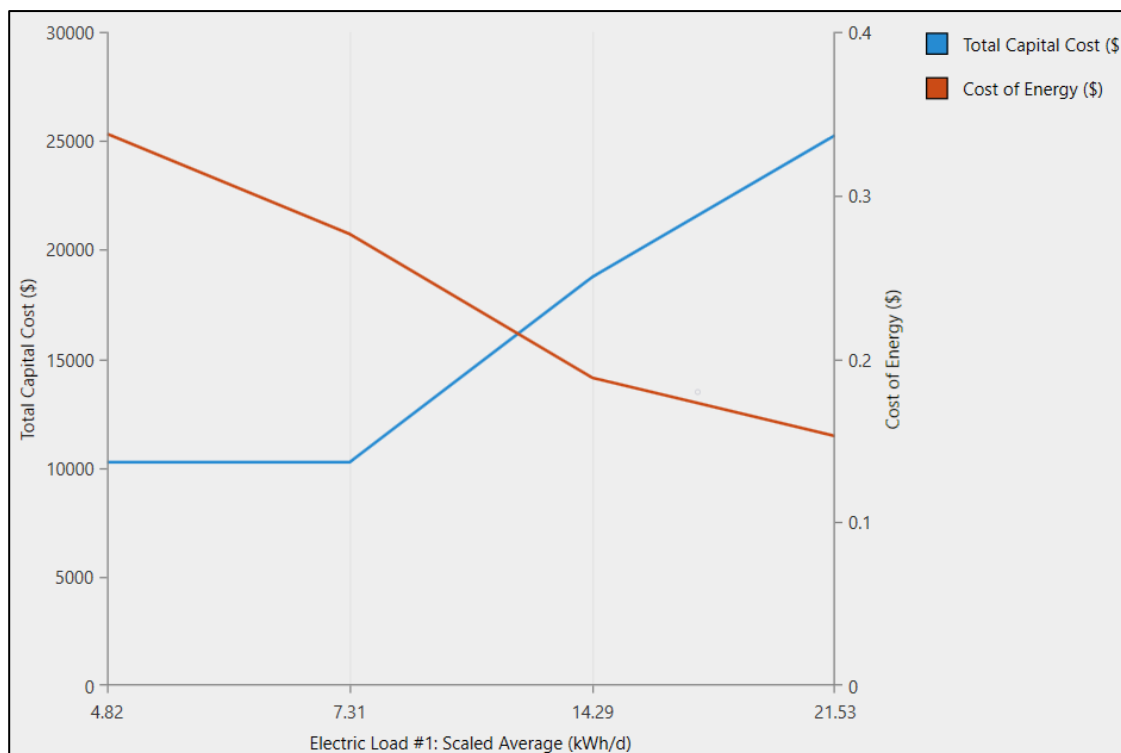


Figure 6-33: Capital cost vs. Cost of energy under \$0.00 FiT regime

Kano and Yola present systems with the same capital costs across all the load profiles modelled. However, Kano presented lower costs of energy and net present costs for the 1st and 2nd systems under the zero FiT regime. This is due to Kano's higher solar potential than Yola's. It is important to note that the 3rd and 4th systems have no excess energy to sell (or waste as there is zero FiT) which indicates that the systems are prioritised for operating cost minimisation. Whereas, the 1st and 2nd systems are prioritised for lower cost of energy. However, the 2nd system is even more prioritised for lower CoE with the omission of a diesel generator. Therefore, it is prone to minute instances of unmet loads during periods of prolonged grid outages due to the lack of a backup generator. This situation is ameliorated by doubling the size of the system's battery bank, a less costly option to having a diesel generator.

Table 6-49 shows cost comparisons between optimised systems and conventional systems under a zero FiT regime. The 1st optimised system bettered its conventional counterpart by \$ 0.335/kWh in cost of energy, \$79,526 in net present cost over the 25-year system lifetime, and by \$2727.68 in operating costs per year. However, the conventional system presented a capital cost that is less costly by

\$17,750. This capital cost difference falls to only \$2,750 for the 3rd and 4th systems while both systems present better figures across the other cost categories.

Table 6-49: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Kano (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.1527	0.488	57,106	136,632	893	3,621	25,250	7,500
14.3	0.1883	0.7	44,876	130,171	733	3,440	18,750	7,500
7.31	0.2763	1.3	26,285	123,944	450	3,265	10,250	7,500
4.82	0.3376	1.94	21,178	121,722	306	3,203	10,250	7,500

6.6.1.4 Capital Cost and Cost of Energy Comparison between all Kano Systems

Kano's systems present a similar general trend between capital cost and the cost of energy with all the city systems explored. However, Kano's systems under the \$0.07/kWh FiT regime show noticeably higher capital costs than the others while presenting the second highest net present costs after Yola. Figure 6-34 show the microgrid options available for Kano under the considered DER components. Under the \$0.17/kWh and \$0.07/kWh FiT regimes, the 4th system presents the lowest cost of energy but the highest CoE under the zero FiT regime.

In all the systems evaluated for Kano, the 1st systems under each FiT regime appears the most cost effective in the long term. Their high capital cost, which is slightly higher than the 2nd system only under the zero FiT regime, result in noticeable cost of energy savings. The 3rd systems are next in terms of cost-effectiveness by presenting lower capital costs and CoEs under the \$0.17/kWh and \$0.07/kWh FiT regimes. Whereas, the 2nd and 4th systems are equally as expensive as the 1st and 3rd systems respectively without presenting substantial long term cost savings.

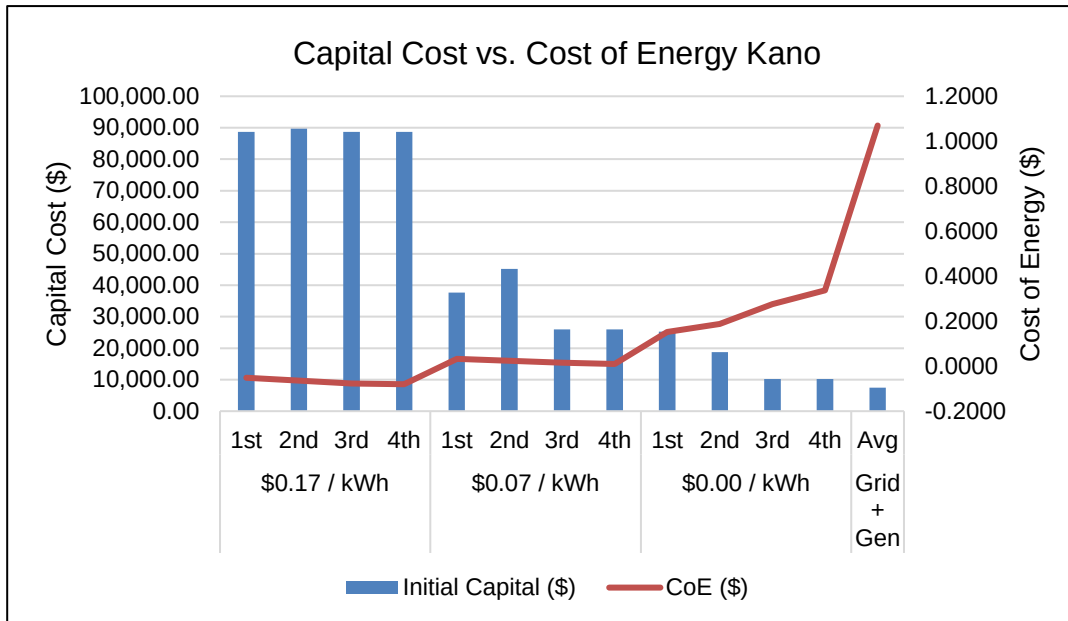


Figure 6-34: Capital cost vs CoE for system configurations in Kano

6.6.2 System and Emission Factors of Optimal System Configurations for Kano

Table 6-50 below shows the technical variables associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Kano.

Table 6-50: Technical factors for system configurations in Kano

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	86	65,863	40,125	7,510	-21,061
	2nd	14.30	PV, Battery x 10, Grid, HydroK	97	60,164	39,044	4,986	-23,979
	3rd	7.31	PV, Battery x 5, Grid, HydroK	99	59,612	39,857	2,564	-24,842
	4th	4.82	PV, Battery x 5, Grid, HydroK	99	59,419	40,387	1,693	-25,299
\$0.07 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	90	35,004	18,674	7,579	-10,168
	2nd	14.30	PV, Gen10, Battery x 5, Grid, HydroK	93	34,236	19,929	5,216	-11,658
	3rd	7.31	Gen10, Battery x 5, Grid, HydroK	88	26,541	13,983	2,668	-7,688
	4th	4.82	Gen10, Battery x 5, Grid, HydroK	92	25,879	14,217	1,759	-8,185
\$0.00 /kWh	1st	21.53	PV, Gen10, Battery x 5, Grid	58	12,231	2,631	7,858	576
	2nd	14.30	PV, Battery x 10, Grid	95	8,143	1,554	5,129	-788
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
	4th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

6.6.2.1 Systems under Kano's \$0.17/kWh FiT regime

Table 6-50 shows that all optimised systems under Kano's \$0.17/kWh FiT regime have the same mix of components like Abuja's systems under the same FiT regime. However, Kano's 2nd system includes ten batteries in its bank of batteries compared to five in the other systems. It would be expected that the 1st system with the largest electric load should also have at least ten batteries instead of five. However, the 1st system uses the cycle charging dispatch strategy to prioritise the charging of its bank of batteries whenever power is available, irrespective of the source (see Section 4.2.3.5.2's description of *Dispatch Strategy*). This helps keep capital costs low, but O&M costs will be higher.

Table 6-51: \$0.17 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	4,298	697	348	226	10,134
Carbon Monoxide	0	0	0	0	48.1
Unburned Hydrocarbons	0	0	0	0	1.75
Particulate Matter	0	0	0	0	2.92
Sulphur Dioxide	18.6	3.02	1.51	0.979	29.2
Nitrogen Oxides	9.11	1.48	0.737	0.479	62.7
Fuel Consumption (L/yr)	0	0	0	0	2,435

All system-related variables shown in Table 6-50 vary in direct proportion to the load sizes in the systems. However, in Table 6-51, the actual CO₂ (including the other pollutants) emission figure for the 1st system is disproportionately high when compared with the other systems. This is because of the system's cycle charging strategy requiring its batteries to be constantly charged whenever power is available. Consequently, more power is purchased from the grid to keep the batteries charged whenever the grid is available. Energy purchased from the grid

by the 1st, 2nd, 3rd and 4th systems are 6,801 kWh, 1,102 kWh, 550 kWh, and 357 kWh respectively (see Appendix H for full city data). This shows a relatively higher grid purchase compared to the other systems.

Generator-related pollutant emissions under the \$0.17/kWh FiT regime in Kano are zero due to the absence of a diesel generator in any of the systems. This allows the optimal Kano systems under this FiT regime to present much cleaner emissions figures than the conventional system's results.

6.6.2.2 Systems under Kano's \$0.07/kWh FiT regime

Under the \$0.07/kWh FiT regime in Kano, the systems for the unprioritised loads (1st and 2nd systems) and systems for prioritised loads (3rd and 4th) have the same sets of DER components respectively. The 1st and 2nd systems have additional PV modules and 22 kW converters compared with 10 kW converters in the 3rd and 4th systems. The 2nd system also has a diesel generator in addition to the components it has in common with the 1st system as shown in Table 6-52.

Table 6-52: Technical factors associated with \$0.07/kWh FiT regime in Kano

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	PV, Battery x 5, Grid, HydroK	90	35,004	18,674	7,579	-10,168
2 nd	14.30	PV, Gen10, Battery x 5, Grid, HydroK	93	34,236	19,929	5,216	-11,658
3 rd	7.31	Gen10, Battery x 5, Grid, HydroK	88	26,541	13,983	2,668	-7,688
4 th	4.82	Gen10, Battery x 5, Grid, HydroK	92	25,879	14,217	1,759	-8,185

However, Kano systems under this FiT regime do have a few things in common. All the systems have the 20 kW hydrokinetic turbine and a battery bank of five 1 kW Li-ion batteries. It is worth noting that each system employed the charging cycle dispatch strategy, that is the charging of the batteries is prioritised along with

supplying the loads with electricity. Consequently, the energy available for sale in each system is commensurate with the amount of DER components in it.

This also affects the renewable fraction of total energy produced by each system. Within the two categories of unprioritised and prioritised loads, systems for the larger loads (1st and 3rd) present lower renewable energy fraction as well as less net CO₂ emission savings. On the other hand, the smaller unprioritised (2nd) and prioritised (4th) loads present higher renewable fraction of power and higher CO₂ emissions savings than their larger counterparts.

Table 6-53: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,634	1,269	1,291	831	10,134
Carbon Monoxide	0	2.51	1.08	0.227	48.1
Unburned Hydrocarbons	0	0.0914	0.0393	0.00826	1.75
Particulate Matter	0	0.152	0.0654	0.0137	2.92
Sulphur Dioxide	7.09	4.74	5.27	3.53	29.2
Nitrogen Oxides	3.47	4.84	3.66	1.96	62.7
Fuel Consumption (L/yr)	0	127	54.6	11.5	2,435

The 1st system, also with the largest electric load, presents the highest amounts of grid-related emissions. However, it presents zero amounts of generator-related emissions. This means that the environment of the 1st system will be the most pollutant-free. The 3rd system presents a higher CO₂ and sulphur dioxide emissions than the 2nd system with a larger electrical load because it does not have a PV module like the 2nd system. It therefore has a more active ICE generator as shown in Figure 6-35. The generators in the systems are more active during the evening periods of the days in the first, second and last quarter of the year. This is due to lower solar radiation during evenings and less precipitation in Kano during those quarters of the year.

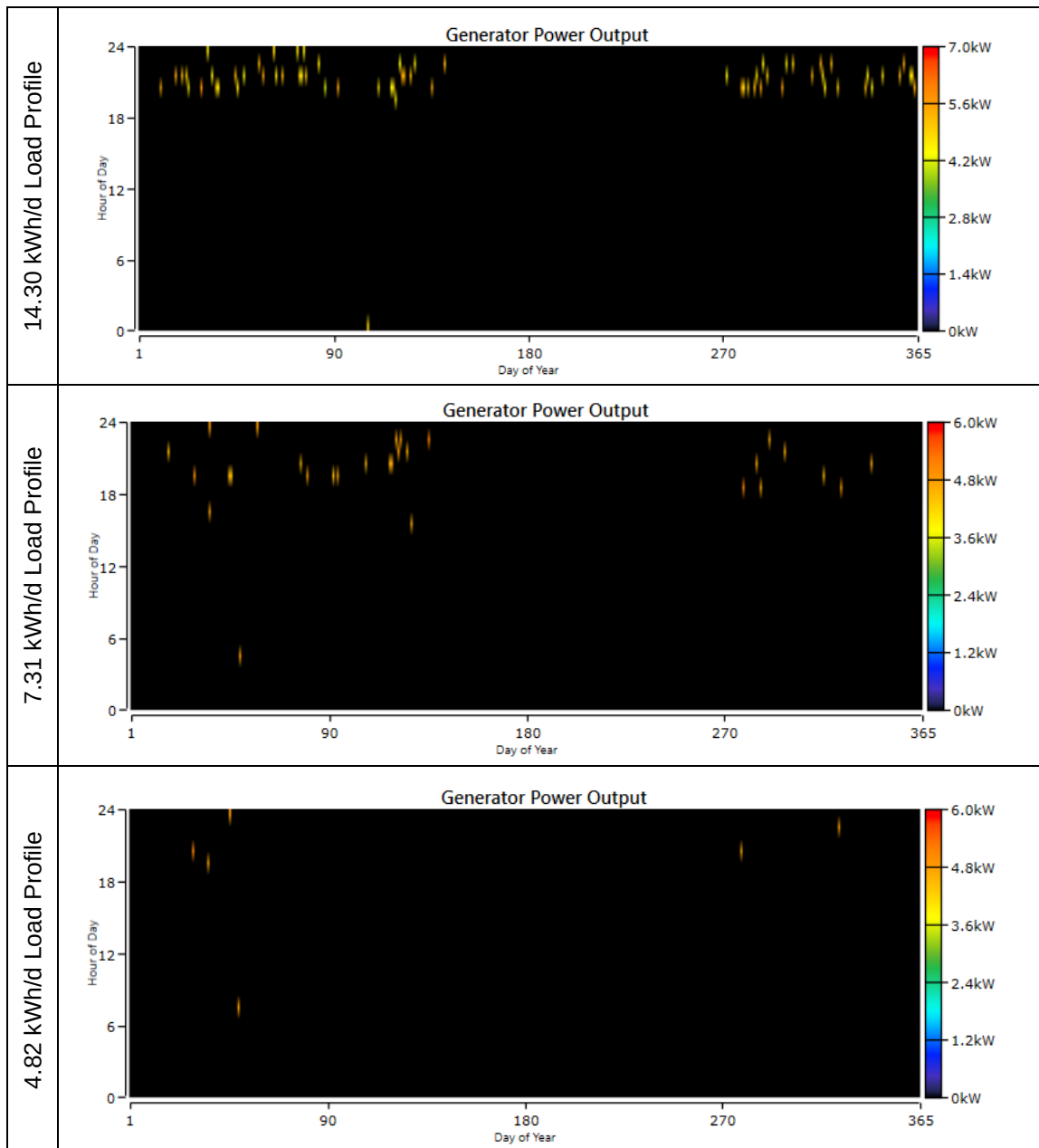


Figure 6-35: Generator outputs under \$0.07/kWh FiT regime

6.6.2.3 Systems under Kano's \$0.00/kWh FiT regime

The presence of solar PV components and absence of hydro components in two of Kano's systems under the zero FiT regime is a demonstration of the city's relatively plentiful solar resource. The 1st and 2nd systems contain PV modules while the 2nd system is the only system without an ICE generator. Consequently, the 2nd system has ten batteries in its bank compared to five in the others.

The characteristics described above are responsible for the irregular patterns presented in the system variables shown in Table 6-54. The 1st system presents a

disproportionately lower renewable fraction of energy produced than the 2nd system. This is because the 1st system employs a charging cycle dispatch strategy where the generator in the system is operated at full capacity to power loads and charge the batteries at the same time. Whereas, the 2nd system employs a load following strategy where the loads are prioritised over charging the batteries using the power generated by the DER components in the system.

Table 6-54: Technical factors associated with \$0.00/kWh FiT regime in Kano

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	PV, Gen10, Battery x 5, Grid	58	12,231	2,631	7,858	576
2 nd	14.30	PV, Battery x 10, Grid	95	8,143	1,554	5,129	-788
3 rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
4 th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

Net CO₂ emission figures are positive for three out of the four systems under this FiT regime. The 2nd system presents CO₂ emission savings because it contains no diesel generator. The actual emission figures shown in Table 6-55 also indicate that the 2nd system has the overall lowest emissions across all pollutants because all its emissions are associated with electricity purchased from the grid. The 4th system also presents comparatively low emissions figures due to its small electrical load.

The 1st system produces the highest quantities of pollutant emission due to both the generator included its mix and its heavier load. It is important to remember that HOMER prioritises components primarily based on cost considerations. Secondary considerations include emissions and reliability factors. Despite the 1st system's relatively high emission figures, it presents lower emissions than a conventional system.

Table 6-55: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1st	2nd	3rd	4th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	3,087	194	1,940	1,248	10,134
Carbon Monoxide	6.42	0	1.54	0.301	48.1
Unburned Hydrocarbons	0.234	0	0.0560	0.0110	1.75
Particulate Matter	0.389	0	0.0932	0.0183	2.92
Sulphur Dioxide	11.4	0.840	7.94	5.32	29.2
Nitrogen Oxides	12.0	0.411	5.43	2.90	62.7
Fuel Consumption (L/yr)	325	0	77.8	15.2	2,435

Figure 6-36 shows that the diesel generator in the 1st system is active on most evenings in Kano under the zero FiT regime. This is due to Kano's vulnerability to solar downtime during evenings. With comparatively little hydro potential, Kano does not benefit from all-day renewable power that is available with the hydrokinetic turbine in southern Nigeria cities. Therefore, systems in Kano have a higher dependence on backup power generators. The trade-off for not having a generator in the 2nd system is the additional five batteries and a bigger exposure to insufficient power during prolonged power outages.

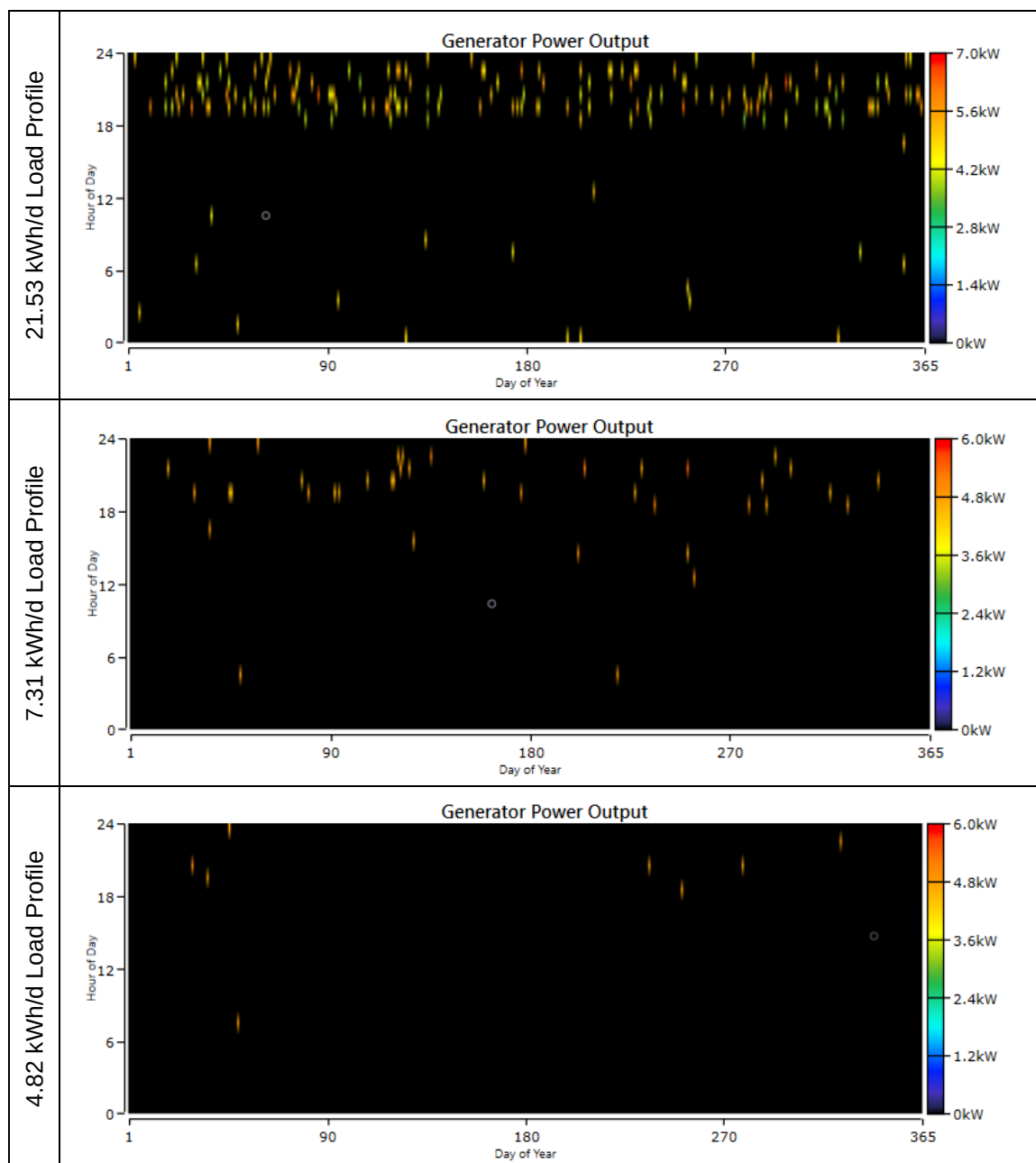


Figure 6-36: Generator outputs under \$0.00/kWh FiT regime

6.6.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Kano Systems

Along with Abuja and Yola, Kano presents some of the highest 1st system CO₂ emission figures. This is due mainly to the relatively higher dependence on the grid for power supply both to the loads and for battery charging. Among the northern cities, the lower load profiles seem to produce systems with relatively lower costs and less pollutant emissions. It is therefore more pertinent for facilities in northern Nigeria to conduct detailed risk assessments of their processes for the purpose of

prioritising critical applications for microgrids to fulfil the dual objective of cost and environmental sustainability.

As obtainable in the other cities' systems, the optimal systems in Kano present better emissions figures than a conventional system. It is also worth stating that the 1st system under the \$0.17/kWh FiT regime presents a disproportionately high CO₂ emission figure. This is mainly because of its larger load profile requiring high amounts of power from the grid to regularly charge the system batteries. This also explains why the particulate matter level is not as high. PM emission is linked only to the generator component.

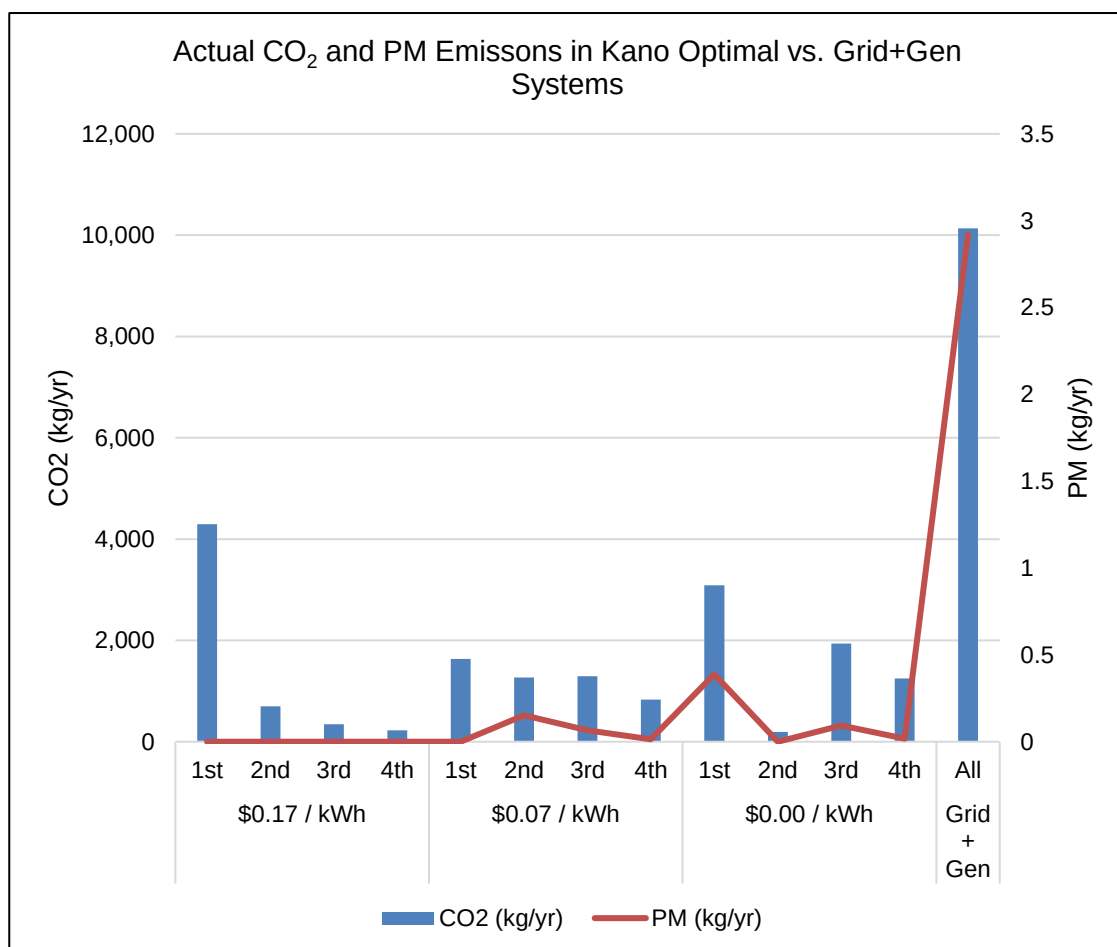


Figure 6-37: CO₂ vs. PM emissions for system configurations in Kano

6.7 Yola (NE Nigeria) Results and Discussions

Like in the other cities, 12,032 solutions were simulated for each FiT regime sensitivity for Yola. 8,172 of these were feasible while 3,860 were infeasible due to capacity shortage constraint under the \$0.17/kWh FiT regime. The \$0.07/kWh FiT regime produced 8,924 feasible solutions and 3,108 infeasible solutions. Whereas, the \$0.00/kWh FiT regime generated 9,856 feasible and 2,176 infeasible solutions.

6.7.1 Costs of Optimal System Configurations for Yola

Table 6-56 shows the costs associated with the optimised system configurations for the four load profiles under the three FiT regimes considered in the city of Yola, Nigeria.

Table 6-56: Cost factors for system configurations in Yola

Sensitivities			Components	Economic/Cost-Related Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	-0.0100	-11,777	84,500	1,102	25,592
	2nd	14.29	PV, Gen10, Battery x 5, Grid, HydroK	-0.0250	-28,697	96,200	6,721	26,938
	3rd	7.31	PV, Battery x 5, Grid, HydroK	-0.0432	-47,422	88,700	367	28,206
	4th	4.82	PV, Battery x 5, Grid, HydroK	-0.0472	-51,201	88,700	560	28,722
\$0.07 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	0.0951	49,653	31,750	2,717	7,060
	2nd	14.29	PV, Gen10, Battery x 5, Grid	0.1310	39,145	25,250	2,364	3,166
	3rd	7.31	PV, Gen10, Battery x 5, Grid	0.1059	25,436	25,250	1,294	4,069
	4th	4.82	Gen10, Battery x 5, Grid	0.3365	21,154	10,250	1,914	3
\$0.00 /kWh	1st	21.53	PV, Gen10, Battery x 5, Grid	0.1598	58,238	25,250	3,662	2,364
	2nd	14.29	PV, Battery x 10, Grid	0.1989	45,409	18,750	429	1,336
	3rd	7.31	Gen10, Battery x 5, Grid	0.2763	26,285	10,250	2,748	0
	4th	4.82	Gen10, Battery x 5, Grid	0.3376	21,178	10,250	1,911	0

6.7.1.1 Costs under Yola's \$0.17/kWh FiT regime

Yola, unlike Kano, its northern counterpart, presents varied sets of components in its optimised systems. Yola's 2nd optimised system contains an additional ICE generator compared with the other systems under the \$0.17/kWh FiT regime. This gave the 2nd system the highest capital cost under this FiT regime as shown in Table 6-56 above.

Meanwhile, the 1st system which, is usually costliest system, presents the lowest capital cost because it contains a converter half the capacity of converters in the other systems. The consequence of this is that the 1st system has less excess energy to sell because it is optimised to generate electricity for the load rather than to sell. Typically, under the \$0.17/kWh FiT regime, the larger capacity systems usually have more excess energy to sell at the higher feed-in-tariff than the smaller systems. Yola is the only city to buck this trend completely under this FiT regime.

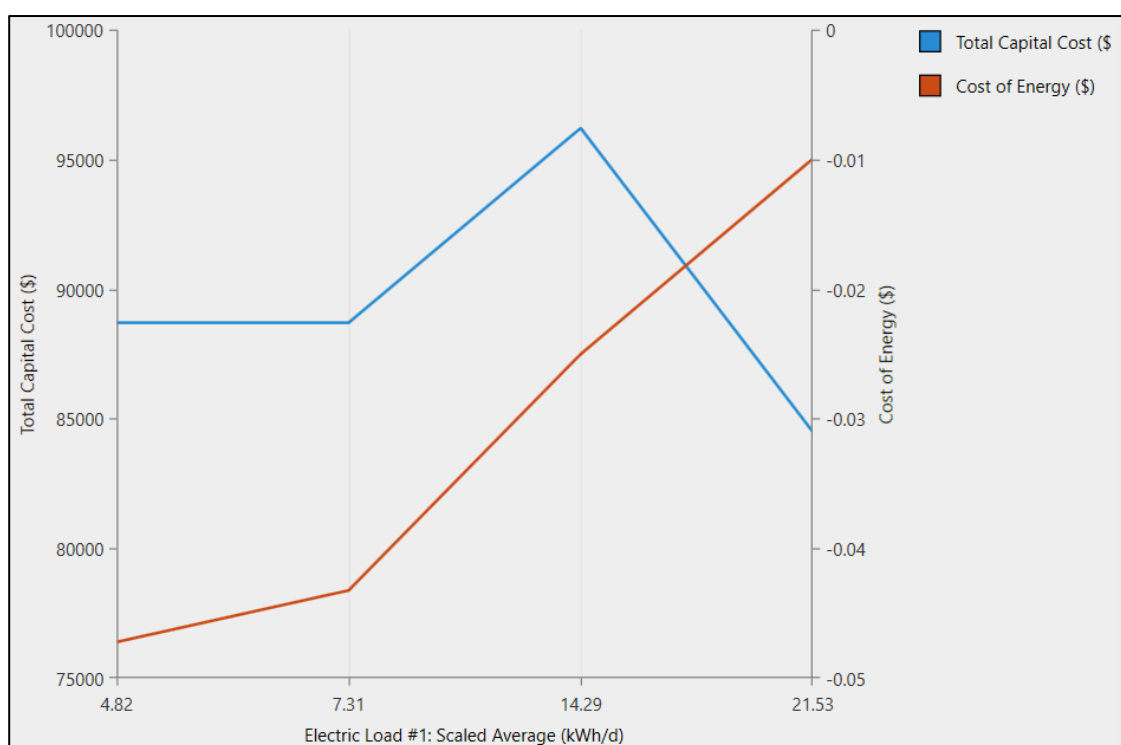


Figure 6-38: Capital cost vs. Cost of energy under \$0.17 FiT regime

As shown in Figure 6-38, the cost of energy followed the more common trend of larger systems having higher costs of energy consumed by local loads. All CoE values are negative, as usual under the \$0.17/kWh FiT regime, indicating income generation for every unit energy used. Although the 1st system seem attractive in

the short term due to its low capital cost, its higher cost of energy results in higher net present cost over the lifetime of the system as shown in Table 6-56. The 2nd system presents higher CoE and capital cost and seem to be the least attractive economically of the four.

On the other hand, the 3rd and 4th systems present equal and comparatively average capital costs but much less CoEs than the other two systems. However, the 3rd system can power 52% more electrical loads than the 4th system while presenting only 8% more cost of energy. This indicates that the components in the 3rd system can be used more efficiently than in the 4th system which will experience more redundancies within its components.

6.7.1.2 Costs under Yola's \$0.07/kWh FiT regime

Like Kano's systems, Yola systems present no negative CoEs or NPCs. This means that optimal systems generated for these cities are only financially viable when they produce little amount of excess energy for sale at the current utility tariff of \$0.07 /kWh. Under this FiT regime, the capital cost trend reverts to the usual where it goes down as the electricity demand reduces. The 4th system shows zero amount of excess energy for sale because it has no renewable energy component.

Table 6-57: Costs associated with \$0.07/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.07/kWh	21.53	0.0951	49,653	31,750	2,717	7,060
	14.29	0.1310	39,145	25,250	2,364	3,166
	7.31	0.1059	25,436	25,250	1,294	4,069
	4.82	0.3365	21,154	10,250	1,914	0

The relationship between the capital cost and cost of energy for Yola's optimised systems under the \$0.07/kWh FiT regime is of inverse proportionality as shown in Figure 6-39. As the capital cost increases, the cost of energy drops and vice versa. While the low capital cost of the 4th system may seem attractive due to absence of PV components, the system has the double disadvantage of higher cost of energy and the lowest energy output. Nevertheless, the 4th system presents the lowest

NPC because it contains less components and therefore lower component replacement costs in the long term.

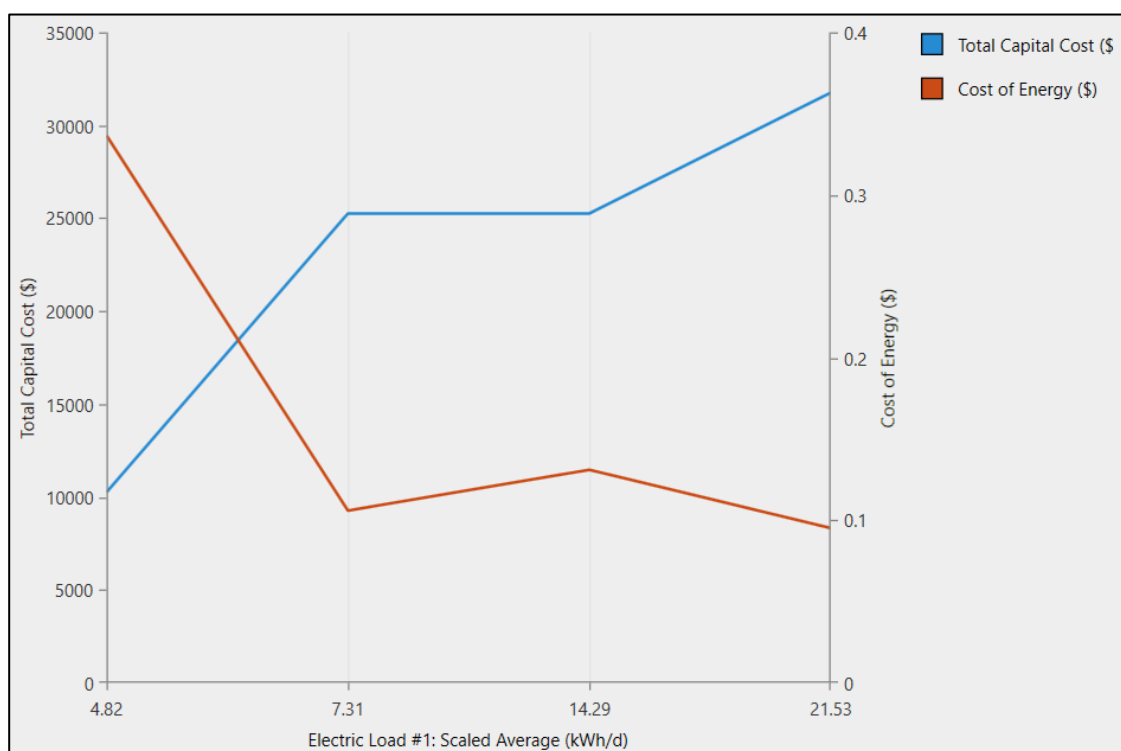


Figure 6-39: Capital cost vs. Cost of energy under \$0.07 FiT regime

On the other hand, the 1st system presents a capital cost that is 3.1 times that of the 4th system but has a CoE that is 3.5 times less. This indicates a slightly more optimal deployment of its component than the 4th system's. However, the 1st system presents NPC that is 2.3 times more than the 4th's over 25 years because of its higher replacement costs. It is also important to note that the 1st load profile is the only Yola system under the \$0.07/kWh FiT regime without an ICE generator. This means that it will be subject to scenarios of unmet loads when there are power outages for extended periods.

Like the other optimised systems in the other cities studied, Yola's systems presented better cost factors than their corresponding conventional systems as shown in Table 6-58. Over a conventional system, Yola's 1st optimised system presented CoE savings of \$0.393 /kWh; NPC advantage of \$86,979 over the system's 25-year lifetime; and annual operating cost savings of \$3,119. All these

savings came at an additional capital cost of \$24,250 over the cost of the conventional system.

Table 6-58: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Yola (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.0951	0.488	49,653	136,632	502	3,621	31,750	7,500
14.3	0.1310	0.7	39,145	130,171	390	3,440	25,250	7,500
7.31	0.1059	1.3	25,436	123,944	5	3,265	25,250	7,500
4.82	0.3365	1.94	21,154	121,722	306	3,203	10,250	7,500

6.7.1.3 Costs under Yola's \$0.00/kWh FiT regime

Yola's optimised systems under the zero FiT regime, present positive cost throughout like the other cities under the same FiT regime. CoE for optimised systems in Yola and Kano under this FiT regime are similar for the 1st and 2nd systems and the same for the 3rd and 4th systems. Meanwhile, Yola is the only city where all system costs are positive under both \$0.07/kWh and \$0.00/kWh FiT regimes. Even Kano, also a northern city, present negative operating costs under the \$0.07/kWh FiT regime. That is, enough income was generated to cover operating cost with some hundred dollars left over.

Table 6-59: Costs associated with \$0.00/kWh FiT regime

FiT Regime	Demand Profile (kWh/d)	CoE (\$)	NPC (\$)	Initial Capital (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
\$0.00/kWh	21.53	0.1598	58,238	25,250	3,662	2,364
	14.29	0.1989	45,409	18,750	429	1,336
	7.31	0.2763	26,285	10,250	2,748	0
	4.82	0.3376	21,178	10,250	1,911	0

The presence of solar PV components in the 1st and 2nd systems of Yola, and Kano, under the zero FiT regime points to the relatively high solar potential in northern Nigerian cities. Whereas, all southern cities had hydrokinetic components

in their optimised systems under the zero FiT regime, confirmation of their comparatively high microhydro potential. Furthermore, the lower costs presented under the zero FiT regime in the southern cities is confirmation that microhydro presents lower capital and operational costs than solar PV. The results also confirm that the energy density output of a hydrokinetic component per unit installed is higher than that of solar PV.

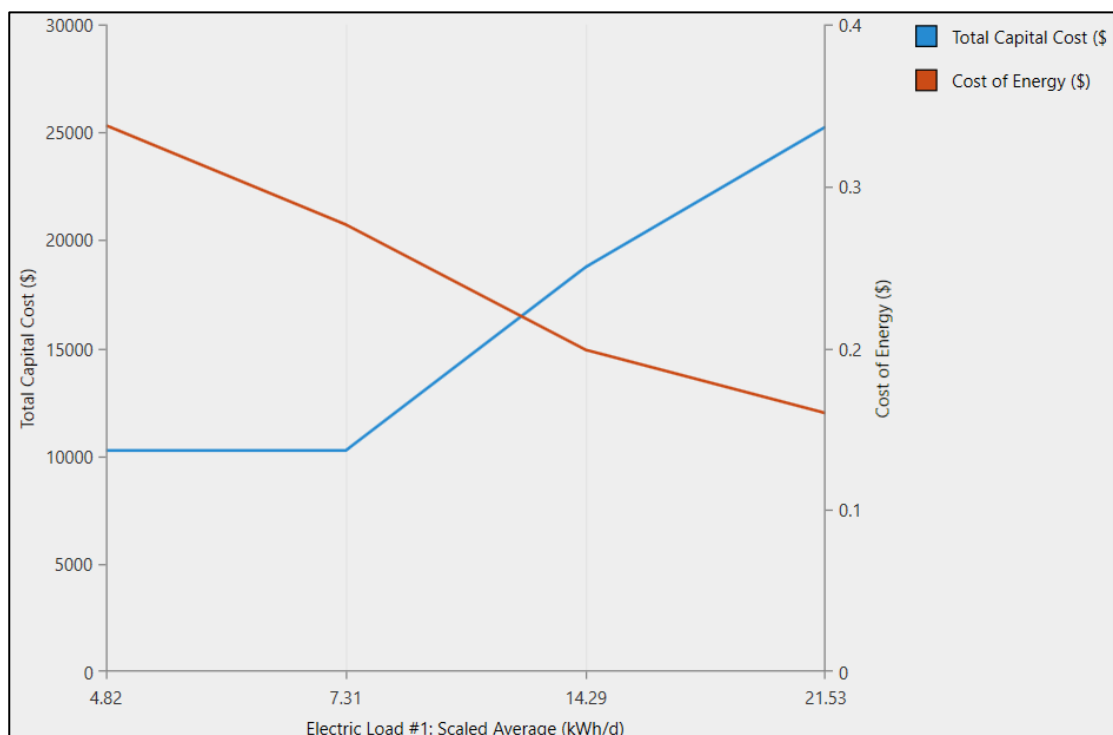


Figure 6-40: Capital cost vs. Cost of energy under \$0.00 FiT regime

Since Kano and Yola's capital costs across all systems under the zero FiT regime are the same and their CoEs are similar, the discussions of the relationship between capital cost and CoE for Kano is applicable to Yola.

On closer analysis, the comparison figures shown in Table 6-60 reveal that Yola's 1st optimised system presented cost savings over its corresponding conventional system as follows: \$0.328 /kWh less CoE; \$78,394 less NPC over 25 years; and \$2,696 less annual operating cost. Whereas, the conventional system presented a capital cost saving of \$17,750. This capital cost saving can be recovered over 6.5 years of operating cost savings from the optimal DER system.

Table 6-60: Optimal system costs vs. conventional system costs

Demand Profile (kWh/d)	CoE (\$)		NPC (\$)		Op Cost (\$/year)		Initial Capital (\$)	
	Optimal System Yola (FiT \$0.07/kWh)	System with Grid + Gen only	Optimal System	Grid+ Gen only	Optimal System	Grid + Gen only	Optimal System	Grid + Gen only
21.53	0.1598	0.488	58,238	136,632	925	3,621	25,250	7,500
14.3	0.1989	0.7	45,409	130,171	748	3,440	18,750	7,500
7.31	0.2763	1.3	26,285	123,944	450	3,265	10,250	7,500
4.82	0.3376	1.94	21,178	121,722	306	3,203	10,250	7,500

6.7.1.4 Capital Cost and Cost of Energy Comparison between all Yola Systems

Solar PV modules are present in all but three of the Yola's twelve optimal systems. This highlights the abundance of solar potential and paucity of other natural energy resources in Yola. It also explains why Yola's optimal systems have a relatively low average capital cost across board while presenting relatively high costs of energy. Yola's optimal systems do not have a regular pattern as some other cities like Kano and Abuja. Nevertheless, the systems under the \$0.07/kWh FiT regime appear to be the most cost effective except for the 4th system presenting a low capital cost and a high CoE. The systems under the other FiT regimes follow the same trend as their counterparts under the city of Kano.

It is important to note that, despite the northern cities' relatively high potential for wind energy compared with southern cities, none of the optimised system solutions includes the available wind turbine among its mix of components. This is mainly due to Nigeria's overall low relative wind speeds. The highest average monthly wind speed among the cities studied is 5.31 m/s recorded in Yola in March.

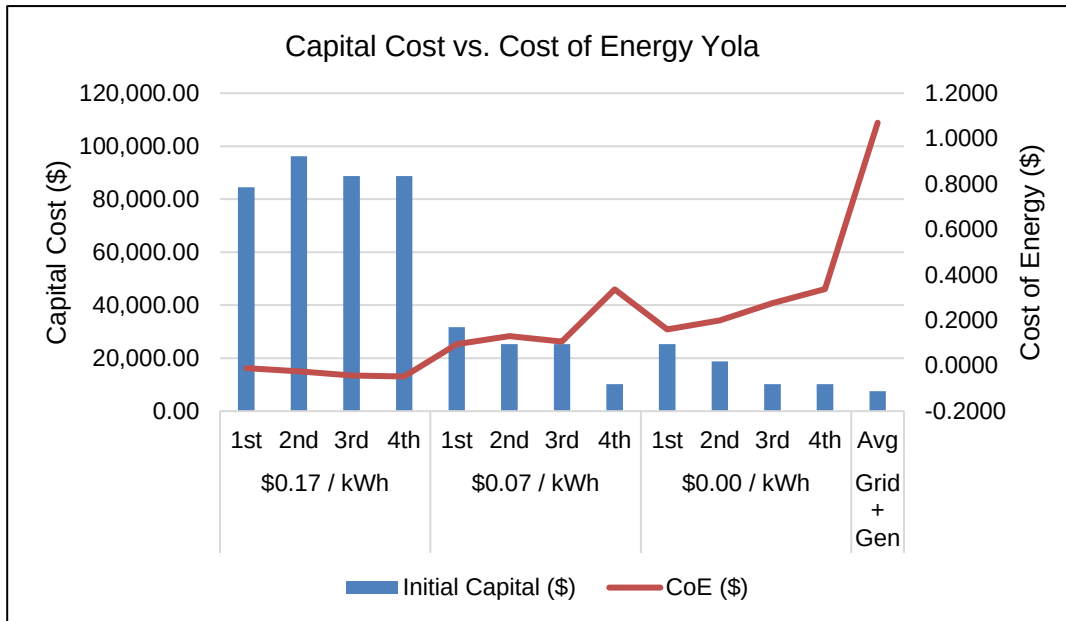


Figure 6-41: Capital cost vs CoE for system configurations in Yola

As stated in Chapter 2, most wind turbines start producing electricity at wind speeds between 3 and 4 m/s. However, Yola's annual average wind speed of 4.4 m/s is not high enough to justify the installation of the normally expensive wind turbines. Nevertheless, installation of offshore wind turbines along Nigeria's extensive coastline can be explored on a national utility scale.

6.7.2 System and Emission Factors of Optimal System Configurations for Yola

Table 6-61 below shows the technical variables associated with the optimised system configurations for the four load profiles under different FiT regimes in the city of Yola.

Table 6-61: Technical factors for system configurations in Yola

Sensitivities			Components	Technical/System Variables				
FiT Regime	Load / System Rank	Demand Profile (kWh/day)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
\$0.17 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	80	48,458	25,592	7,509	-15,478
	2nd	14.30	PV, Gen10, Battery x 5, Grid, HydroK	95	43,428	26,938	5,216	-12,777
	3rd	7.31	PV, Battery x 5, Grid, HydroK	98	42,297	28,206	2,553	-17,594
	4th	4.82	PV, Battery x 5, Grid, HydroK	99	42,105	28,722	1,686	-17,798
\$0.07 /kWh	1st	21.53	PV, Battery x 5, Grid, HydroK	81	19,646	7,060	7,576	-2,745
	2nd	14.30	PV, Gen10, Battery x 5, Grid	66	10,126	3,166	5,216	-507
	3rd	7.31	PV, Gen10, Battery x 5, Grid	80	8,621	4,069	2,668	-1,753
	4th	4.82	Gen10, Battery x 5, Grid	0	1,954	0	1,759	1,208
\$0.00 /kWh	1st	21.53	PV, Gen10, Battery x 5, Grid	56	11,845	2,364	7,858	821
	2nd	14.30	PV, Battery x 10, Grid	93	7,726	1,336	5,067	-573
	3rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
	4th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

6.7.2.1 Systems under Yola's \$0.17/kWh FiT regime

Besides the 2nd system that contains an additional ICE generator, Yola's optimised systems have the same set of components. The mix of components in Yola's systems are similar to that of Kano's. However, the energy produced by Yola's systems are conspicuously less than Kano's by an average of 17,200 kWh/year. This indicates that Yola's systems produce less renewable power than Kano's. This difference is evident in the hydro power output for both cities because Kano enjoys more annual precipitation than Yola (see Figure 4-14). Yola's average hydrokinetic power output across its systems under this FiT regime is 9,632 kWh/year whereas, Kano's average is 24,582 kWh/year.

Table 6-62: \$0.17 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1 st	2 nd	3 rd	4 th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	4,248	1,430	354	232	10,134
Carbon Monoxide	0	5.55	0	0	48.1
Unburned Hydrocarbons	0	0.202	0	0	1.75
Particulate Matter	0	0.336	0	0	2.92
Sulphur Dioxide	18.4	4.51	1.53	1.01	29.2
Nitrogen Oxides	9.01	7.78	0.750	0.492	62.7
Fuel Consumption (L/yr)	0	281	0	0	2,435

Furthermore, Yola systems under \$0.17/kWh FiT regime present lower net CO₂ emissions than Kano's, again, because of its lower renewable energy production. Nevertheless, their net emissions figures are similar across the 1st, 3rd and 4th systems where the composition of components are the same. This occurs because systems in both cities draw similar amount of power from the grid annually (see Appendix H).

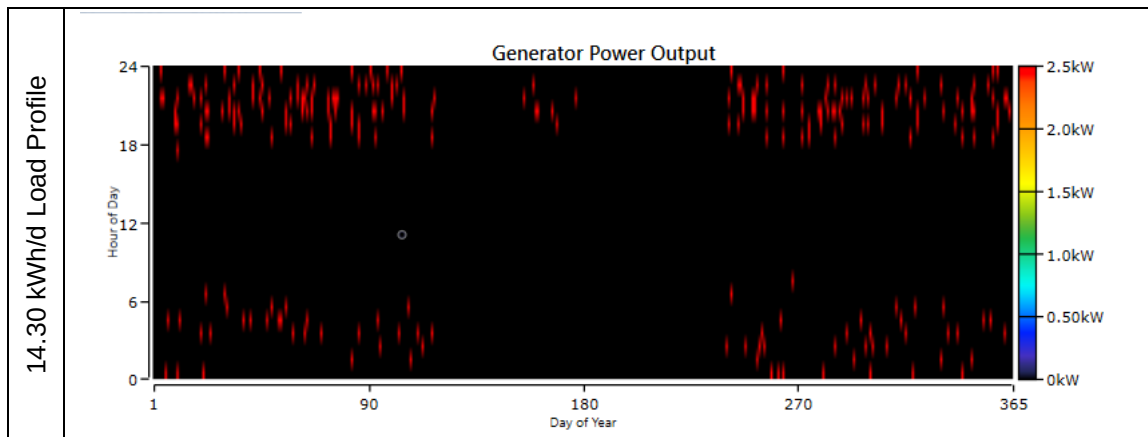


Figure 6-42: Generator outputs under \$0.17/kWh FiT regime

The 2nd Yola system bucks the trend of similarities between systems in Yola and Kano. This system presents a diesel generator in its mix of components and consequently a higher degree of pollutant emissions. Under this FiT regime, only the 2nd system presents generator-related emissions as shown Table 6-62. The system's annual generator activity is shown in the DMap in Figure 6-42. The concentration of generator activity during daytime hours confirms the relative abundance of solar resource in Yola. Furthermore, the paucity of generator activity during day and night time in the mid-year months shows availability of hydro power during this period.

6.7.2.2 Systems under Yola's \$0.07/kWh FiT regime

Under the \$0.07/kWh FiT regime, only two optimised systems, 2nd and 3rd, present the same mix of DER components as shown in Table 6-63. However, the 1st and 2nd systems present different mixes to the others. The 1st system is the only system that contains a hydrokinetic turbine and lacks a diesel generator. On the other hand, the 4th system is the only one that lacks a PV module. Understandably, the 4th system has only two DER components as the system with the smallest load. Whereas, the other systems have three DER components in addition to the grid.

One of the implications of the above is that the 1st system presents a substantial quantity of CO₂ savings – or the least net CO₂ emission - in relation to its load size and compared with the other system. However, the system will be prone to instances of unmet loads during periods of extended power outages. Another implication is that the 4th system presents the largest net CO₂ despite having the least load size. This is caused by the 4th system's lack of a renewable energy

component. The 2nd and 3rd systems both present net CO₂ savings in line with the percentage of renewable fraction of energy produced by each system.

Table 6-63: Technical factors associated with \$0.07/kWh FiT regime in Yola

Sensitivities		Components	Technical/System Variables				
System Rank	Demand Profile (kWh/d)		Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	PV, Battery x 5, Grid, HydroK	81	19,646	7,060	7,576	-2,745
2 nd	14.30	PV, Gen10, Battery x 5, Grid	66	10,126	3,166	5,216	-507
3 rd	7.31	PV, Gen10, Battery x 5, Grid	80	8,621	4,069	2,668	-1,753
4 th	4.82	Gen10, Battery x 5, Grid	0	1,954	0	1,759	1,208

The actual emission figures presented in Table 6-63 show a different pattern of emission levels between the systems compared with the pattern of net CO₂ emissions in Table 6-63. The 2nd system presents the highest actual emissions whereas, it had the second highest net CO₂ emission. This is caused by a combination of the system's relatively large electric load and the diesel generator in its component mix. Furthermore, the 1st system presents the second highest actual CO₂ emissions. However, it had the lowest net CO₂ emission. The 3rd system presents the overall lowest actual pollutant emissions because of the presence of a renewable energy producing component and its relatively small-sized load. On the other hand, the 4th system presents a disproportionately heavy emission figures because it has no renewable energy component.

Table 6-64: \$0.07 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1st	2nd	3rd	4th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	1,717	1,957	848	1,250	10,134
Carbon Monoxide	0	3.51	0.224	0.301	48.1
Unburned Hydrocarbons	0	0.128	0.00816	0.0110	1.75
Particulate Matter	0	0.213	0.0136	0.0183	2.92
Sulphur Dioxide	7.44	7.41	3.61	5.33	29.2
Nitrogen Oxides	3.64	7.15	1.99	2.91	62.7
Fuel Consumption (L/yr)	0	177	11.3	15.2	2,435

As shown in Figure 6-43 the generator activity for the 2nd system during night hours is high throughout the year. This is because the generator is required to charge the ten batteries in the system so that they can power the facility during daytime hours. The 3rd system presents a less active annual generator profile than the 4th system despite having a larger load. This is because the 3rd system contains an additional PV array which the 4th system does not possess. It is important to point out that Yola's optimised systems under the \$0.07/kWh FiT regime present the lowest generator activities across the different systems compared with the other cities.

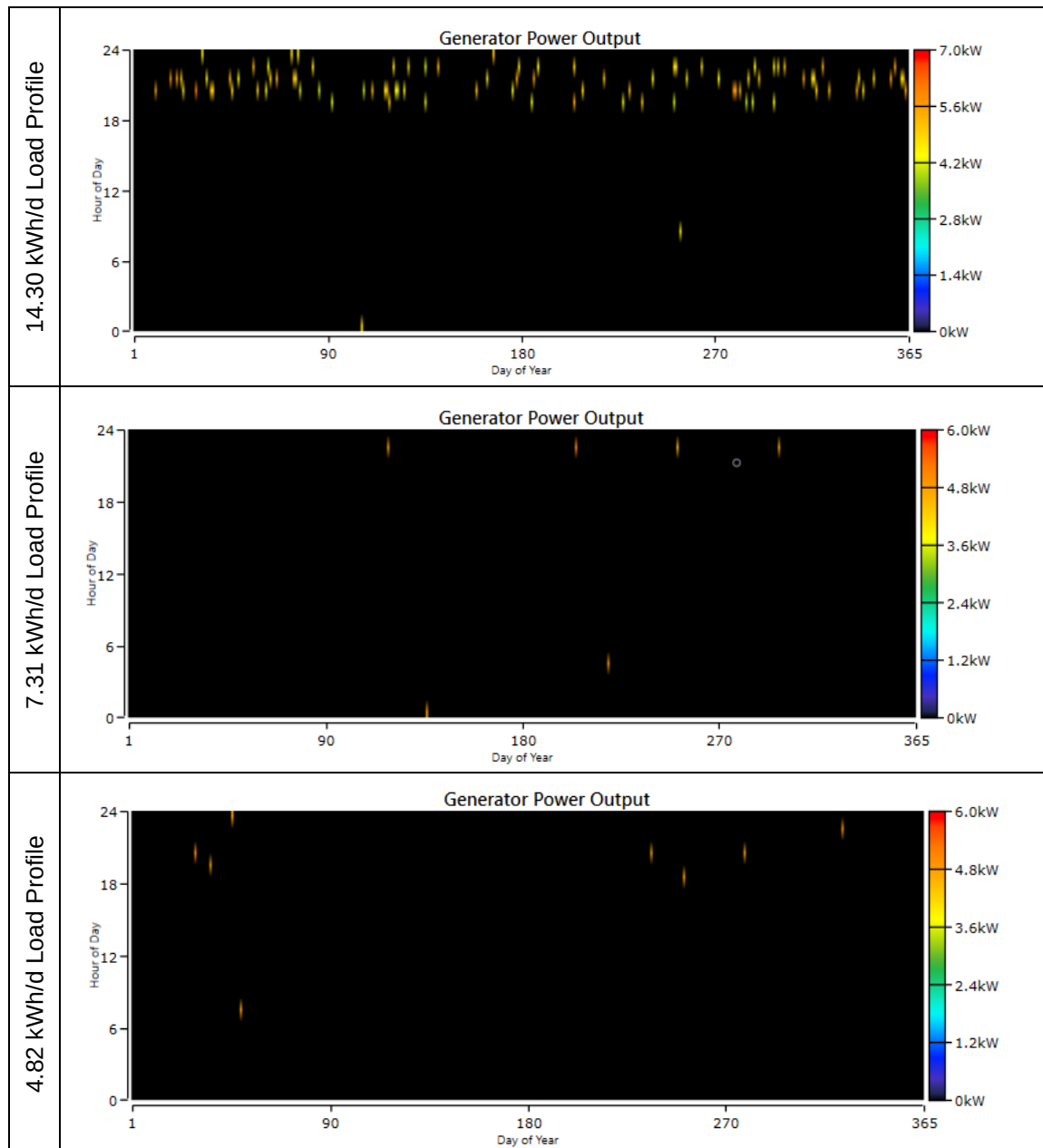


Figure 6-43: Generator outputs under \$0.07/kWh FiT regime

6.7.2.3 Systems under Yola's \$0.00/kWh FiT regime

Yola's optimised systems under the zero FiT regime are similar in component composition and in energy and pollutant emission outputs. The effect of Kano's higher solar potential is reflected more in the outputs for the 1st and 2nd systems due to the relatively large sizes of their loads. However, the 3rd and 4th systems present equal outputs for both cities under the \$0.00/kWh FiT regime. Yola's optimised 1st and 2nd systems present 56% and 93% renewable fraction of energy produced respectively compared with Kano's 58% and 95%. The other variables presented in Table 6-65 for Yola follow the same pattern of similarity with their Kano

counterpart. Hence the discussions under Kano's zero FiT regime are applicable to Yola's.

Table 6-65: Technical factors associated with \$0.00/kWh FiT regime in Yola

Sensitivities			Technical/System Variables				
System Rank	Demand Profile (kWh/d)	Components	Ren Fraction (%)	Energy Produced (kWh/yr)	Energy Sold (kWh/yr)	Energy used by Loads (kWh/yr)	Net CO ₂ (kg/yr)
1 st	21.53	PV, Gen10, Battery x 5, Grid	56	11,845	2,364	7,858	821
2 nd	14.30	PV, Battery x 10, Grid	93	7,726	1,336	5,067	-573
3 rd	7.31	Gen10, Battery x 5, Grid	0	2,951	0	2,668	1,737
4 th	4.82	Gen10, Battery x 5, Grid	0	1,951	0	1,759	1,208

Similarly, emission figures for Yola's optimised systems under this FiT regime are close to Kano's. The 1st and 2nd Yola systems (see Table 6-66) present slightly higher emissions figures than Kano's (see Table 6-55). However, the 3rd and 4th systems present the same emission figures. These similarities between Yola and Kano under the zero FiT regime is because of their similar solar resource potential and the lack of financial incentive to generate additional renewable power. When there is a positive fee-in-tariff in place, Kano's higher hydro potential is more evident in the higher amount of electrical power it produces compared with Yola.

Consequently, the discussions under Kano's \$0.00/kWh FiT regime emissions results are applicable to Yola. Similarly, the generator activity in the optimised systems for the two cities under this FiT regime are also similar as portrayed in Figure 6-44 and Figure 6-35.

Table 6-66: \$0.00 FiT optimal systems vs. conventional system emissions

Pollutant Emissions (kg/year) & Fuel Consumption (L/year)	Demand Profiles (kWh/d)				Grid + Gen Only
	1st	2nd	3rd	4th	
	21.53	14.30	7.31	4.82	
Carbon Dioxide (Actual)	3,201	271	1,940	1,248	10,134
Carbon Monoxide	6.70	0	1.54	0.301	48.1
Unburned Hydrocarbons	0.244	0	0.0560	0.0110	1.75
Particulate Matter	0.406	0	0.0932	0.0183	2.92
Sulphur Dioxide	11.8	1.18	7.94	5.32	29.2
Nitrogen Oxides	12.5	0.575	5.43	2.90	62.7
Fuel Consumption (L/yr)	339	0	77.8	15.2	2,435

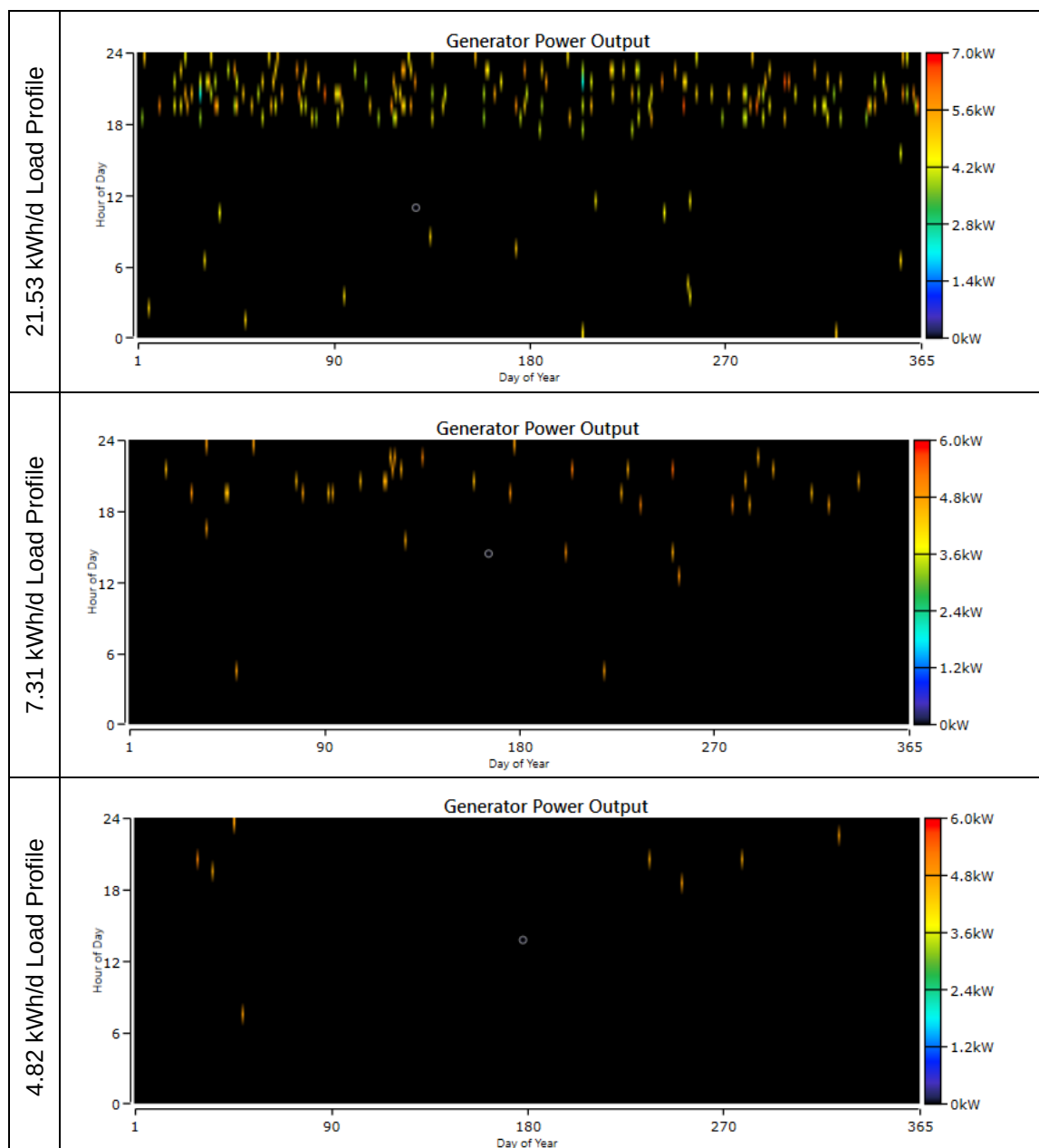


Figure 6-44: Generator outputs under \$0.00/kWh FiT regime

6.7.2.4 CO₂ and Particulate Matter (PM) Emissions Comparison between all Yola Systems

The key similarities between Yola's optimised systems and Kano's are limited to the zero FiT regime because of reasons explained in Section 6.7.2.3 above. Yola's 2nd systems under the \$0.17/kWh and \$0.07/kWh FiT regimes present relatively high particulate matter emissions. Whereas, the 1st systems under these two regimes present zero PM emissions in Yola (see Figure 6-45), just as obtainable in Kano (see Figure 6-37). Overall, the 3rd systems under Yola present the best CO₂ and PM emissions across all the FiT regimes.

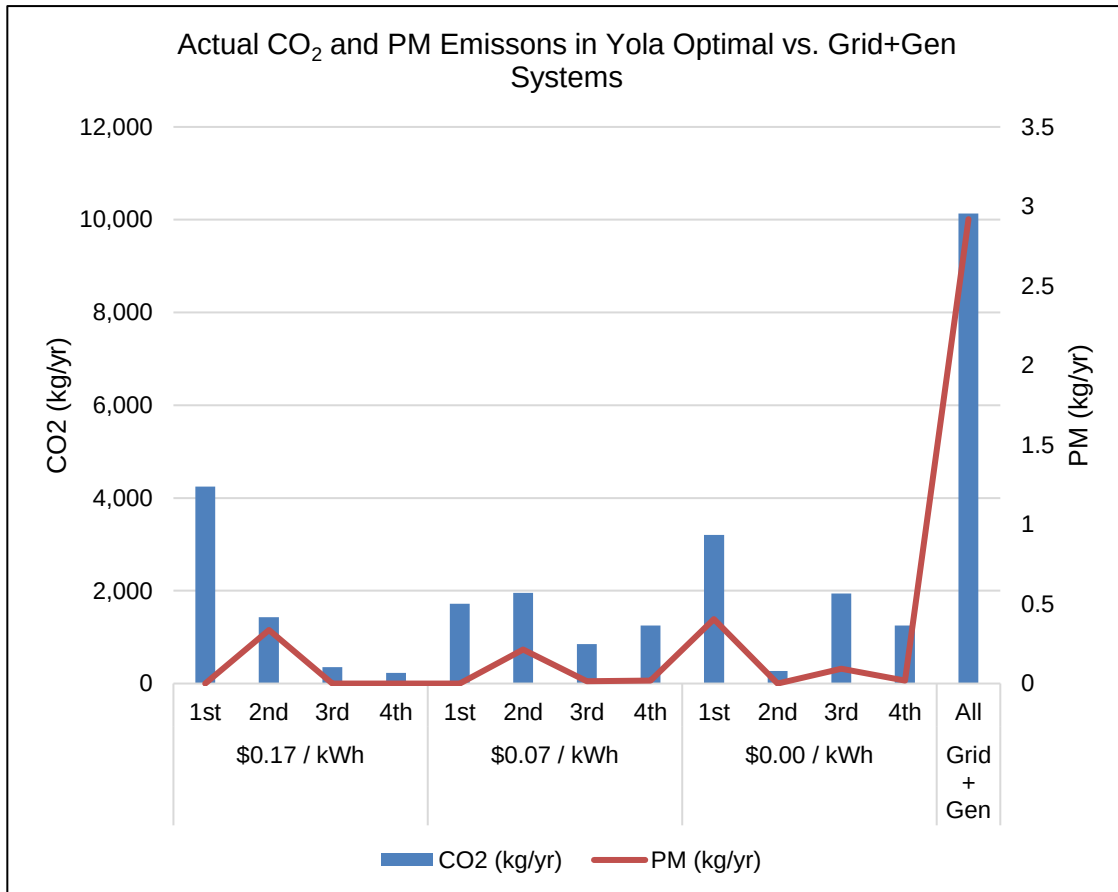


Figure 6-45: CO₂ vs. PM emissions for system configurations in Yola

6.8 Comparisons of 1st System Variables between Cities

Table 6-67 shows the configurations of all the optimised 1st systems modelled for the six Nigerian cities studied. The 1st systems provide power supply for the 21.53 kWh/day electric load profile for each city. Cities with similar renewable energy potentials largely present similar components in their systems under each FiT regime.

Table 6-67: 1st system components for all cities studies

City	FiT Regime	Components
Ibadan	\$0.17 / kWh	PV, Battery x 5, Grid, HydroK
Port Harcourt		PV, Battery x 5, Grid, HydroK
Awka		PV, Grid, HydroK
Abuja		PV, Battery x 5, Grid, HydroK
Kano		PV, Battery x 5, Grid, HydroK
Yola		PV, Battery x 5, Grid, HydroK
Ibadan	\$0.07 / kWh	Gen10, Battery x 5, Grid, HydroK
Port Harcourt		Battery x 5, Grid, HydroK
Awka		Battery x 5, Grid, HydroK
Abuja		Gen10, Battery x 5, Grid, HydroK
Kano		PV, Battery x 5, Grid, HydroK
Yola		PV, Battery x 5, Grid, HydroK
Ibadan	\$0.00 / kWh	Gen10, Battery x 5, Grid, HydroK
Port Harcourt		Battery x 5, Grid, HydroK
Awka		Battery x 5, Grid, HydroK
Abuja		Battery x 10, Grid
Kano		PV, Gen10, Battery x 5, Grid
Yola		PV, Gen10, Battery x 5, Grid

Systems under the \$0.17/kWh FiT regime generally have the same set of components. This is because of the availability of a high feed-in-tariff making the production of excess renewable energy for sale an attractive investment opportunity. Awka bucks the trend under this regime by presenting a wholly

renewable energy-based components in its system because of its more balanced hydro and solar potential. Port Harcourt and Awka present the same system components under the \$0.07/kWh and \$0.00/kWh FiT regimes due to the similarities in their renewable energy resource potentials. Similarly, Kano and Yola present the same system components under these FiT schemes. Ibadan and Abuja present dissimilar resource potentials with the other cities. Hence, their optimal systems generally have different mixes from the systems in other cities.

6.8.1 Comparing 1st System Costs between Cities

Table 6-68 shows the cost of energy and initial capital cost comparison between the six cities studied under the \$0.17/kWh FiT regime. The cities are ranked from the lowest to the highest. Port Harcourt, with the most abundant microhydro resource, presents the system with the best CoE under this FiT regime. On the other hand, Yola, with the highest CoE, presents the least capital cost under this FiT regime. Nevertheless, Port Harcourt presents the second lowest capital cost. The northern cities generally present higher costs than the southern cities because of their lower renewable energy potentials. Ibadan has the highest costs among the southern cities.

Table 6-68: Cost factor ranks under \$0.17/kWh

Rank	City	CoE (\$)	FiT Regime	City	Initial Capital (\$)
1	Port Harcourt	-0.1095	\$0.17 /kWh	Yola	84,500
2	Awka	-0.0882		Port Harcourt	88,700
3	Kano	-0.0510		Kano	88,700
4	Abuja	-0.0330		Awka	116,740
5	Ibadan	-0.0183		Ibadan	117,740
6	Yola	-0.0100		Abuja	117,740

Under the \$0.07/kWh FiT regime in Table 6-69, the CoE trend for the southern cities continues. Whereas, Kano took over from Abuja as the lowest CoE system among northern Nigerian cities. All the southern cities' systems present lower capital costs than any of their northern counterparts with Port Harcourt's system taking over from Yola's with the least capital cost. These indicate that selling excess energy at grid rates is more cost effective in southern Nigeria than in the north.

Table 6-69: Cost factor ranks under \$0.07/kWh

Rank	City	CoE (\$)	FiT Regime	City	Initial Capital (\$)
1	Port Harcourt	-0.0377	\$0.07 /kWh	Port Harcourt	22,700
2	Awka	-0.0284		Awka	22,700
3	Abuja	0.0294		Ibadan	26,000
4	Kano	0.0329		Abuja	30,200
5	Ibadan	0.0499		Yola	31,750
6	Yola	0.0951		Kano	37,700

In scenarios where there are no feed-in-tariffs in place, Port Harcourt still presents the system with the least cost of energy and the second lowest capital cost as shown in Table 6-70. On the other hand, Abuja' system with the lowest capital cost presents the highest cost of energy. This is because the optimisation of available resources in Abuja presents no financially viable renewable power component in the 1st system under the zero FiT regime. Hence, the low capital cost and the consequential high cost of energy.

Table 6-70: Cost factor ranks under \$0.00/kWh

Rank	City	CoE (\$)	FiT Regime	City	Initial Capital (\$)
1	Port Harcourt	0.0574	\$0.00 /kWh	Abuja	3,750
2	Awka	0.0581		Port Harcourt	16,750
3	Ibadan	0.1040		Awka	16,750
4	Kano	0.1527		Ibadan	24,250
5	Yola	0.1598		Kano	25,250
6	Abuja	0.2224		Yola	25,250

Overall, Port Harcourt proves to be the most cost effective city to set up a DER system because of its relatively abundant hydro potential. However, Yola presents the highest cost of energy and capital cost overall. Among the southern cities, Ibadan is the costliest. Whereas, Abuja, with an average ranking of 3.5, has the least costly system among the northern cities. From Kano, the systems start becoming unaffordable because they cost more than the benchmark cost of \$0.14/kWh. However, they all present lower costs than a reliable conventional system with an average cost of \$1.107/kWh.

6.8.2 Comparing 1st System CO₂ and PM Emissions between Cities

Despite Awka's system producing the second highest quantity of energy per annum, it has the lowest actual annual CO₂ emission under the \$0.17/kWh FiT

regime as shown in Table 6-71. This is because Awka has a combination of relatively high hydro and solar potential. Awka has the second highest overall precipitation levels after Port Harcourt and the second highest solar radiation among southern cities. On the other hand, the systems of Yola and Kano, two northern cities, present the highest CO₂ emissions with some of the lowest annual power production. However, Kano presents a higher annual energy production than the southern city of Ibadan due to its high solar resource.

Table 6-71: CO₂ emission and energy produced ranks under \$0.17/kWh

Rank	City	CO ₂ (kg/yr)	FiT Regime	City	Energy Produced (kWh/yr)
1	Awka	588	\$0.17 /kWh	Port Harcourt	119,422
2	Port Harcourt	711		Awka	96,760
3	Ibadan	729		Abuja	68,451
4	Abuja	3,974		Kano	65,863
5	Yola	4,248		Ibadan	52,384
6	Kano	4,298		Yola	48,458

Again, Awka presents the lowest CO₂ emissions under the \$0.07/kWh FiT regime despite producing the second highest quantity of electric energy as shown in Table 6-72. Systems in the northern cities emit comparatively less pollutant emissions under this FiT regime because of the moderate incentive to generate renewable energy. This means that, instead of the systems to be optimised for energy sale, charging of the batteries is prioritised. When renewable energy generation is optimised for energy sale, as is obtainable on the \$0.17/kWh FiT regime, the grid and generator are prioritised for the charging of the energy storage system. This results in higher emissions figures.

Table 6-72: CO₂ emission and energy produced ranks under \$0.07/kWh

Rank	City	CO ₂ (kg/yr)	FiT Regime	City	Energy Produced (kWh/yr)
1	Awka	1,573	\$0.07 /kWh	Port Harcourt	95,725
2	Kano	1,634		Awka	71,472
3	Yola	1,717		Kano	35,004
4	Port Harcourt	1,958		Abuja	34,562
5	Ibadan	2,581		Ibadan	26,514
6	Abuja	3,495		Yola	19,646

The southern cities of Port Harcourt and Awka remain the leading renewable energy producers under the \$0.07/kWh FiT regime due to their relatively high hydro potential. Kano, with the best solar potential, is a distant third highest energy producer followed by Abuja with a balanced solar and microhydro potential. Ibadan and Yola have the overall lowest renewable energy potentials respectively.

Systems in the northern cities present high CO₂ emissions and low energy production because of the high cost of solar PV. When there is no feed-in-tariff scheme in place, the installation of PV modules for systems with heavy loads becomes less cost effective. Hence, the systems in the northern cities under the zero FiT regime contain little renewable energy components with few solar PV modules of 5 kW compared with 22 kW under the \$0.17/kWh FiT regime.

Table 6-73: CO₂ emission and energy produced ranks under \$0.00/kWh

Rank	City	CO ₂ (kg/yr)	FiT Regime	City	Energy Produced (kWh/yr)
1	Awka	1,571	\$0.07 /kWh	Port Harcourt	95,722
2	Port Harcourt	1,956		Awka	71,469
3	Ibadan	2,579		Ibadan	26,511
4	Kano	3,087		Kano	12,231
5	Yola	3,201		Yola	11,845
6	Abuja	5,187		Abuja	8,208

Table 6-73 shows that systems in Port Harcourt and Awka present the best CO₂ emission and energy production results. Overall, the southern cities produced systems that performed better in these two categories than the northern cities under zero feed-in-tariff settings. Under this FiT regime, the systems have presented energy production rankings in an order that is proportional to the combined solar and hydro potential of each city.

6.8.3 Comparing CO₂ Emissions in Grams of CO₂ Equivalent Per kWh Electricity Generated (gCO_{2-eq}/kWh)

In line with previous discussions, southern Nigerian cities generally present systems with lower CO₂ emissions per kWh energy produced due to their higher hydro potentials. Figures Figure 6-46, Figure 6-47 and Figure 6-48 illustrate CO₂ emissions comparisons between the cities considered in gCO_{2-eq}/kWh under \$0.17/kWh, \$0.07/kWh and \$0.00/kWh FiT regimes respectively. It is important to point out that, every optimised system presented gCO_{2-eq}/kWh emission figures

well below the environmental sustainability and health benchmark of ≤ 1000 gCO₂-eq/kWh. The highest optimal system CO₂ emission per energy produced is 692.64 gCO₂-eq/kWh in Abuja's 2nd system under the zero FiT regime.

In Figure 6-46, the 1st system in every city presented the highest emission per unit energy. Generally, emission per unit energy increases as energy demand increases. It is possible to assume that, while larger systems produce larger overall emissions, they should produce less CO₂ per unit energy due to economies of scale. However, these results suggest that the higher intensity of energy consumption by the larger loads and the consequential need to regularly supplement renewable power with conventional power is responsible. Nevertheless, it is important to note that the higher emissions per unit energy presented by the 1st systems are only in tens of grams of CO₂ more than the other systems for each city.

Figure 6-47 shows a milder difference between the 1st systems and the other systems in each city under the \$0.07/kWh FiT regime. Port Harcourt and Awka systems present much lower CO₂ emission per unit energy than the other cities as expected. However, Yola's 4th system presents a significantly high CO₂ emission per unit energy that was not evident when actual CO₂ emissions are considered as illustrated in Figure 6-45.

It is therefore important for decision makers to differentiate between total actual CO₂ emissions and CO₂ emission per unit energy. Generally, a system with a relatively small load but regularly operates its diesel generator will present a low total CO₂ emission but significantly high CO₂ per unit energy produced.

Figure 6-48 highlights the CO₂ emission per unit energy for systems under the zero FiT regime in each city. The 1st and 2nd systems in all the cities present much lower gCO₂-eq/kWh emissions than the other systems except for Abuja. Abuja's 1st and 2nd systems present similar emission levels as its 3rd and 4th systems. This is because none of the Abuja optimal systems contain a renewable power component.

In summary, CO₂ emissions per unit energy produced tend to be less when energy demand is low and there are renewable power components in the system

compared to scenarios where energy demand is high. On the other hand, CO₂ emissions per unit energy tend to be higher in systems with less loads but no renewable power components compared with equivalent systems with larger loads.

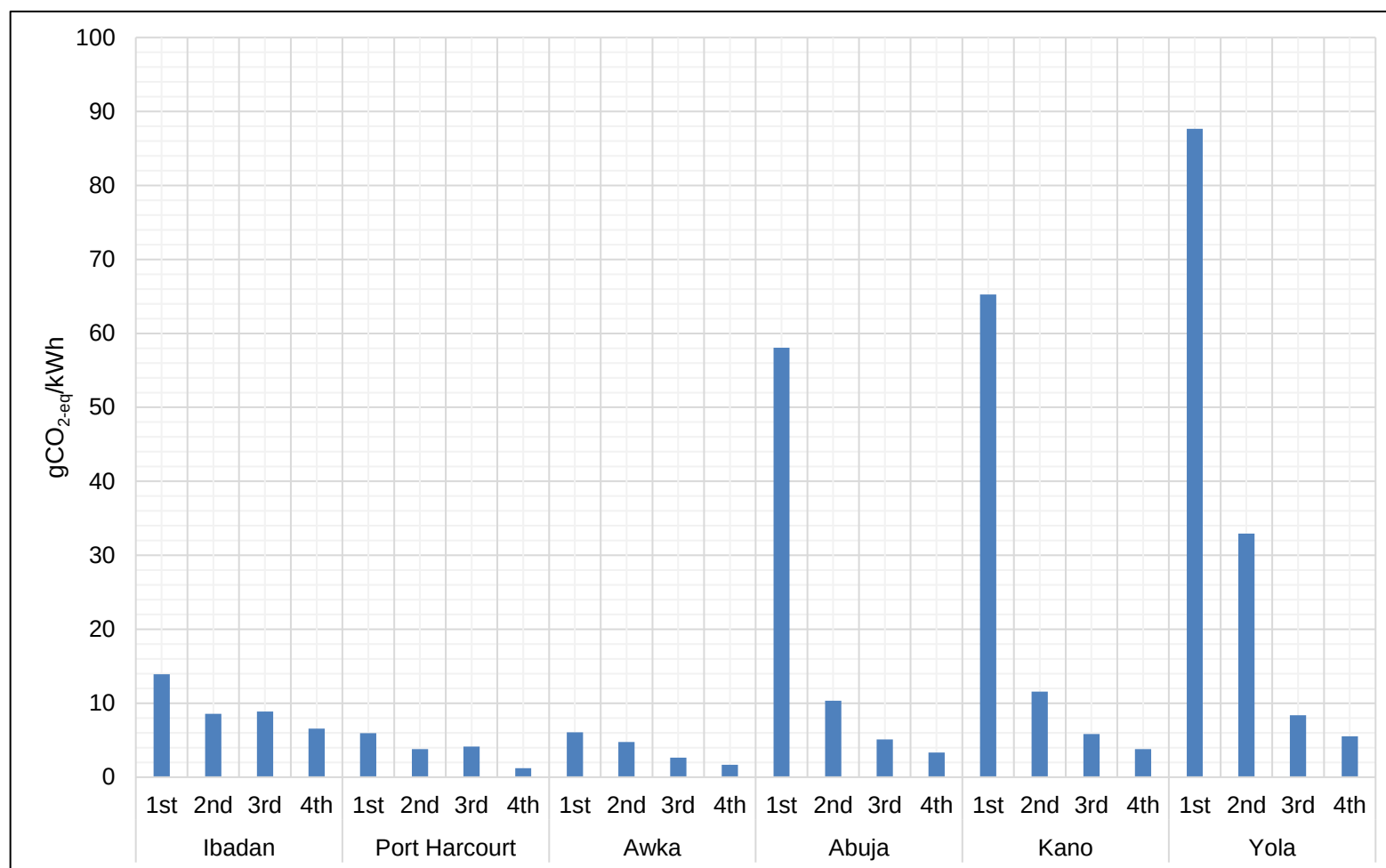


Figure 6-46: Carbon dioxide emissions per unit energy produced under \$0.17/kWh FiT regime

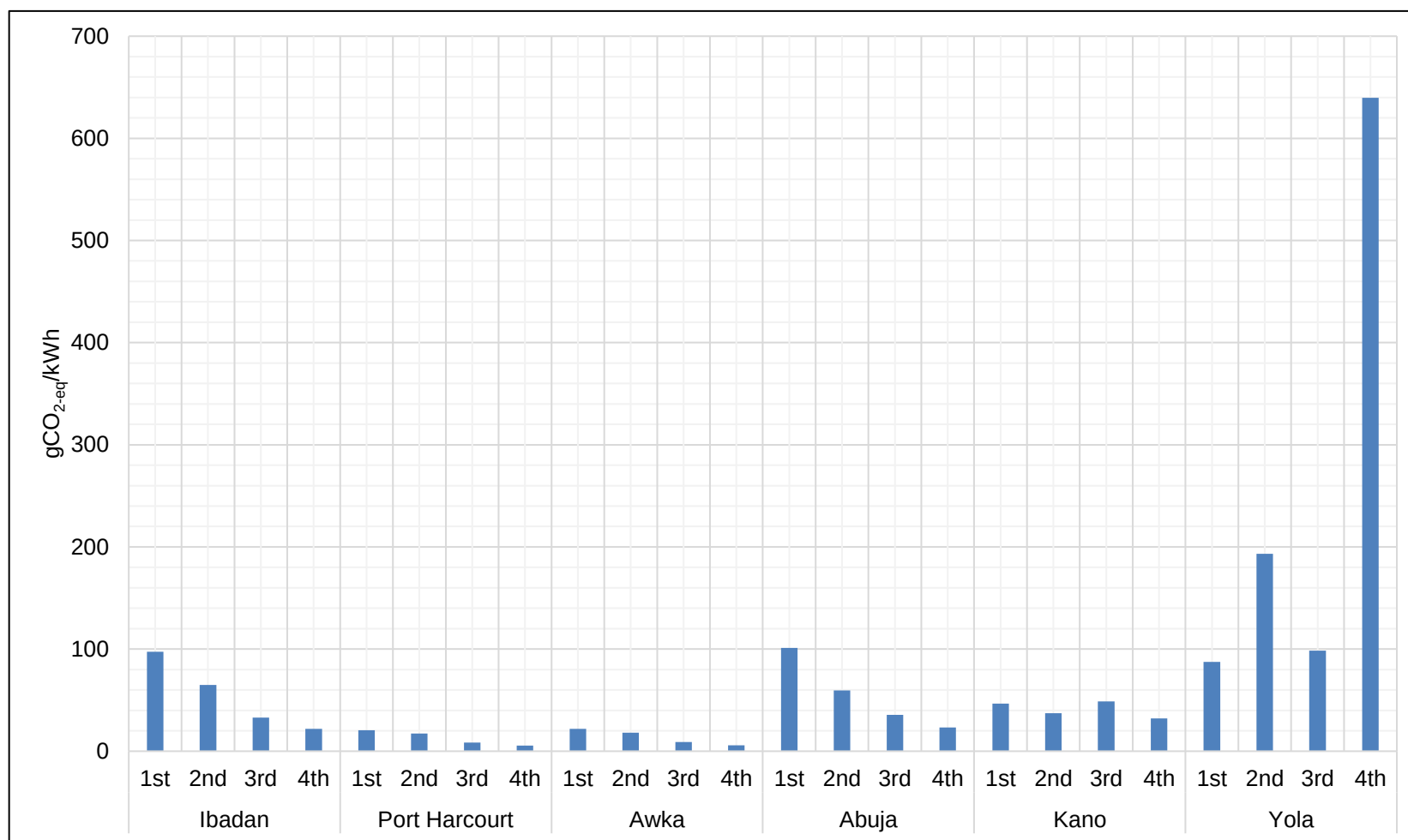


Figure 6-47: Carbon dioxide emissions per unit energy produced under \$0.07/kWh FiT regime

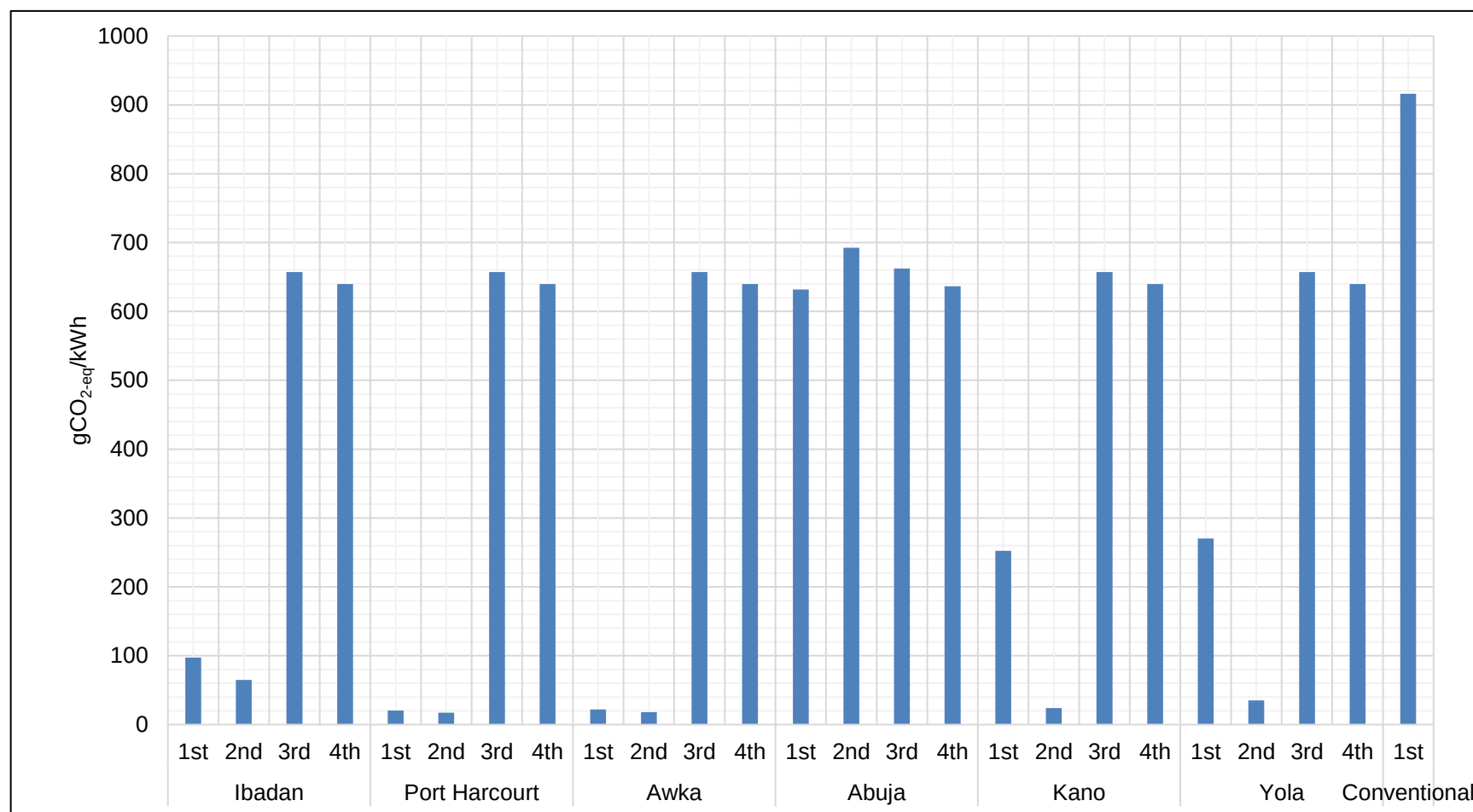


Figure 6-48: Carbon dioxide emissions per unit energy produced under \$0.00/kWh FiT regime + conventional system

6.9 Summary and Contribution to Knowledge

Distributed energy resource systems were modelled for six cities in Nigeria's six geopolitical regions. The models were based on four energy demand profiles in a pre-determined common emergency treatment process for a typical secondary health facility. The energy demand profiles include 21.53, 14.29, 7.31 and 4.82 kWh/day of daily energy demand, representing electrical energy demand for essential conventional devices, essential energy-efficient devices, critical conventional devices, and critical energy-efficient devices respectively. The models included the simulation of power generating systems that included components of 1 kW solar PV modules, 10 kW wind turbine, 10 kW hydrokinetic turbine, 10 kW diesel generator, and 1 kWh Li-ion batteries combined with Nigeria's 50% reliable utility grid.

Furthermore, three feed-in-tariff regimes were considered for evaluating the cost of energy for the optimal power supply configurations generated from the simulations conducted. \$0.17/kWh FiT regime represented the feed-in-tariff in place in Nigeria in 2016. The \$0.07/kWh FiT regime represented the grid tariff for health facilities in Nigeria in 2016. This mirrors scenarios where excess power generated by the facility cannot be fed into the grid but can be sold to other users. Lastly, the \$0.00/kWh FiT regime represented situations where, excess electricity generated can neither be absorbed by the grid nor can it be sold to other users. Direct cost, system and emission comparisons between optimal systems generated and conventional (grid and diesel gen only) systems for each city were made. CoE benchmark of $\leq \$0.14/\text{kWh}$ was determined to measure affordability of each optimised system. Also, CO₂ emission benchmark of $\leq 1000 \text{ gCO}_2\text{-eq/kWh}$ was determined to evaluate their environmental sustainability.

Following the conclusion of the simulations, the following contributions to knowledge were discussed:

- The inclusion of a bank of Li-ion batteries to a power system goes a long way to stabilise the system without increasing capital and operating costs significantly. This is more relevant in low energy demand scenarios where daily requirements are below 8 kWh/day. In higher energy demand

scenarios, there is need for additional source of power generation to recharge the batteries. This can be in the form of increasing the size of the diesel generator which will result in higher operational costs and harmful emissions. Otherwise, the inclusion of low cost and low maintenance renewable energy components like the hydrokinetic turbine with the mix of batteries, grid, and diesel generator is economically viable. Although very popular, solar PV is comparatively viable only in scenarios when there is a feed-in-tariff regime in place because of the potential to sell excess energy generated.

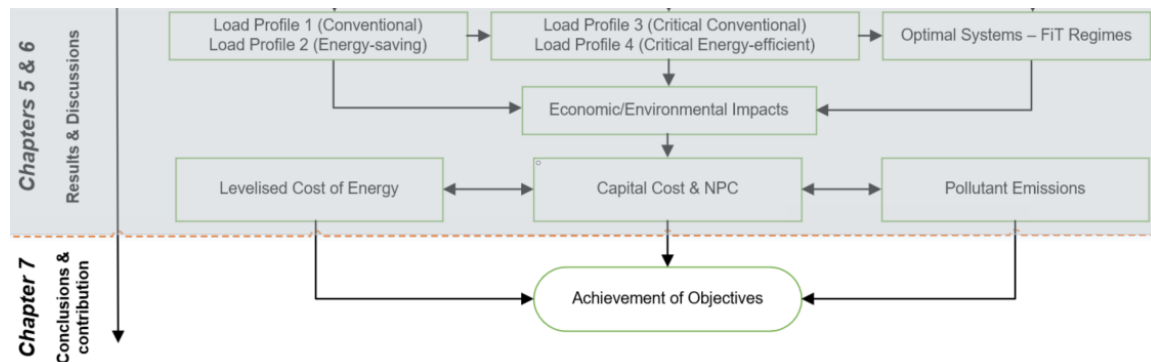
- Ibadan presented optimised systems with the highest capital costs while Awka presented the lowest. Port Harcourt presented the least CoE while Yola had the highest. Port Harcourt also presented the lowest CO₂ emissions and Yola had the highest. Optimised systems in Nigeria's south-south cities presented more systems with the hydrokinetic turbine than the other regions. Whereas, the two inner northern cities of Kano and Yola presented more PV modules in their optimal systems. These are in line with the level of hydro and solar potential of these cities, highlighted in Chapter 4.
- In Ibadan, systems generated under the \$0.17/kWh FiT regime have significantly higher capital costs ($\geq \$117,740$) compared with the other regimes ($\leq \$26,000$). Whereas, the costs of energy across the \$0.17/kWh FiT regime are not as significantly lower than in the systems under the \$0.07/kWh FiT regime. Nevertheless, there is a net income for energy generated under the \$0.17/kWh FiT regime. The CoEs across the zero FiT regime are much higher than the CoE for the other FiT regimes. Every optimal system generated for Ibadan presented CoE below \$0.338/kWh compared with the benchmark of \$0.14/kWh and average CoE of \$1.107/kWh for conventional systems. The hydrokinetic turbine featured in all but two systems, PV only in the four systems under the \$0.17/kWh FiT regime. Whereas, none of the Ibadan optimal systems presented a wind turbine in their configurations. Furthermore, the optimised DER system with the highest CO₂ emission in Ibadan presented with 13.92 gCO₂-eq/kWh compared with the CO₂ emission benchmark of ≤ 1000 gCO₂-eq/kWh.

- In Port Harcourt, the optimal systems under the \$0.17/kWh FiT regime presented much higher capital costs ($\geq \$87,700$) compared with systems under the other FiTs ($\leq \$30,200$) across the load profiles considered but not much lower CoEs compared with systems under the other FiT regimes. CoE of every optimised system under the \$0.17/kWh and \$0.07/kWh FiT regimes in Port Harcourt presented net income for every kWh of electrical energy generated. Meanwhile, CoEs of systems under the zero FiT regime are much higher than under the other FiT regimes. Every optimal system generated for Port Harcourt presented CoE below \$0.3376/kWh. The hydrokinetic turbine featured in all but two systems, PV only in the four systems and no wind turbine in any of the optimised systems. The optimised DER system with the highest CO₂ emission in Port Harcourt presented with 5.95 gCO₂-eq/kWh.
- In Awka, the capital costs under the \$0.17/kWh FiT regime ($\geq \$43,300$) are not as significantly higher than under the other FiT regimes ($\leq \$30,200$) like Ibadan and Port Harcourt. Like Port Harcourt, CoE of every optimised system under the \$0.17/kWh and \$0.07/kWh FiT regimes in Awka presented net income for every kWh of energy generated. The zero FiT regime presented much higher CoE compared with the other regimes. Every optimal system generated for Awka presented CoE below \$0.3376/kWh like Port Harcourt. The mix of power generating components are also similar to those under Port Harcourt. However, the optimised DER system with the highest CO₂ emission in Awka presented with 6.08 gCO₂-eq/kWh.
- In Abuja, the capital costs of optimal systems under the \$0.17/kWh FiT regime (\$117,740) are much higher than the other FiT regimes ($\leq \$30,200$), like in Ibadan and Port Harcourt. The CoE of all the systems under the \$0.17/kWh FiT regime and one system under the \$0.07/kWh FiT regime presented net income for energy produced. Similar to the other cities, systems under the zero FiT regime present much higher CoEs than the other FiT regimes. Every optimal system generated for Kano presented CoE below \$0.3324/kWh. The hydrokinetic turbine featured in all systems under the \$0.17/kWh and \$0.07/kWh FiT regimes but in none of the \$0.00/kWh

FiT regime systems. PV presented only in the four systems and no wind turbine in any of the systems. The optimised DER system with the highest CO₂ emission in Abuja presented with 58.06 gCO_{2-eq}/kWh.

- In Kano, the capital costs of optimal systems under the \$0.17/kWh FiT regime ($\geq$ \$88,700) are fairly higher than in the other FiT regimes ($\leq$ \$45,200), and not as significantly higher like in Ibadan and Port Harcourt. Only optimal systems under the \$0.17/kWh FiT regime presented net income for every unit energy produced. CoE under zero FiT regime is much higher than in systems under the other FiT regimes. Every optimal system generated for Kano presented CoE below \$0.3376/kWh. The hydrokinetic turbine featured in all systems under the \$0.17/kWh and \$0.07/kWh FiT regimes but in none of the \$0.00/kWh FiT regime systems. However, PV presented in all \$0.17/kWh FiT regime systems and in two systems each under the \$0.07/kWh and \$0.00/kWh FiT regimes, making eight systems with PVs in Kano. There is no wind turbine in any of Kano systems. The optimised DER system with the highest CO₂ emission in Kano presented with 65.26 gCO_{2-eq}/kWh.
- In Yola, the capital costs of optimal systems under the \$0.17/kWh FiT regime ($\geq$ \$84,500) are fairly higher than in the other FiT regimes ($\leq$ \$31,750), similar to Kano. Only optimal systems under Yola's \$0.17/kWh FiT regime presented net income for unit energy generated. Like in other cities, CoE under zero FiT regime is much higher than in systems under other FiT regimes. Every optimal system generated for Yola presented CoE below \$0.3376/kWh, like in Kano. System component configurations in Yola's systems are similar to those in Kano, except for Yola having PV modules in one more system than Kano. Like optimal systems in every other city considered, there is no wind turbine in any of Yola's systems. The optimised DER system with the highest CO₂ emission in Yola presented with 87.66 gCO_{2-eq}/kWh.

7 CONCLUSIONS, CONTRIBUTION AND RECOMMENDATIONS FOR FUTURE WORK



7.1 Introduction

The deductions made from preceding chapters and the conclusions drawn from this study are presented in this chapter in line with the research objectives. The key contributions of this doctoral research are outlined. Furthermore, the areas outside the scope of this research are identified and presented as potential areas for further investigation.

7.2 Conclusions

In this research, an advancement to existing health energy provision frameworks has been developed using the Health Failure Modes and Effects analysis to create lower levels of health facility energy demand. Economic and environmental sustainability metrics parameters have also been used to determine cost effective and environment friendly energy supply options. The following are the conclusions of this research presented in line with the three phases of the research, which are aligned to the research objectives:

7.2.1 The identification, classification and energy demand assessment of essential electrical applications in a health facility

Electricity needs in health facilities have been identified and classified under infrastructure (e.g. lighting), medical devices (e.g. blood chemistry analyser) and appliances for specific services (e.g. vaccine refrigerator). Using a team of secondary health facility staff, an emergency treatment process requiring relatively substantial electrical energy was determined. An energy assessment was

conducted based on all the essential electrical equipment required for the treatment. Daily energy requirement for the identified essential loads amount to a maximum 21.53 kWh/day for conventional equipment and minimum 14.29 kWh/day for energy-efficient equipment.

The results of the focus group-based energy assessment for essential electrical applications for a secondary or tier 3 health facility agrees fairly with WHO's assessment of a lower level health facility. This study's assessment resulted in the figures stated above. Whereas, WHO's assessment indicated 8.61 kWh/day and 5.95 kWh/day energy demand for conventional and energy-efficient devices respectively in a primary health facility or a tier 2 health clinic.

7.2.2 The prioritisation of critical treatment applications using HFMEA to create lower levels of energy demand

The HFMEA approach was employed to assess the selected treatment process for the prioritisation of the treatment sub-processes and their applications. Employing another team of 6 health professionals, for main steps were identified in the treatment process, and the diagnostics step was selected as the most critical step requiring the highest level of energy demand. A reduced energy demand profile was created based on the diagnostic process. A maximum critical energy demand of 7.31 kWh/day was determined for conventional diagnostic devices. Whereas, a minimum critical energy demand of 4.82 kWh/day was determined for energy-efficient diagnostic devices. Within the diagnostic process, the blood chemistry analyser was identified as priority due its importance and lack of DC alternatives. Using the maximum and minimum essential and critical energy demand profiles, an Event Resilience Index of 0.34 was determined. This implied that any alternative energy supply system created for the facility must be able to provide at least 34% of the facility's energy demand at any time for the facility to provide its primary functions.

7.2.3 The techno-economic analysis of competing DERs through HOMER to determine cost effective and environment friendly microgrid systems

The Hybrid Optimisation of Multiple Energy Resources modelling software was used to simulate multiple configurations and mixes of solar, wind, microhydro, Li-

ion battery storage, and diesel generator components with the Nigerian utility grid. Six cities from Nigeria's six geopolitical regions were selected for the modelling of distributed energy resources to match the identified energy demand profiles. Three feed-in-tariff regimes were created as follows: 1) \$0.17/kWh FiT regime representing Nigeria's current (2016) feed-in-tariff for renewable power generation; 2) \$0.07/kWh FiT regime to represent Nigeria's current grid tariff for health facilities; and 3) \$0.00/kWh FiT regime representing situations where excess renewable power cannot be sold for an income. The following conclusions can be drawn from the results of the techno-economic and environmental sustainability results:

- Southern Nigerian cities presented higher numbers of DER systems with hydrokinetic turbines, confirming evidences from literature regarding higher hydro potential in southern Nigeria. Similarly, northern Nigerian cities presented higher numbers of systems containing solar PV modules than southern cities due to their higher solar potentials. Therefore, microhydro systems are more financially and reliably viable in southern Nigeria while solar PV has the potential to deliver energy more reliably in northern Nigeria.
- On the average, capital cost for solar power in Nigeria is 6.2 times more expensive per kWh of capacity installed compared to hydrokinetic power. Furthermore, solar PV modules require a lot more installation space per kWh than hydrokinetic turbine technology.
- When feed-in-tariff is high (e.g. FiT higher than utility tariff), investment in the expansion of DER capacity presents quick cost recovery and higher income potentials. This can in turn result in an optimised system prioritising RE generation for sale instead of storage, leaving the facility to require back-up generators during extended power outages
- Powering a facility using microgrids, even in mixes containing diesel generators, present lower net pollutant emissions when compared with total dependence on a reliable utility grid.
- DER systems that are required to supply large electrical (≥ 20 kWh/day) The inclusion of solar PV components in off-grid electricity systems becomes financially viable when the feed-in-tariff regime is in effect.

Otherwise, the use of Li-ion batteries combined with a diesel generator and the grid are suitable for low-energy demand scenarios less than 8 kWh/day with the inclusion of a hydrokinetic turbine when demand is higher.

- loads require back-up generators to ensure reliability of supply. The cost of purchasing and replacing ESS to cover large electrical loads can be prohibitive in poor settings compared with cheaper diesel generators.
- Every optimal system generated included the grid connection in its mix of power sources despite the poor reliability of the Nigerian electricity grid. However, this is based on a 50% reliability index for Nigeria's grid. This can be less in some places. Lower measures of grid reliability need to be modelled to ascertain the level of reliability where grid connection will no longer be economically and reliably viable.
- Despite the inclusion of a wind turbine in the mix of renewable energy generating components, none of the optimised systems presented a wind turbine. This is at odds with claims of high wind potential in northern Nigeria highlighted in some texts reviewed. Due to the relatively low wind speeds in the Nigerian cities studied, the installation of a wind turbine will present a weak investment in terms of return on investment over the system's lifetime.
- Systems containing a diesel generator that power smaller loads will present a relatively high $\text{gCO}_2\text{-eq/kWh}$ of CO_2 emissions compared with systems with large loads. Whereas, systems that produce less energy will present lower kg/kWh of CO_2 emissions.

7.3 Contribution to Knowledge

In line with the stated objectives, the key contributions and findings of this research are outlined as follows:

- Through in-depth review of literature, essential electrical applications in healthcare facilities identified and classified as: 1) Infrastructure such as lighting, computer systems and communication equipment. 2) Medical devices such as heart monitors, suction devices and x-ray equipment. 3) Specific services such as refrigeration, blood analysis and neo-natal incubation.

- By evaluating the essential electrical applications using a selected emergency treatment case, the energy demand of a typical Nigerian secondary healthcare facility is assessed as 21.53 kWh and 14.29 kWh per day for conventional and energy-efficient devices respectively.
- Following the application of the HFMEA risk assessment methodology on the essential electrical applications above, the diagnostic process was identified as the most critical process and the blood chemistry analysis as the most critical application.
- Two lower levels of energy demand resulted from the HFMEA assessment, namely: 7.31 kWh and 4.82 kWh per day for conventional and energy-efficient devices respectively.
- An Event Resilience Index of 0.34 is derived from the reduced energy demand. This indicates that, approximately 34% of the total essential energy demand of a healthcare facility is necessary to ensure that the most critical functions stay operational.
- The techno-economic analysis of competing DER and ESS technologies using HOMER indicate the inclusion of a bank of Li-ion batteries can provide an economically viable and environment friendly means of stabilising existing conventional power supply in Nigerian healthcare facilities when the energy demand is lower than 14 kWh per day.
- At higher energy demands than 14 kWh/day, the addition of a renewable energy supply component becomes necessary to maintain economic viability and environmental safety. Higher energy demand scenarios require more batteries, more charge cycles using diesel generator and more battery changes. The environmental effect of Li-ion battery disposal in Nigeria requires investigation.
- Successful application of feed-in-tariffs makes the investment in DERs such as solar PV and hydrokinetic turbines economically viable for healthcare facilities as they can be a source of income that can be invested in other areas of provision. Even when FiT is not available, investment in DERs for healthcare facilities can turn them into profitable energy hubs in their communities for electricity supply at standard tariff rates.
- Nigeria's low wind speeds make wind power economically unviable.

7.4 Implication of Research for Government Policies and Operational Decisions in Healthcare

Under the most common power supply scenarios in Nigerian healthcare facilities (i.e. grid power supported by diesel generator with zero Feed-in-Tariff in place), the provision of electricity for energy demand scenarios that are lower than 14 kWh/day requires the addition of Li-ion batteries to be effective, affordable and environment friendly. Furthermore, the successful implementation of the official feed-in-tariff system will make the inclusion of renewable energy generation components in a power supply system economically viable. When there is an effective Feed-in-Tariff system in place, healthcare facilities can become viable energy hubs for electricity generation where system redundancies can be used to provide power in their communities when grid failure occurs.

On the other hand, in scenarios where necessary daily energy demand is greater than 14 kWh/day, the inclusion of a low cost and low impact renewable energy generation component like the hydrokinetic turbine in combination with batteries becomes necessary for the power system to be economically viable. The inclusion of solar PV components in off-grid electricity systems is expensive and only becomes financially viable when the feed-in-tariff regime is in effect. Otherwise, the use of Li-ion batteries combined with a diesel generator and the grid are suitable for low-energy demand scenarios less than 14 kWh/day with the inclusion of a hydrokinetic turbine when energy demand is higher.

A structured approach of determining and prioritising critical healthcare applications in developing countries has been created using a combination of existing energy and risk assessment methodologies. Having a uniform and structured national framework will help improve decision-making in public health especially with regards to resource allocation. The framework for assessing health energy demand has been advanced to include an additional layer of criticality assessment using HFMEA to determine lower energy demand levels. This approach produces four energy demand profiles compared to two in existing approaches. It provides more options to consider for low cost and low health/environment impact DER systems.

The inclusion of a spatial analysis in the energy demand assessment for health facilities in developing countries helps to gain an understanding of a facility's energy demand per unit area. This measure is noticeably absent in many existing literature and official documents from Nigeria compared to documents from developed countries. Again, having this information in the national public health database will help improve resource allocation.

An ERI of 0.34 indicates the percentage of a facility's essential electricity demand that must be met for it to continue performing its primary functions. While the value of a human life is immeasurable, the cost of electricity supply intervention should be considered necessary if the cost of supplying 34% of essential energy demand is less than or equal to \$750,000 (i.e. economic welfare value of a human life in low- and middle-income countries). This study has shown that the highest capital cost of a system providing 34% of energy demand in a typical Nigerian secondary hospital is \$125,240.

A novel optimisation modelling approach using three feed-in-tariffs (i.e. different levels of potential for excess energy sale) to determine optimal microgrid configurations has been developed to consider scenarios where: 1) institutional feed-in-tariffs are operational; 2) excess power generated can be sold at grid tariff price; and 3) there is no potential for sale of excess power. This approach can be used to evaluate the benefits (besides desirable health outcomes for patients) of investing in expensive alternative power supply in healthcare facilities in different locations.

Nigeria has considerable microhydro potential and it presents a potentially more reliable and less expensive RE alternative to solar PV. However, more investment in research and development of the technology is required to turn this potential into a viable energy source.

7.5 Recommendations for Future Work

The key achievements of this doctoral research have been identified in the previous section. For deeper understanding of the subject areas studied, some areas of research requiring further inquiry have been identified as follows:

- In Chapter 5, the power quality attribute of electricity supply was applied in determining failure modes for treatment processes. Other attributes identified in Chapter 2 can be employed in the determination of failure modes in treatment processes requiring electricity.
- A framework called “the disease burden from outdoor air pollution” is recommended for the evaluation of specific health benefits of using hybrid DER systems compared with conventional systems that include heavy reliance on diesel generators. This can be attached to the conceptual framework developed in Chapter 3 for the evaluation of emission costs.
- A comparative analysis of available services and equipment in several secondary health facilities is recommended to arrive at a more representative energy demand for Nigerian secondary health facilities.
- Only electrical loads were considered in this study and therefore, only electricity generating components were modelled. The inclusion of thermal loads and heat is recommended for further studies.
- The energy demand assessment of other secondary health facilities is recommended in order to verify the Event Resilience Index (ERI) of 0.34 determined in this research.
- The method of determining river flow speeds in m/s was not validated with experimental field data. Therefore, actual average river flow speed measurements during different months of the year and in the six case study cities are recommended to verify the water speeds used in the simulations carried out in this research.
- The wind speeds considered in this study are based on inland windspeeds. Consequently, no simulated optimal system presented a wind turbine in its configuration. Measurement of actual wind speeds in coastal areas in Nigeria is recommended to evaluate Nigeria's viable wind potentials. Comparing measured wind speeds in the studied cities with their HOMER synthesised wind data is also an area for further studies.
- A grid reliability of 50% has been employed in this study based on the World Bank's 2015 estimates. A continuous annual measurement of Nigeria's grid availability is recommended in order to verify this estimate and obtain more current and accurate grid reliability data.

- A single grid reliability figure of 50% was modelled in this research. Therefore, every simulated optimal system included the grid as a power source. Modelling of grid reliability of $< 50\%$ is recommended for more sensitivity analysis to identify the reliability threshold when optimal systems will no longer contain grid connections.
- The inclusion of a thermal boiler in the mix of power generating components is recommended to explore Nigeria's biomass potential in future studies when more accurate and verifiable biomass figures become available.

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APPENDICES

Appendix A Standard HFMEA Rating Scales

Table A-1: Standard HFMEA severity rating scale (DeRosier et al., 2002)

Catastrophic Event <i>(Traditional FMEA rating of 10—Failure could cause death or injury.)</i>	Major Event <i>(Traditional FMEA rating of 7—Failure causes a high degree of customer dissatisfaction.)</i>
<p><i>Patient Outcome:</i> Death or major permanent loss of function (sensory, motor, physiologic, or intellectual), suicide, rape, haemolytic transfusion reaction, surgery/procedure on the wrong patient or wrong body part, infant abduction or infant discharge to the wrong family</p> <p><i>Visitor Outcome:</i> Death or hospitalization of 3 or more visitors</p> <p><i>Staff Outcome:</i> A death or hospitalization of 3 or more staff</p> <p><i>Equipment or facility:</i> Damage equal to or more than \$250,000</p> <p><i>Fire:</i> Any fire that grows larger than an incipient stage</p>	<p><i>Patient Outcome:</i> Permanent lessening of bodily functioning (sensory, motor, physiologic, or intellectual), disfigurement, surgical intervention required, increased length of stay for 3 or more patients, increased level of care for 3 or more patients</p> <p><i>Visitor Outcome:</i> Hospitalization of 1 or 2 visitors</p> <p><i>Staff Outcome:</i> Hospitalization of 1 or 2 staff or 3 or more staff experiencing lost time or restricted-duty injuries or illnesses</p> <p><i>Equipment or facility:</i> Damage equal to or more than \$100,000</p> <p><i>Fire:</i> Not applicable—See "Moderate" and "Catastrophic"</p>
Moderate Event <i>(Traditional FMEA rating of 4—Failure can be overcome with modifications to the process or product, but there is minor performance loss.)</i>	Minor Event <i>(Traditional FMEA rating of 1—Failure would not be noticeable to the customer and would not affect delivery of the service or product.)</i>
<p><i>Patient Outcome:</i> Increased length of stay or increased level of care for 1 or 2 patients</p> <p><i>Visitor Outcome:</i> Evaluation and treatment for 1 or 2 visitors (less than hospitalization)</p> <p><i>Staff Outcome:</i> Medical expenses, lost time, or restricted-duty injuries or illness for 1 or 2 staff</p> <p><i>Equipment or facility:</i> Damage more than \$10,000 but less than \$100,000</p> <p><i>Fire:</i> Incipient stage or smaller</p>	<p><i>Patient Outcome:</i> No injury nor increased length of stay nor increased level of care</p> <p><i>Visitor Outcome:</i> Evaluated and no treatment required or refused treatment</p> <p><i>Staff Outcome:</i> First aid treatment only, with no lost time or restricted-duty injuries or illnesses</p> <p><i>Equipment or facility:</i> Damage less than \$10,000 or loss of any utility without adverse patient outcome (eg, natural gas, electricity, water, communications, transport, heat/air conditioning).</p> <p><i>Fire:</i> Not applicable—See "Moderate" and "Catastrophic"</p>

Table A-2: Traditional HFMEA probability rating scale

Probability Rating	Standard HFMEA Description
Frequent	Likely to occur immediately or within a short period (may happen several times in 1 year).
Occasional	Probably will occur (may happen several times in 1 to 2 years).
Uncommon	Possible to occur (may happen sometime in 2 to 5 years).
Remote	Unlikely to occur (may happen sometime in 5 to 30 years).

Appendix B HFMEA Worksheet

Table A-3: Worksheet Process. Source: (Taleghani, Rezaei and Sheikhbardsiri, 2016)

Failure mode	Potential causes	Hazard analysis							Action and outcome measures	
		Scoring			Decision tree analysis				Action type	Actions or rate for stopping
		Severity	Occurrence	Hazard score	Weakness point	Existing control measures	Detectability	Proceed?		
Recording the incorrect information in triage sheet	→	3	3	9	→	No	No	Yes	C	1) Assessing the patient's ability to communicate effectively with healthcare providing; 2) Detailed examination of the patient and not limited to what patient said
	1) Giving false information from the patient or not having knowledgeable person	3	3	9	→	No	No	Yes	C	1) Assessing the patient's ability to communicate effectively with healthcare providing; 2) Detailed examination of the patient and not limited to what patient said
	2) Lack of a correct communication of physician with patient	3	2	6	→	No	No	Yes	C	1) Assessing the patient's ability to communicate effectively with healthcare providing; 2) Developing the criteria of performance evaluation and monitoring clinical process; 3) Training course of effective communication and respect to the rights of service recipients
Error in patient transfer to the emergency surgery (incorrect refer of patient)	3) Lack of confidence of the patient and patient's caregiver to the nurse	3	3	9	→	No	Yes	No	C	1) Assessing the ability of patient to communicate effectively with healthcare provider; 2) Catches the patient's desire for giving information; 3) Implementation of the ethics nursing codes in the hospital for better interaction with the patient
	→	3	3	9	→	No	No	Yes	C	1) Correct communication with patient; 2) Detailed examination and complete knowledge of the patient's clinical condition; 3) Correct history taking from the patient; 4) Taking into account the advice of other clinicians by the service provider if necessary
	1) Incorrect decision by physician	3	2	6	→	No	No	Yes	C	1) Correct communication with patient; 2) Detailed examination and complete knowledge of the patient's clinical condition; 3) Correct history taking from the patient; 4) Taking into account the advice of other clinicians by the service provider if necessary
Delay to refer patient to the radiology	2) Lack of a good protocol to determine the correct situation of patient	3	3	9	→	No	Yes	No	C	1) Assessing the patient's ability to communicate effectively with healthcare provider; 2) Detailed examination of the patient and not limited to what patient said
	→	3	3	9	→	No	No	Yes	C	1) Coordination in medical team; 2) Sharing information in medical team; 3) Responsibility about patient safety
	1) Absence of nurse aid or the intern	3	3	9	→	No	Yes	No	C	1) Coordination in medical team; 2) Sharing information in medical team; 3) Responsibility about patient safety
Unnecessary graph for patient is requested by the physician	2) Lack of cooperation of patient and being unstable of the patient	3	4	12	→	No	No	Yes	C	1) Cooperation for receiving information and consequences of each method; 2) Awareness of patient about the need to do radiology; 3) Monitoring the work process; 4) To pass information sharing between the medical team
	3) Lack of cooperation, coordination and team problems between radiology and emergency surgery	3	3	9	→	No	No	Yes	C	1) Sharing the information between medical team; 2) Training courses of team work; 3) Continuous monitoring of doing process; 4) Coordinated acting of medical team
	4) Overcrowding in radiology and or emergency surgery	3	3	9	→	No	Yes	No	C	1) Supply of additional power; 2) Fitting the work volume with number of human resources; 3) Coordination of medical team and establishment of stress management; 4) Determination of standard range and keeping client data in the standard range; 5) Coordination between radiology and surgery wards
Unnecessary graph for patient is requested by the physician	→	3	3	9	→	No	No	Yes	C	1) Assessing the patient's ability to communicate effectively with healthcare provider; 2) Developing criteria of performance evaluation and monitoring the clinical process; 3) Training course of effective communication and respect to the rights of service recipients
	1) Lack of correct communication of physician with the patient	3	2	6	→	No	No	Yes	C	1) Assessing the patient's ability to communicate effectively with healthcare provider; 2) Developing criteria of performance evaluation and monitoring the clinical process; 3) Training course of effective communication and respect to the rights of service recipients
	2) Lack of knowledge and enough skill by physician	3	2	6	→	No	No	Yes	C	1) Encourage physicians to ask about the ambiguity (taking into account the comments of other experts); 2) Periodic training for clinical staff

Delay in the beginning of the test on the intended sample in laboratory	→	3	4	12	→	No	No	Yes		
1) Overcrowding of the laboratory		3	4	12	→	No	Yes	No	C	1) Reducing the workload and arranging the tables of work shifts and avoid of row shifts; 2) Supply of additional power; 3) Fit the work volume with the number of human resources; 4) Coordination of medical team and establishment of stress management
2) Lack of awareness of the importance of the subject		3	3	9	→	No	No	Yes	C	1) Performing a justification course at the beginning; 2) Determination a leader or supervisor for the team; 3) Sharing information with medical team; 4) Continuous monitoring of healthcare providing
3) Lack of monitoring of a technical responsible on the process of doing work		3	3	9	→	No	No	Yes	C	1) Periodic monitoring and evaluation of laboratory; 2) Checking the competence of the team leader and responsible person; 3) Continuous monitoring of doing processes
Failure (error) in entering test answer in the system through laboratory	→	3	3	9	→	No	No	Yes	C	
1) High work volume and staff fatigue		3	4	12	→	No	No	Yes	C	1) Programing and management of actions during the shift; 2) Work division; 3) Setting shift tables and lack of giving long shifts
2) Lack of enough experience		3	2	6	→	No	No	Yes	C	1) Evaluation and control of activity and checking the final test answers by technical manager; 2) Developing the careers of introduction of new entrants personnel to the ward's criteria

Appendix C How HOMER Calculates the Radiation Incident on the PV Array (HOMER Resources Tab) (HOMER, 2017)

The Solar GHI Resource page allows you to specify the global horizontal radiation (GHI) for each time step in the HOMER simulation. The GHI is the total amount of solar radiation striking the horizontal surface on the earth. But the power output of the PV array depends on the amount of radiation striking the surface of the PV array, which in general is not horizontal. So in each time step, HOMER must calculate the global solar radiation incident on the surface of the PV array. The following describes that process, which is based on the methods in the first two chapters of [Duffie and Beckman \(1991\)](#).

We can describe the orientation of the PV array using two parameters: a slope and an azimuth. The slope is the angle formed between the surface of the panel and the horizontal, so a slope of zero indicates a horizontal orientation, whereas a 90° slope indicates a vertical orientation. The azimuth is the direction towards which the surface faces. HOMER uses the convention whereby zero azimuth corresponds to due south, and positive values refer to west-facing orientations. So an azimuth of -45° corresponds to a southeast-facing orientation, and an azimuth of 90° corresponds to a west-facing orientation.

The other factors relevant to the geometry of the situation are the latitude, the time of year, and the time of day. The time of year affects the solar declination, which is the latitude at which the sun's rays are perpendicular to the earth's surface at solar noon. HOMER uses the following equation to calculate the solar declination:

$$\delta = 23.45^\circ \sin\left(360^\circ \frac{284 + n}{365}\right)$$

where:

n = the day of the year [a number 1 through 365]

The time of day affects the location of the sun in the sky, which we can describe by an hour angle. HOMER uses the convention whereby the hour angle is zero at solar noon (the time of day at which the sun is at its highest point in the sky), which is negative before solar noon, and positive after solar noon. HOMER uses the following equation to calculate the hour angle:

$$\omega = (t_s - 12\text{hr}) \cdot 15^\circ/\text{hr}$$

where:

t_s = the solar time [hr]

The value of t_s is 12 hr at solar noon, and 13.5 hr ninety minutes later. The equation above is based on the fact that the sun moves across the sky at 15 degrees per hour.

HOMER assumes that all time-dependent data, such as solar radiation data and electric load data, are specified not in solar time, but in civil time (also called local standard time). HOMER calculates solar time from civil time using the following equation:

$$t_s = t_c + \frac{\lambda}{15^\circ/\text{hr}} - Z_c + E$$

where:

t_c = the civil time in hours corresponding to the midpoint of the time step [hr]

λ = the longitude [°]

Z_c = the time zone in hours east of GMT [hr]

E = the equation of time [hr]

Note: West longitudes are negative, and time zones west of GMT are negative as well.

The equation of time accounts for the effects of obliquity (the tilt of the earth's axis of rotation relative to the plane of the ecliptic) and the eccentricity of the earth's orbit. HOMER calculates the equation of time as follows:

$$E = 3.82 \left(0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B \right. \\ \left. - 0.014615 \cdot \cos 2B - 0.04089 \cdot \sin 2B \right)$$

where B is given by:

$$B = 360^\circ \frac{(n-1)}{365}$$

where n is the day of the year, starting with 1 for January 1st.

Now, for a surface with any orientation, we can define the angle of incidence, meaning the angle between the sun's beam radiation and the normal to the surface, using the following equation:

$$\begin{aligned} \cos \theta = & \sin \delta \sin \phi \cos \beta \\ & - \sin \delta \cos \phi \sin \beta \cos \gamma \\ & + \cos \delta \cos \phi \cos \beta \cos \omega \\ & + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega \\ & + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned}$$

where:

θ = the angle of incidence [°]

β = the slope of the surface [°]

γ = the azimuth of the surface [°]

ϕ = the latitude [°]

δ = the solar declination [°]

ω = the hour angle [°]

An incidence angle of particular importance, is the zenith angle, meaning the angle between a vertical line and the line to the sun. The zenith angle is zero when the sun is directly overhead, and 90° when the sun is at the horizon. Because a horizontal surface has a slope of zero, we can find a equation for the zenith angle by setting $\beta = 0^\circ$ in the equation above, which yields:

$$\cos \theta_z = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta$$

where:

θ_z = the zenith angle [°]

When addressing the amount of solar radiation arriving at the top of the atmosphere over a particular point on the earth's surface, HOMER assumes the output of the sun is constant in time. But the amount of sunlight striking the top of the earth's atmosphere varies over the year because the distance between the sun and the earth varies over the year due to the eccentricity of earth's orbit. To calculate the extraterrestrial normal radiation, defined as the amount of solar radiation striking a surface normal (perpendicular) to the sun's rays at the top of the earth's atmosphere, HOMER uses the following equation:

$$G_{on} = G_{sc} \left(1 + 0.033 \cdot \cos \frac{360n}{365} \right)$$

where:

G_{on} = the extraterrestrial normal radiation [kW/m²]

G_{sc} = the solar constant [1.367 kW/m²]

n = the day of the year [a number between 1 and 365]

To calculate the extraterrestrial horizontal radiation, defined as the amount of solar radiation striking a horizontal surface at the top of the atmosphere, HOMER uses the following equation:

$$G_o = G_{on} \cos \theta_z$$

where:

G_o = the extraterrestrial horizontal radiation [kW/m²]

G_{on} = the extraterrestrial normal radiation [kW/m²]

θ_z = the zenith angle [°]

Because HOMER simulates on a time-step-by-time-step basis, we integrate the equation above over one time step to find the average extraterrestrial horizontal radiation over the time step:

$$\overline{G_o} = \frac{12}{\pi} G_{on} \left[\cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180^\circ} \sin \phi \sin \delta \right]$$

where:

$\overline{G_o}$ = the extraterrestrial horizontal radiation averaged over the time step [kW/m²]

G_{on} = the extraterrestrial normal radiation [kW/m²]

ω_1 = the hour angle at the beginning of the time step [°]

ω_2 = the hour angle at the end of the time step [°]

The equation above gives the average amount of solar radiation striking a horizontal surface at the top of the atmosphere in any time step. The solar resource data give the average amount of solar radiation striking a horizontal surface at the bottom of the atmosphere (the surface of the earth) in every time step. The ratio of the surface radiation to the extraterrestrial radiation is called the [clearness index](#). The following equation defines the clearness index:

$$k_T = \frac{\overline{G}}{\overline{G}_o}$$

where:

- $\overline{G}$ = the global horizontal radiation on the earth's surface averaged over the time step [kW/m²]
 $\overline{G}_o$ = the extraterrestrial horizontal radiation averaged over the time step [kW/m²]

As for the solar radiation on the earth's surface, some of the radiation is *beam radiation*, defined as solar radiation that travels from the sun to the earth's surface without any scattering by the atmosphere. Beam radiation (sometimes called direct radiation) casts a shadow. The rest of the radiation is *diffuse radiation*, defined as solar radiation whose direction has been changed by the earth's atmosphere. Diffuse radiation comes from all parts of the sky and does not cast a shadow. The sum of beam and diffuse radiation is called global solar radiation, a relation expressed by the following equation:

$$\overline{G} = \overline{G}_b + \overline{G}_d$$

where:

- $\overline{G}_b$ = the beam radiation [kW/m²]
 $\overline{G}_d$ = the diffuse radiation [kW/m²]

The distinction between beam and diffuse radiation is important when calculating the amount of radiation incident on an inclined surface. The orientation of the surface has a stronger effect on the beam radiation, which comes from only one part of the sky, than it does on the diffuse radiation, which comes from all parts of the sky.

However, in most cases, we measure only the global horizontal radiation, not its beam and diffuse components. For that reason, you need to enter global horizontal radiation in HOMER's Solar Resource Inputs. Then, in every time step, HOMER must resolve the global horizontal radiation into its beam and diffuse components to find the radiation incident on the PV array. For this purpose, HOMER uses correlation of [Erbs et al. \(1982\)](#), which gives the *diffuse fraction* as a function of the clearness index as follows:

$$\frac{\overline{G}_d}{\overline{G}} = \begin{cases} 1.0 - 0.09 \cdot k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604 \cdot k_T + 4.388 \cdot k_T^2 - 16.638 \cdot k_T^3 + 12.336 \cdot k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases}$$

For each time step, HOMER uses the average global horizontal radiation to calculate the clearness index, then the diffuse radiation. It then calculates the beam radiation by subtracting the diffuse radiation from the global horizontal radiation.

To calculate the global radiation striking the tilted surface of the PV array, HOMER uses the HDKR model, which assumes that there are three components to the diffuse solar radiation: an isotropic component that comes from all parts of the sky equally, a circumsolar component that emanates from the direction of the sun, and a horizon brightening component that emanates from the horizon. Before applying this model, we must first define three more factors.

The following equation defines R_b , the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface:

$$R_b = \frac{\cos \theta}{\cos \theta_z}$$

The anisotropy index, with symbol A_i , is a measure of the atmospheric transmittance of beam radiation. This factor is used to estimate the amount of circumsolar diffuse radiation, also called forward scattered radiation. The anisotropy index is given by the following equation:

$$A_i = \frac{\overline{G}_b}{\overline{G}_o}$$

Finally, we need to define a factor used to account for horizon brightening, or the fact that more diffuse radiation comes from the horizon than from the rest of the sky. This term is related to the cloudiness and is given by the following equation:

$$f = \sqrt{\frac{\overline{G}_b}{\overline{G}}}$$

The HDKR model calculates the global radiation incident on the PV array according to the following equation:

$$\overline{G}_T = (\overline{G}_b + \overline{G}_d A_i) R_b + \overline{G}_d (1 - A_i) \left(\frac{1 + \cos \beta}{2} \right) \left[1 + f \sin^3 \left(\frac{\beta}{2} \right) \right] + \overline{G} \rho_g \left(\frac{1 - \cos \beta}{2} \right)$$

where:

β = the slope of the surface [°]

ρ_g = the ground reflectance, which is also called the albedo [%]

HOMER uses this quantity to calculate the cell temperature and the power output of the PV array.

Appendix D Finding Data to Run HOMER (HOMER, 2017)

Electric Load Data

We are aware of only one source of hourly load data, the DG marketplace. This website sells typical residential, commercial, and industrial load data for locations across the US.

Geography

To find your latitude and longitude, check maps.google.com. For help with Google Maps, see the Latitude and longitude coordinates Google Support article.

To find your time zone, check www.worldtimezone.com.

Solar Radiation Data

HOMER accepts solar radiation data as monthly averages or as a time series. Time series solar radiation data is most commonly available with an hourly time step, but HOMER can accept any time step down to one minute. Two of the best sources of solar radiation data are the TMY2 and TMY3 data sets provided for free by the US National Renewable Energy Laboratory. You can import TMY2 and TMY3 files directly into HOMER's Solar Resource Inputs window.

- NREL provides TMY2 data at http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/tmy2/.
- NREL provides TMY3 data at http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/.
- NASA's Surface Solar Energy Data Set provides monthly average solar radiation data for everywhere on earth at <http://eosweb.larc.nasa.gov/sse/>.
- This help file contains a table of monthly solar data for selected worldwide locations.
- The US Renewable Resource Data Center provides US data and maps at www.nrel.gov/rredc/solar_resource.html.
- The World Radiation Data Center provides worldwide solar data at <http://wrdc-mgo.nrel.gov>. Note that data from this website need a lot of processing to be useful in HOMER.
- GeoModel Solar has many solar data sets available at various resolutions: <http://solargis.info>.

Wind Speed Data

It can be difficult to obtain measured wind speed data. Proper measurement of wind speed is expensive and time consuming, and average wind speeds can vary markedly over short distances because of terrain effects. For these reasons, it is often necessary to synthesize wind data from estimated monthly average wind speeds.

Many countries have published wind atlases:

- Wind maps for many US states are available at apps2.eere.energy.gov/wind/windexchange/windmaps/.
- The Canadian Wind Atlas is available at www.windatlas.ca.
- The Brazilian Wind Atlas is available at www.cresesb.cepel.br/publicacoes/index.php?task=livro&cid=1.

A few other websites provide wind speed data:

- The US Renewable Resource Data Center provides information on wind data at http://www.nrel.gov/rredc/wind_resource.html.
- The www.weatherbase.com website provides monthly average wind speed data for many cities around the world.
- The Windustry website maintains a list of US wind data resources at www.windustry.com/resources/windmaps.htm.
- The US National Climatic Data Center provides monthly average wind speed data for many US cities at <http://www1.ncdc.noaa.gov/pub/data/ccd-data/wndspd12.txt>. To convert from mph to m/s, divide by 2.23694.
- The Technical University of Denmark maintains a database of wind characteristics at www.winddata.com.

Renewable Power System Components

Several retailers sell components for renewable power systems. The website www.ecobusinesslinks.com maintains a list of renewable power retailers around the world. A few have very helpful websites providing cost and performance data for PV panels, wind turbines, hydro turbines, batteries, converters, and other system components. See the following websites:

- The Alternative Energy Store
- SolarEnergy.com
- Solar Biz
- The Energy Development Co-operative

Other sources of cost and performance data for renewable power system components include:

- Renewable Energy Technology Characterizations, a detailed report on the performance and costs of solar, wind, and biomass power systems. This report includes predictions of future performance and costs out to the year 2030.
- SolarBuzz, which provides price data for PV modules, inverters, batteries, and charge controllers.
- The EPA provides a prices and references for renewable technologies at <http://www.epa.gov/cleanenergy/energy-resources/renewabledatabase.html>.

Generators

A very useful document covering the technology, emissions, and costs of natural gas-fired reciprocating generators, microturbines, fuel cells, and Stirling engines is the Gas-Fired Distributed Energy Resource Technology Characterizations.

PV

PV WATTS v.1 is a simple and useful tool for estimating a PV derating factor. <http://rredc.nrel.gov/solar/calculators/pvwatts/version1/derate.cgi>.

Emissions

The following provide emissions information:

- The US Grid Emissions Factors section of the help contains a table of US grid emissions factors.
- The US Environmental Protection Agency provides emissions coefficients for CO₂, SO₂, and NO_x for US locations at their Power Profiler website at http://oaspub.epa.gov/powpro/ept_pack.charts.
- The EPA's eGRID website contains even more emissions data, including state-by-state average emissions factors for all the pollutants that HOMER models.
- Additional data, such as The EPA document Emissions Factors, Global Warming Potentials, Unit Conversions, Emissions, and Related Facts, November 1999, at www.epa.gov/appdstar/pdf/brochure.pdf.

Policies and Incentives

The following provide information about policies and incentives:

- For information on current net metering policies across the United States, see the US Department of Energy web page on the topic at www.eere.energy.gov/greenpower/markets/netmetering.shtml

For a list of renewable energy incentives across the United States, see the Database of State Incentives for Renewable Energy at www.dsireusa.org.

Appendix E Solar GHI Resource in HOMER

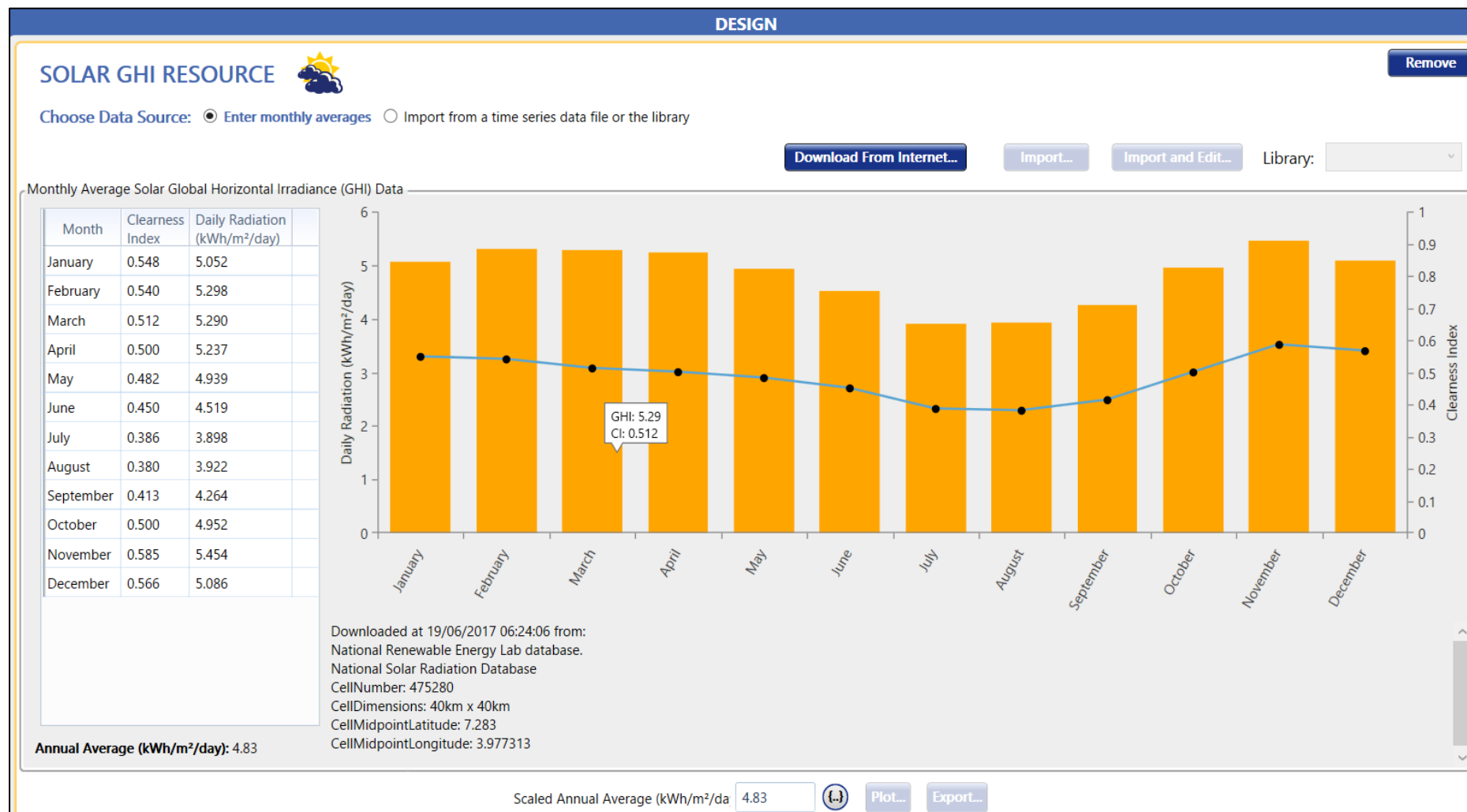


Figure E-1: Solar GHI Resource in HOMER

Appendix F Wind Resource Page in HOMER

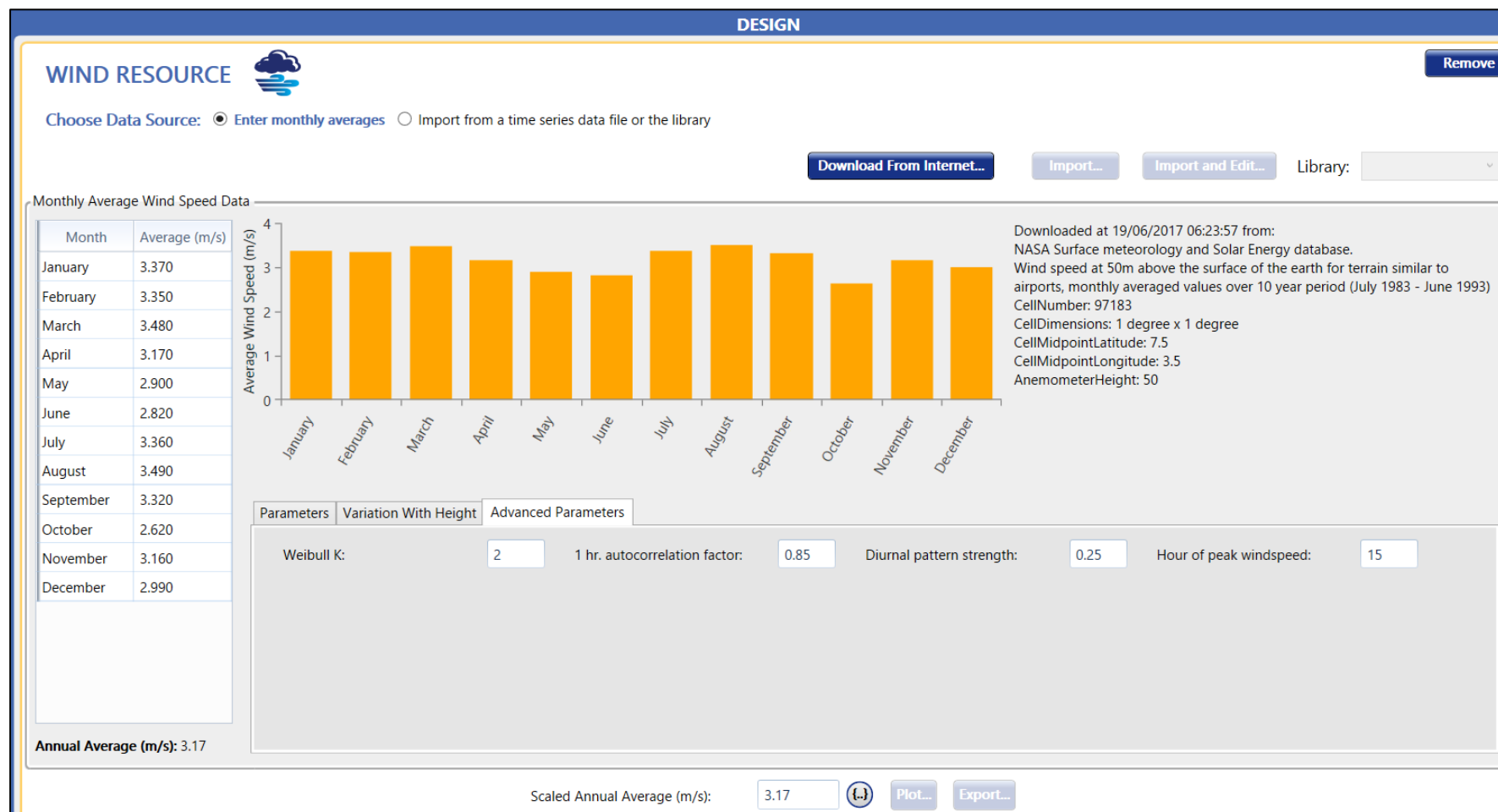


Figure F-1: Wind Resource Page in HOMER

Appendix G Table of Measured Wind Parameters (HOMER Energy, 2017)

No	City	State	v_{ave}	k	r_1	δ	φ
1	Anchorage	AK	3.277	1.681	0.769	0.125	17
2	Annette	AK	4.206	1.65	0.973	0.132	13
3	Barrow	AK	5.482	2.234	0.948	0.036	15
4	Bethel	AK	5.659	2.166	0.95	0.059	16
5	Bettles	AK	3.148	1.689	0.873	0.112	14
6	Big Delta	AK	4.069	1.297	0.966	0.091	17
7	Cold Bay	AK	7.661	2.019	0.913	0.075	15
8	Fairbanks	AK	2.506	1.289	0.787	0.16	17
9	Gulkana	AK	2.651	0.809	0.934	0.183	16
10	King Salmon	AK	4.882	1.874	0.932	0.143	16
11	Kodiak	AK	4.652	1.468	0.895	0.082	15
12	Kotzebue	AK	6.005	1.833	0.934	0.03	14
13	McGrath	AK	2.482	1.428	0.894	0.202	16
14	Nome	AK	4.774	1.621	0.92	0.117	15
15	St. Paul Island	AK	7.802	2.084	0.966	0.052	14
16	Talkeetna	AK	2.465	1.03	0.876	0.268	15
17	Yakutat	AK	2.964	1.359	0.945	0.218	14
18	Birmingham	AL	3.163	1.521	0.831	0.345	13
19	Huntsville	AL	3.626	1.619	0.838	0.276	13
20	Mobile	AL	3.684	1.852	0.849	0.268	13
21	Montgomery	AL	3.023	1.658	0.794	0.338	13
22	Fort Smith	AR	3.235	1.845	0.901	0.307	14
23	Little Rock	AR	3.435	1.887	0.807	0.284	14
24	Flagstaff	AZ	3.238	1.537	0.922	0.447	14
25	Phoenix	AZ	2.984	2.016	0.727	0.148	14
26	Prescott	AZ	3.734	1.927	0.847	0.272	15
27	Tucson	AZ	3.935	2.127	0.858	0.16	15
28	Arcata	CA	3.051	1.366	0.911	0.424	14
29	Bakersfield	CA	2.852	1.75	0.83	0.267	16
30	Dagget	CA	4.901	1.75	0.933	0.028	21
31	Fresno	CA	2.986	1.88	0.867	0.194	17
32	Long Beach	CA	2.702	1.595	0.85	0.549	15
33	Los Angeles	CA	3.575	1.961	0.676	0.469	15
34	Sacramento	CA	3.251	1.413	0.894	0.276	15
35	San Diego	CA	3.224	1.983	0.798	0.412	14
36	San Francisco	CA	4.53	1.689	0.876	0.405	17
37	Santa Maria	CA	3.356	1.271	0.871	0.632	15
38	Alamosa	CO	3.746	1.502	0.9	0.336	17
39	Boulder/Denver	CO	3.639	1.849	0.678	0.208	16

40	Colorado Springs	CO	4.356	1.89	0.831	0.185	15
41	Eagle	CO	2.712	0.944	0.836	0.579	16
42	Grand Junction	CO	3.56	1.784	0.823	0.086	14
43	Pueblo	CO	4.097	1.678	0.842	0.311	16
44	Bridgeport	CT	5.423	2.336	0.88	0.173	14
45	Hartford	CT	3.831	1.878	0.882	0.275	14
46	Wilmington	DE	4.134	1.977	0.899	0.252	14
47	Daytona Beach	FL	3.811	1.795	0.895	0.416	14
48	Jacksonville	FL	3.283	1.555	0.775	0.463	14
49	Key West	FL	5.089	2.506	0.942	0.069	13
50	Miami	FL	4.337	2.214	0.803	0.292	14
51	Tallahassee	FL	2.901	1.432	0.841	0.46	14
52	Tampa	FL	3.579	2.147	0.762	0.336	14
53	West Palm Beach	FL	4.391	1.984	0.926	0.297	14
54	Athens	GA	3.314	2.002	0.92	0.209	14
55	Atlanta	GA	3.947	2.152	0.808	0.17	14
56	Augusta	GA	3.158	1.587	0.86	0.338	14
57	Columbus	GA	2.95	1.604	0.889	0.346	14
58	Macon	GA	3.287	1.689	0.78	0.307	14
59	Savannah	GA	3.565	1.969	0.918	0.324	14
60	Hilo	HI	3.142	2.263	0.839	0.26	14
61	Honolulu	HI	4.95	2.433	0.822	0.306	15
62	Kahului	HI	5.712	2.305	0.88	0.374	15
63	Lihue	HI	5.503	3.024	0.951	0.086	15
64	Des Moines	IA	4.696	1.999	0.922	0.216	13
65	Mason City	IA	5.079	2.052	0.898	0.21	13
66	Sioux City	IA	4.885	2.03	0.894	0.208	14
67	Waterloo	IA	4.763	1.904	0.897	0.235	13
68	Boise	ID	3.81	1.845	0.779	0.201	15
69	Pocatello	ID	4.728	1.731	0.881	0.192	15
70	Chicago	IL	4.62	2.152	0.847	0.195	14
71	Moline	IL	4.619	1.896	0.905	0.26	13
72	Peoria	IL	4.379	2.124	0.859	0.224	13
73	Rockford	IL	4.665	2.137	0.903	0.234	13
74	Springfield	IL	4.804	2.178	0.909	0.159	13
75	Evansville	IN	3.525	1.492	0.858	0.327	13
76	Fort Wayne	IN	4.468	2.115	0.899	0.2	14
77	Indianapolis	IN	4.063	1.966	0.89	0.209	14
78	South Bend	IN	4.503	2.084	0.894	0.225	14
79	Dodge City	KS	5.79	2.404	0.847	0.13	13
80	Goodland	KS	5.831	2.396	0.855	0.084	13
81	Topeka	KS	4.392	1.843	0.847	0.249	14
82	Wichita	KS	5.214	2.205	0.909	0.175	14
83	Covington	KY	3.95	2.076	0.856	0.207	14

84	Lexington	KY	3.942	2.277	0.929	0.18	13
85	Louisville	KY	3.672	1.876	0.831	0.268	15
86	Baton Rouge	LA	3.239	1.647	0.872	0.311	14
87	Lake Charles	LA	3.775	1.973	0.832	0.286	14
88	New Orleans	LA	3.582	1.828	0.864	0.258	13
89	Shreveport	LA	3.464	1.746	0.841	0.279	14
90	Boston	MA	5.43	2.401	0.838	0.126	14
91	Worcester	MA	4.319	1.944	0.903	0.087	13
92	Baltimore	MD	4.108	1.995	0.842	0.264	14
93	Caribou	ME	4.593	1.769	0.909	0.172	14
94	Portland	ME	3.904	1.908	0.856	0.295	14
95	Alpena	MI	3.693	1.943	0.897	0.289	14
96	Detroit	MI	4.507	2.123	0.848	0.243	14
97	Flint	MI	4.378	2.027	0.886	0.212	14
98	Grand Rapids	MI	4.454	2.199	0.892	0.215	14
99	Houghton	MI	4.06	2.338	0.909	0.161	15
100	Lansing	MI	4.344	1.855	0.933	0.223	14
101	Muskegon	MI	4.888	2.104	0.931	0.19	14
102	Sault Ste. Marie	MI	3.806	1.987	0.862	0.244	15
103	Traverse City	MI	3.993	1.818	0.868	0.241	14
104	Duluth	MN	4.701	2.205	0.924	0.156	14
105	International Falls	MN	4.019	1.977	0.871	0.221	13
106	Minneapolis/St. Paul	MN	4.624	2.016	0.897	0.223	14
107	Rochester	MN	5.789	2.441	0.926	0.13	12
108	St. Cloud	MN	3.661	1.73	0.942	0.274	14
109	Columbia	MO	4.439	2.322	0.874	0.157	13
110	Kansas City	MO	4.482	2.527	0.842	0.166	14
111	Springfield	MO	4.506	2.284	0.858	0.19	12
112	St. Louis	MO	4.401	2.094	0.857	0.172	14
113	Jackson	MS	3.322	1.607	0.857	0.324	13
114	Meridian	MS	2.769	1.247	0.825	0.434	13
115	Billings	MT	5.155	2.324	0.885	0.079	14
116	Cut Bank	MT	5.672	1.761	0.946	0.225	15
117	Glasgow	MT	4.802	2.059	0.933	0.13	14
118	Great Falls	MT	5.513	1.898	0.906	0.156	14
119	Helena	MT	3.527	1.537	0.876	0.281	16
120	Kalispell	MT	2.828	1.139	0.905	0.255	14
121	Lewistown	MT	4.245	1.745	0.917	0.149	14
122	Miles City	MT	4.624	2.04	0.836	0.102	14
123	Missoula	MT	3.023	1.296	0.831	0.327	17
124	Asheville	NC	3.48	1.308	0.854	0.313	14
125	Cape Hatteras	NC	5.157	2.419	0.954	0.1	14
126	Charlotte	NC	3.139	1.825	0.791	0.291	14

127	Greensboro	NC	3.116	1.861	0.823	0.287	13
128	Raleigh/Durham	NC	3.503	2.005	0.816	0.245	14
129	Wilmington	NC	3.67	1.822	0.904	0.309	14
130	Bismarck	ND	4.42	1.608	0.875	0.308	14
131	Fargo	ND	5.377	2.026	0.927	0.158	14
132	Minot	ND	5.489	2.31	0.879	0.138	14
133	Grand Island	NE	5.336	2.246	0.91	0.175	14
134	Norfolk	NE	5.455	1.71	0.924	0.229	14
135	North Platte	NE	4.651	1.692	0.862	0.264	15
136	Omaha	NE	4.493	1.838	0.922	0.176	13
137	Scottsbluff	NE	4.663	1.82	0.813	0.235	14
138	Concord	NH	2.865	1.149	0.838	0.441	14
139	Atlantic City	NJ	4.42	1.935	0.948	0.262	14
140	Newark	NJ	4.624	2.345	0.809	0.157	15
141	Albuquerque	NM	4.009	1.723	0.789	0.255	17
142	Tucumcari	NM	4.335	1.907	0.911	0.208	14
143	Elko	NV	2.7	1.195	0.827	0.47	15
144	Ely	NV	4.374	1.963	0.879	0.078	13
145	Las Vegas	NV	4.063	1.809	0.854	0.139	18
146	Reno	NV	2.839	1.124	0.856	0.555	17
147	Tonopah	NV	4.317	1.804	0.826	0.167	15
148	Winnemucca	NV	3.63	1.833	0.851	0.245	15
149	Albany	NY	3.958	1.567	0.856	0.259	14
150	Binghamton	NY	4.509	2.357	0.891	0.155	14
151	Buffalo	NY	5.135	2.152	0.889	0.181	14
152	Massena	NY	3.632	1.52	0.885	0.267	13
153	NYC (Central Park)	NY	5.185	2.676	0.933	0.13	15
154	Rochester	NY	4.377	1.983	0.916	0.183	14
155	Syracuse	NY	4.1	1.903	0.877	0.202	14
156	Akron/Canton	OH	4.173	2.179	0.89	0.21	13
157	Cleveland	OH	4.506	2.186	0.842	0.191	14
158	Columbus	OH	3.728	1.898	0.847	0.288	14
159	Dayton	OH	4.311	2.106	0.847	0.185	14
160	Mansfield	OH	4.786	2.342	0.93	0.159	13
161	Toledo	OH	4.15	1.914	0.898	0.266	14
162	Youngstown	OH	4.407	2.312	0.893	0.178	14
163	Oklahoma City	OK	5.352	2.253	0.937	0.183	13
164	Tulsa	OK	4.811	2.173	0.902	0.222	14
165	Astoria	OR	3.987	1.876	0.916	0.254	15
166	Burns	OR	3.213	1.652	0.946	0.24	15
167	Eugene	OR	3.366	1.904	0.89	0.273	14
168	Medford	OR	2.255	1.262	0.765	0.484	16
169	North Bend	OR	4.276	1.768	0.911	0.322	15
170	Pendleton	OR	3.826	1.749	0.885	0.125	16

171	Portland	OR	3.58	1.56	0.872	0.23	16
172	Redmond/Bend	OR	3.64	1.913	0.835	0.295	15
173	Salem	OR	3.127	1.387	0.897	0.291	14
174	Allentown	PA	4.143	1.684	0.884	0.289	14
175	Bradford	PA	3.66	1.765	0.921	0.26	14
176	Erie	PA	5.141	2.216	0.91	0.104	12
177	Harrisburg	PA	3.353	1.513	0.845	0.278	14
178	Philadelphia	PA	4.307	2.19	0.831	0.203	14
179	Pittsburgh	PA	3.922	1.76	0.85	0.284	14
180	Wilkes-Barre	PA	3.641	2.146	0.836	0.222	14
181	Williamsport	PA	3.442	1.295	0.87	0.297	14
182	Guam	PI	4.205	2.189	0.973	0.307	13
183	San Juan	PR	3.823	1.788	0.869	0.504	15
184	Providence	RI	4.702	2.157	0.881	0.257	14
185	Charleston	SC	3.892	2.069	0.821	0.318	14
186	Columbia	SC	3.035	1.555	0.773	0.382	14
187	Greenville	SC	2.982	1.81	0.896	0.277	13
188	Huron	SD	4.842	1.956	0.918	0.202	14
189	Pierre	SD	5.102	1.884	0.92	0.194	14
190	Rapid City	SD	5.342	1.677	0.928	0.231	13
191	Sioux Falls	SD	5.023	2.021	0.927	0.217	14
192	Bristol	TN	2.397	1.174	0.833	0.437	15
193	Chattanooga	TN	2.507	1.108	0.801	0.493	15
194	Knoxville	TN	3.023	1.545	0.845	0.262	15
195	Memphis	TN	3.998	1.903	0.887	0.229	13
196	Nashville	TN	3.642	1.902	0.803	0.25	14
197	Abilene	TX	5.205	2.418	0.915	0.119	14
198	Amarillo	TX	5.929	2.411	0.878	0.129	14
199	Austin	TX	4.062	1.895	0.835	0.238	14
200	Brownsville	TX	5.266	2.13	0.924	0.361	14
201	Corpus Christi	TX	5.377	2.197	0.918	0.303	15
202	El Paso	TX	3.534	1.612	0.798	0.241	16
203	Fort Worth	TX	4.433	1.984	0.909	0.191	14
204	Houston	TX	3.777	2.112	0.775	0.321	14
205	Lubbock	TX	5.196	2.164	0.89	0.184	15
206	Lufkin	TX	3.068	1.515	0.854	0.395	14
207	Midland/Odessa	TX	5.05	2.184	0.832	0.225	14
208	Port Arthur	TX	4.367	2.176	0.885	0.261	14
209	San Angelo	TX	4.638	2.15	0.863	0.199	14
210	San Antonio	TX	4.2	2.332	0.864	0.202	15
211	Victoria	TX	4.487	2.158	0.929	0.308	14
212	Waco	TX	4.842	2.323	0.906	0.138	14
213	Wichita Falls	TX	5.675	2.414	0.944	0.164	14
214	Cedar City	UT	3.554	1.179	0.861	0.439	16

215	Salt Lake City	UT	3.968	1.667	0.762	0.119	13
216	Lynchburg	VA	3.061	1.454	0.867	0.359	14
217	Norfolk	VA	4.883	2.207	0.862	0.183	13
218	Richmond	VA	3.653	2.11	0.897	0.227	14
219	Roanoke	VA	3.63	1.662	0.859	0.265	15
220	Sterling	VA	3.49	1.694	0.821	0.291	14
221	Burlington	VT	4.064	2.004	0.806	0.204	13
222	Olympia	WA	3.06	1.441	0.883	0.303	14
223	Quillayute	WA	2.787	1.559	0.871	0.372	14
224	Seattle	WA	3.897	2.108	0.76	0.121	15
225	Spokane	WA	4.333	1.934	0.875	0.122	12
226	Yakima	WA	3.296	1.725	0.87	0.139	18
227	Eau Claire	WI	3.974	1.888	0.872	0.275	14
228	Green Bay	WI	4.438	1.999	0.918	0.232	13
229	La Crosse	WI	3.706	1.645	0.887	0.199	14
230	Madison	WI	4.223	1.86	0.892	0.26	13
231	Milwaukee	WI	4.944	2.087	0.868	0.194	13
232	Charleston	WV	2.764	1.433	0.86	0.326	14
233	Elkins	WV	2.932	0.971	0.906	0.37	14
234	Huntington	WV	3.101	1.917	0.822	0.241	14
235	Casper	WY	5.652	2.075	0.929	0.216	13
236	Cheyenne	WY	5.735	1.996	0.868	0.173	13
237	Lander	WY	3.363	1.459	0.759	0.255	17
238	Rock Springs	WY	5.097	1.629	0.874	0.28	15
239	Sheridan	WY	3.367	1.494	0.833	0.265	14

Table G-1: Table of Measured Wind Parameters Data

Appendix H Simulation Results of Nigerian Cities’ DER Power Systems

Ibadan, South-West Nigeria

Table H-1: Ibadan simulation results

Ibadan SW			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Battery x 5, Grid, HydroK	-0.0183	-25,141	-4,006.73	117,740	0	-4,544.90	97.01	52,383.82	38,614.77	-18,901	1,153.10	31,059.04	0.00	95,040.00	28,363.00	0.00	22,867.00	7,555.73
	14.30	PV, Battery x 5, Grid, HydroK	-0.0270	-36,290	-4,319.37	117,740	0	-4,869.43	98.13	51,934.88	37,677.49	-20,171	704.16	32,621.06	0.00	95,040.00	28,363.00	0.00	22,867.00	5,056.43
	7.31	PV, Gen10, Battery x 5, Grid, HydroK	-0.0371	-48,942	-4,884.48	125,240	68.92	-5,176.17	98.56	51,764.23	36,960.28	-21,460	336.02	34,292.13	197.50	95,040.00	28,363.00	0.00	22,867.00	2,668.15
	4.82	PV, Gen10, Battery x 5, Grid, HydroK	-0.0412	-53,763	-5,019.67	125,240	55.83	-5,292.87	98.96	51,611.31	36,631.32	-21,900	220.59	34,872.02	160.00	95,040.00	28,363.00	0.00	22,867.00	1,759.30
\$0.07 / kWh	21.53	Gen10, Battery x 5, Grid, HydroK	0.0499	31,919	166.00	26,000	211.35	-152.99	79.70	26,514.00	17,921.53	-4,535	2,887.00	10,063.00	758.88	0.00	0.00	0.00	22,867.00	7,858.53
	14.30	Gen10, Battery x 5, Grid, HydroK	0.0341	19,874	-171.78	26,000	118.11	-352.56	85.70	25,211.00	16,352.28	-5,825	1,919.00	11,136.00	424.72	0.00	0.00	0.00	22,867.00	5,216.28
	7.31	Gen10, Battery x 5, Grid, HydroK	0.0164	8,758	-483.51	26,000	21.99	-522.54	91.90	24,079.00	14,943.79	-7,042	1,133.00	12,276.00	78.45	0.00	0.00	0.00	22,867.00	2,667.79
	4.82	Gen10, Battery x 5, Grid, HydroK	0.0113	5,814	-566.06	26,000	8.38	-584.77	94.50	23,665.00	14,440.64	-7,530	767.00	12,681.00	30.05	0.00	0.00	0.00	22,867.00	1,759.64
\$0.00 / kWh	21.53	Gen10, Battery x 5, Grid, HydroK	0.1040	53,814	829.05	24,250	211.35	551.20	74.90	26,510.56	14,500.33	-2,375	2,884.00	6,642.00	758.88	0.00	0.00	0.00	22,867.00	7,858.33
	14.30	Gen10, Battery x 5, Grid, HydroK	0.0965	44,487	567.50	24,250	118.11	427.86	81.90	25,207.96	12,931.00	-3,665	1,916.00	7,715.00	424.72	0.00	0.00	0.00	22,867.00	5,216.00
	7.31	Gen10, Battery x 5, Grid	0.2760	26,285	449.65	10,250	56.79	496.53	0.00	2,951.19	2,668.15	1,737	2,748.00	0.00	203.20	0.00	0.00	0.00	0.00	2,668.15
	4.82	Gen10, Battery x 5, Grid	0.3380	21,178	306.45	10,250	11.12	421.14	0.00	1,950.95	1,759.30	1,208	1,911.00	0.00	39.85	0.00	0.00	0.00	0.00	1,759.30

Port-Harcourt, South-South Nigeria

Table H-2: Port-Harcourt simulation results

Port-Harcourt SS			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Battery x 5, Grid, HydroK	-0.1095	-315619	-11338	88700	0	-11964	99	119422	80844	-45,611	1,126	73,295	-	66,000	25,670	-	92,627	7,549
	14.30	PV, Battery x 5, Grid, HydroK	-0.1146	-326757	-11650	88700	0	-12281	99	119012	79942	-46,883	715	74,897	-	66,000	25,670	-	92,627	5,045
	7.31	PV, Gen10, Battery x 5, Grid, HydroK	-0.1199	-338794	-12198	96200	79	-12577	99	118856	79222	-48,171	334	76,554	225	66,000	25,670	-	92,627	2,668
	4.82	PV, Grid, HydroK	-0.1273	-357688	-12490	87700	0	-12767	100	118527	78822	-48,607	230	77,141	-	66,000	25,670	-	92,627	1,681
\$0.07 / kWh	21.53	Battery x 5, Grid, HydroK	-0.0377	-90836	-3184	22700	0	-3691	95	95725	67527	-35,979	3,098	60,026	-	-	-	-	92,627	7,501
	14.30	Gen10, Battery x 5, Grid, HydroK	-0.0413	-97749	-3588	30200	114	-3861	96	94995	66414	-37,440	1,958	61,198	410	-	-	-	92,627	5,216
	7.31	Gen10, Battery x 5, Grid, HydroK	-0.0468	-108481	-3889	30200	21	-4025	98	93857	64998	-38,662	1,156	62,330	75	-	-	-	92,627	2,668
	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0484	-111314	-3968	30200	7	-4084	99	93436	64489	-39,149	785	62,730	25	-	-	-	92,627	1,759
\$0.00 / kWh	21.53	Battery x 5, Grid, HydroK	0.0574	48058	878	16750	0	510	87	95722	23493	-8,151	3,095	15,993	-	-	-	-	92,627	7,500
	14.30	Gen10, Battery x 5, Grid, HydroK	0.0553	44107	557	24250	114	423	89	94991	22380	-9,612	1,954	17,164	410	-	-	-	92,627	5,216
	7.31	Gen10, Battery x 5, Grid	0.2763	26285	450	10250	57	497	0	2951	2668	1,737	2,748	0	203	-	-	-	-	2,668
	4.82	Gen10, Battery x 5, Grid	0.3376	21178	306	10250	11	421	0	1951	1759	1,208	1,911	0	40	-	-	-	-	1,759

Awka, South-East Nigeria

Table H-3: Awka simulation results

Awka SE			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Grid, HydroK	-0.0882	-211004	-9191	116740	0	-9468	99	96760	67063	-37,031	931	59524	0	95040	26846	0	68983	7539
	14.30	PV, Grid, HydroK	-0.1124	-230752	-8291	64900	0	-8568	99	81802	57590	-32,844	616	52584	0	43200	12203	0	68983	5006
	7.31	PV, Grid, HydroK	-0.1289	-241916	-7998	43300	0	-8275	99	75397	52623	-31,441	313	50062	0	21600	6101	0	68983	2561
	4.82	PV, Grid, HydroK	-0.1317	-245855	-8109	43300	0	-8386	100	75284	52330	-31,878	200	50639	0	21600	6101	0	68983	1691
\$0.07 / kWh	21.53	Battery x 5, Grid, HydroK	-0.0284	-51682	-2086	22700	0	-2594	95	71472	51063	-25,907	2489	43481	0	0	0	0	68983	7582
	14.30	Gen10, Battery x 5, Grid, HydroK	-0.0337	-60073	-2531	30200	88	-2766	96	70836	49998	-27,333	1535	44783	319	0	0	0	68983	5216
	7.31	Gen10, Battery x 5, Grid, HydroK	-0.0401	-69625	-2799	30200	15	-2927	98	69943	48747	-28,549	907	46079	54	0	0	0	68983	2668
	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0419	-72115	-2869	30200	7	-2985	99	69614	48298	-29,030	606	46539	25	0	0	0	68983	1759
\$0.00 / kWh	21.53	Battery x 5, Grid, HydroK	0.0581	45911	818	16750	0	450	89	71469	22154	-7,638	2486	14572	0	0	0	0	68983	7582
	14.30	Gen10, Battery x 5, Grid, HydroK	0.0543	40807	464	24250	88	369	91	70833	21089	-9,064	1532	15873	319	0	0	0	68983	5216
	7.31	Gen10, Battery x 5, Grid	0.2763	26285	450	10250	57	497	0	2951	2668	1,737	2748	0	203	0	0	0	0	2668
	4.82	Gen10, Battery x 5, Grid	0.3376	21178	306	10250	11	421	0	1951	1759	1,208	1911	0	40	0	0	0	0	1759

Abuja, North-Central Nigeria

Table H-4: Abuja simulation results

Abuja NC			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Battery x 5, Grid, HydroK	-0.0330	-57109	-4903	117740	0	-5689	87	68451	48579	-21,937	6288	40999	0	95040	32600	0	29563	7580
	14.30	PV, Battery x 5, Grid, HydroK	-0.0484	-76924	-5459	117740	0	-6026	98	63194	44615	-24,394	1031	39628	0	95040	32600	0	29563	4986
	7.31	PV, Battery x 5, Grid, HydroK	-0.0564	-87913	-5767	117740	0	-6339	99	62669	43677	-25,659	506	41105	0	95040	32600	0	29563	2572
	4.82	PV, Battery x 5, Grid, HydroK	-0.0594	-91725	-5874	117740	0	-6449	99	62492	43331	-26,104	329	41633	0	95040	32600	0	29563	1698
\$0.07 / kWh	21.53	Gen10, Battery x 5, Grid, HydroK	0.0294	26985	-90	30200	257	-575	81	34562	25733	-8,721	4076	17875	923	0	0	0	29563	7858
	14.30	Battery x 5, Grid, HydroK	0.0165	13916	-246	22700	0	-754	87	32633	23692	-9,851	3070	18657	0	0	0	0	29563	5035
	7.31	Gen10, Battery x 5, Grid, HydroK	0.0021	1664	-800	30200	34	-955	92	31260	22139	-11,310	1576	19471	121	0	0	0	29563	2668
	4.82	Gen10, Battery x 5, Grid, HydroK	-0.0030	-2315	-912	30200	3	-1021	95	30685	21524	-11,788	1112	19764	10	0	0	0	29563	1759
\$0.00 / kWh	21.53	Battery x 10, Grid	0.2224	59820	1572	3750	0	1071	0	8208	7542	5,187	8208	0	0	0	0	0	0	7542
	14.30	Gen10, Battery x 5, Grid	0.2394	44532	961	10250	263	704	0	5680	5216	2,994	4737	0	942	0	0	0	0	5216
	7.31	Gen10, Battery x 5, Grid	0.2813	26764	463	10250	68	493	0	2933	2668	1,699	2689	0	244	0	0	0	0	2668
	4.82	Gen10, Battery x 5, Grid	0.3324	20851	297	10250	7	418	0	1940	1759	1,210	1915	0	25	0	0	0	0	1759

Kano, North-West Nigeria

Table H-5: Kano simulation results

Kano NW			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Battery x 5, Grid, HydroK	- 0.0510	-86547	-4914	88700	0	-5735	86	65863	47634	-21,061	6801	40125	0	66000	34480	0	24582	7510
	14.30	PV, Battery x 10, Grid, HydroK	- 0.0644	-101061	-5349	89700	0	-6087	97	60164	44030	-23,979	1102	39044	0	66000	34480	0	24582	4986
	7.31	PV, Battery x 5, Grid, HydroK	- 0.0770	-116428	-5752	88700	0	-6340	99	59612	42421	-24,842	550	39857	0	66000	34480	0	24582	2564
	4.82	PV, Battery x 5, Grid, HydroK	- 0.0802	-120412	-5864	88700	0	-6453	99	59419	42080	-25,299	357	40387	0	66000	34480	0	24582	1693
\$0.07 / kWh	21.53	PV, Battery x 5, Grid, HydroK	0.0329	30771	-194	37700	0	-702	90	35004	26253	-10,168	2586	18674	0	15000	7836	0	24582	7579
	14.30	PV, Gen10, Battery x 5, Grid, HydroK	0.0240	21523	-664	45200	93	-905	93	34236	25145	-11,658	1484	19929	335	15000	7836	0	24582	5216
	7.31	Gen10, Battery x 5, Grid, HydroK	0.0158	9389	-466	26000	40	-531	88	26541	16651	-7,688	1817	13983	142	0	0	0	24582	2668
	4.82	Gen10, Battery x 5, Grid, HydroK	0.0093	5326	-580	26000	8	-598	92	25879	15977	-8,185	1267	14217	30	0	0	0	24582	1759
\$0.00 / kWh	21.53	PV, Gen10, Battery x 5, Grid	0.1527	57106	893	25250	237	674	58	12231	10489	576	3542	2631	169	15000	7836	0	0	7858
	14.30	PV, Battery x 10, Grid	0.1883	44876	733	18750	0	231	95	8143	6683	-788	306	1554	0	15000	7836	0	0	5129
	7.31	Gen10, Battery x 5, Grid	0.2763	26285	450	10250	57	497	0	2951	2668	1,737	2748	0	41	0	0	0	0	2668
	4.82	Gen10, Battery x 5, Grid	0.3376	21178	306	10250	11	421	0	1951	1759	1,208	1911	0	8	0	0	0	0	1759

Yola, North-East Nigeria

Table H-6: Yola simulation results

Yola NE			COST						SYSTEM				GRID		GEN10	PV		WIND	HYDROK	LOAD USE
FiT Regime	Demand Profile (kWh/day)	Components	CoE (\$)	NPC (\$)	Op Cost (\$/year)	Initial Capital (\$)	Fuel Cost (\$/yr)	O&M (\$/yr)	Ren Fraction (%)	System Output (kWh/yr)	Power Consumed (kWh/yr)	CO ₂ (kg/yr)	Energy Purchased (kWh)	Energy Sold (kWh)	Gen Output (kWh/yr)	PV Cap Cost (\$)	PV Output (kWh/yr)	Wind T. Output (kWh/yr)	HydroK Output (kWh/yr)	Power used by loads (kWh/yr)
\$0.17 / kWh	21.53	PV, Battery x 5, Grid, HydroK	- 0.0100	-11777	-2700	84500	0	-3229	80	48458	33101	-15,478	6,721	25,592	0	66000	32106	0	9632	6163
	14.30	PV, Gen10, Battery x 5, Grid, HydroK	- 0.0250	-28697	-3502	96200	205	-4006	95	43428	32154	-12,777	1,102	26,938	588	66000	32106	0	9632	6562
	7.31	PV, Battery x 5, Grid, HydroK	- 0.0432	-47422	-3817	88700	0	-4359	98	42297	30759	-17,594	560	28,206	0	66000	32106	0	9632	2038
	4.82	PV, Battery x 5, Grid, HydroK	- 0.0472	-51201	-3923	88700	0	-4469	99	42105	30408	-17,798	367	28,722	0	66000	32106	0	9632	2201
\$0.07 / kWh	21.53	PV, Battery x 5, Grid, HydroK	0.0951	49653	502	31750	0	134	81	19646	14635	-2,745	2717	7060	0	15000	7297	0	9632	7576
	14.30	PV, Gen10, Battery x 5, Grid	0.1310	39145	390	25250	129	330	66	10126	8382	-507	2364	3166	466	15000	7297	0	0	5216
	7.31	PV, Gen10, Battery x 5, Grid	0.1059	25436	5	25250	8	124	80	8621	6737	-1,753	1294	4069	30	15000	7297	0	0	2668
	4.82	Gen10, Battery x 5, Grid	0.3365	21154	306	10250	11	420	0	1954	1763	1,208	1914	3	40	0	0	0	0	1759
\$0.00 / kWh	21.53	PV, Gen10, Battery x 5, Grid	0.1598	58238	925	25250	248	688	56	11845	10222	821	3662	2364	886	15000	7297	0	0	7858
	14.30	PV, Battery x 10, Grid	0.1989	45409	748	18750	0	246	93	7726	6403	-573	429	1336	0	15000	7297	0	0	5067
	7.31	Gen10, Battery x 5, Grid	0.2763	26285	450	10250	57	497	0	2951	2668	1,737	2748	0	203	0	0	0	0	2668
	4.82	Gen10, Battery x 5, Grid	0.3376	21178	306	10250	11	421	0	1951	1759	1,208	1911	0	40	0	0	0	0	1759

Appendix I Severity Ranking of Barriers to Renewable Energy Technology Uptake

Table I-1: Unpublished survey rankings of indicators of factors affecting impeding the uptake of renewable energy technology in Nigeria (Adewole, 2017)

#	Answer	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6	Rank 7	Rank 8	Rank 9	Rank 10	Rank 11	Replies	Mean Rank
1	Upfront cost (Economic - demand-side)	0	0	0	0	0	0	1	2	4	14	4	25	9.72
2	O&M costs (Economic - demand-side)	0	2	3	10	4	4	1	1	0	0	0	25	4.48
3	Inadequate cost recovery (Economic - supply-side)	21	4	0	0	0	0	0	0	0	0	0	25	1.16
4	High cost of infrastructure (Economic - supply-side)	0	0	3	4	4	10	4	0	0	0	0	25	5.32
5	Quality & performance (Technical)	1	8	9	5	1	0	1	0	0	0	0	25	3.04
6	Low technical capacity (Technical)	0	0	0	1	2	3	9	4	4	1	1	25	7.36
7	Political (Political and institutional)	0	0	0	0	0	1	2	5	12	3	2	25	8.80
8	Institutional weaknesses/corruption (Political & institutional)	0	0	0	0	0	0	0	1	2	4	18	25	10.56
9	Political invisibility (Political and institutional)	0	1	2	2	11	5	3	1	0	0	0	25	5.20
10	Technology-Social practices misalignment (Cul./soc.)	0	0	0	1	1	3	3	11	3	3	0	25	7.72
11	Desirability of RETs (Cultural/social)	3	10	7	2	2	0	1	0	0	0	0	25	2.76
	Total	25	25	24	25	25	26	25	25	25	25	25	-	-

Appendix J Service Availability and Readiness Assessment (SARA)

Table J-1: SARA core infrastructure: main components (WHO, 2015a: p. 74)

COVER PAGE	
<ul style="list-style-type: none"> • Interviewer visits • Facility identification • Geographical coordinates 	
MODULE 1: SERVICE AVAILABILITY	
Section 1	Services available
Section 2	Staffing
Section 3	Inpatient and observation beds
MODULE 2: SERVICE READINESS	
Section 4	Infrastructure <ol style="list-style-type: none"> 1. Communications 2. Ambulance/transport for emergencies 3. Power supply 4. Basic client amenities 5. Infection control 6. Processing of equipment for re-use 7. Health-care waste management 8. Supervision 9. Basic equipment 10. Infection control precaution
Section 5	Available services <ol style="list-style-type: none"> 1. Reproductive, maternal and newborn health <ul style="list-style-type: none"> • Family planning services • Antenatal services • Prevention of mother-to-child transmission • Obstetric and newborn care services • Caesarean section 2. Child and adolescent health <ul style="list-style-type: none"> • Child immunization • Child preventative and curative care services • Adolescent health services 3. Communicable diseases <ul style="list-style-type: none"> • HIV counseling and testing • HIV treatment • HIV care and support • Sexually transmitted infections • Tuberculosis • Malaria 4. Noncommunicable diseases <ul style="list-style-type: none"> • Diabetes • Cardiovascular diseases • Chronic respiratory diseases • Cervical cancer 5. Surgery <ul style="list-style-type: none"> • Surgical services • Blood transfusion
Section 6	Diagnostics
Section 7	Medicines and commodities

Table J-2: SARA Indicators (WHO, 2015a: p. 75)

Domain	Tracer Indicators, Items or services
I. Service availability	
1. Health infrastructure	<ul style="list-style-type: none"> • Number of health facilities per 10 000 population • Number of inpatient beds per 10 000 population • Number of maternity beds per 1000 pregnant women
2. Health workforce	<ul style="list-style-type: none"> • Number of health workers per 10 000 population
3. Service utilization	<ul style="list-style-type: none"> • Outpatient visits per capita per year • Hospital discharges per 100 population per year
II. General service readiness	
1. Basic amenities	Mean availability of seven basic amenities items (%): power, improved water source, room with privacy, adequate sanitation facilities, communication equipment, access to computer with Internet, emergency transportation
2. Basic equipment	Mean availability of six basic equipment items (%): adult scale, child scale, thermometer, stethoscope, blood pressure apparatus, light source
3. Standard precautions for infection prevention	Mean availability of nine standard precautions items (%): safe final disposal of sharps, safe final disposal of infectious wastes, appropriate storage of sharps waste, appropriate storage of infectious waste, disinfectant, single-use disposable/auto-disable syringes, soap and running water or alcohol-based hand rub, latex gloves and guidelines for standard precautions
4. Diagnostic capacity	Mean availability of eight laboratory tests available on-site and with appropriate equipment (%): haemoglobin, blood glucose, malaria diagnostic capacity, urine dipstick for protein, urine dipstick for glucose, HIV diagnostic capacity, syphilis rapid diagnostic test and urine pregnancy test
5. Essential medicines	Mean availability of 20 essential medicines (%): amitriptyline tablet, amlodipine tablet or alternative calcium channel blocker, amoxicillin (syrup/suspension or dispersible tablets AND tablet), ampicillin powder for injection, beclomethasone inhaler, ceftriaxone injection, enalapril tablet or alternative ACE inhibitor, fluoxetine tablet, gentamicin injection, glibenclamide tablet, ibuprofen tablet, insulin regular injection, metformin tablet, omeprazole tablet or alternative, oral rehydration solution, paracetamol tablet, salbutamol inhaler, simvastatin tablet or other statin and zinc sulphate (tablet or syrup)
III. Service-specific readiness	
For each service, the readiness score is computed as the mean availability of service-specific tracer items in four domains: staff and training; equipment; diagnostics; and medicines and commodities	<ul style="list-style-type: none"> • Family planning • Antenatal care • Basic obstetric care • Comprehensive obstetric care • Child health immunization • Child health preventive and curative care • Adolescent health services • Life-saving commodities for women and children • Malaria diagnosis and treatment • Tuberculosis services • HIV: (i) counselling and testing, (ii) care and support services, (iii) antiretroviral prescription and client management, (iv) prevention of mother-to-child transmission • Sexually transmitted infections diagnosis or treatment • Noncommunicable diseases diagnosis or management: (i) diabetes, (ii) cardiovascular disease, (iii) chronic respiratory disease, and (iv) cervical cancer screening • Basic and comprehensive surgical care, including: (i) incision and drainage of abscesses, (ii) wound debridement, (iii) acute burn management, (iv) suturing, (v) closed treatment (reduction) of fracture, (vi) cricothyroidotomy, (vii) male circumcision, (viii) hydrocele reduction, (ix) chest tube insertion • Blood transfusion • Laboratory capacity

Appendix K SARA Survey List of Electrical Equipment and Devices in a Health Facility

Table K-1: Electrical equipment and devices in WHO's SARA (WHO, 2015a: p. 72)

41X-1 (Proposed additional question)	Which of the following devices are available at the health facility? If available, does the facility have sufficient power to run them when needed during the day?	Total number of devices available	Does the facility have sufficient electricity to run them?	
			Yes	No
LIGHTING				
01 A	Number of rooms with lights			
01 B	LED light bulbs			
01 C	CFL light bulbs			
01 D	Fluorescent lights (other than CFLs)			
01 E	Incandescent light bulbs			
01 F	Flashlights/portable electric lanterns/headlamps			
01 G	Kerosene lamps			
INFRASTRUCTURE				
02	Cell phones			
03	Computer			
04	Internet			
05	Printer			
06	VHF radio			
07	Fan			
08	Evaporative cooler			
09	Air conditioner unit			
10	Space heater unit			
11	Central air conditioning for facility			
12	Heating for all facility			
13	Piped water			
14	Electric water pump			
CLINICAL APPLIANCES				
15	Electric equipment sterilization autoclave (pressure and wet heat)			
16	Solar equipment sterilization autoclave			
17	Non-electric equipment sterilization autoclave			
18	Electric dry heat sterilizer			
19	Electric boiler or steamer (no pressure)			
20	Non-electric pot with cover for boiling/steam			
21	General purpose refrigerator (size in litres: ____)			
22	Heat source for non-electric equipment			
CLINICAL MEDICAL DEVICES				
23	Micro-nebulizer			
24	Oxygen concentrator			
25	Vaccine/lab refrigerator (specify size: ____ litres)			
26	Suction apparatus			
27	Vacuum aspirator or D&C kit			
28	Incubator			
29	X-ray machine			
30	Anaesthesia machine			
31	Refrigerator for blood storage			
32	Blood chemistry analyzer			
33	Centrifuge			
34	CD4 counter			
35	LED microscope			
36	Bright light microscope			
37	Mercury or xenon microscope			
38	Halogen microscope			
39	ELISA equipment			
40	Vortex mixer			
41	Ultrasound equipment			
42	CT scanner			
43	ECG			
44	Waste autoclave or microwave			
45	Waste incinerator			

Appendix L Indicative Power Requirements of Electrical Devices Based on SARA classifications

Table L-1: Equipment categorisation and power requirements
(WHO, 2015a: p.23)

Health services	Electrical devices (features and characteristics)	Indicative power rating [W] operation mode	AC power supply	DC power supply or battery port
INFRASTRUCTURE	Basic amenities			
	Basic lighting ⁱ requirements for health clinics are estimated at: ~162 lux (lumens/m ²), which may be achieved by various types of lamps:			
	✱ Incandescent lamp (~10–15 lm/W)	40–100 W	110/220 V AC	–
	✱ Halogen lamp (~15–20 lm/W)	20–50 W	110/220 V AC	12 V DC
	✱ CFL ^{viii} (~45–65 lm/W)	10–20 W	110/220 V AC	12 V DC
	✱ LED lamp (~70–90 lm/W)	5–13 W	110/220 V AC	10–30 V DC ³
	Security lighting, outdoors (LED)	10–100 W ⁴	110/220 V AC	10–30 V DC
	Mobile phone battery (charging)	5–20 W ⁵	110/220 V AC	5–16.5 V DC
	Desktop computer ^{ix}	15 ⁶ –200 W ^{7,8}	110/220 V AC	8–20 V DC ⁹
	Laptop computer	20–60 W	110/220 V AC	12–20 V DC ¹⁰
	Internet (V-Sat connection)	85–500 W ¹¹	110/220 V AC	15–24 V DC ¹²
	Printer, ink jet	65 ¹³ –100 W ¹⁴	110/220 V AC	12–20 V DC ¹⁵
	Printer, laser	150–1100 W ¹⁶	110/220 V AC	–
	VHF radio receiver: Stand-by	2 W ¹⁷	110/220 V AC	12 V DC
	Transmitting	30 W ¹⁸	–	–
	Ceiling fan (AC)	30–100 W ^{19,19a}	110/220 V AC	–
	Ceiling fan (DC)	28 W ^{20,22}	–	12 V DC
	Refrigerator, 165 L (for food & water) (AC)	150–200 W ^{23,x}	110/220 V AC	–
	(DC)	40–80 W ^{24,xi}	–	12 V DC
	Portable electric space heater	1392–1500 W ²⁵	110/220 V AC	48 V DC
	Portable air conditioner (AC & DC variants)	1000–1500 W	110/220 V AC ²⁶	48 V DC ²⁷
SPECIFIC SERVICES	Processing of equipment for reuse			
	Countertop autoclave (steam sterilizer) (19–45 L)	1200–2850 W ^{28,29}	110/220 V AC	–
	Dry heat sterilizer	500 W ³⁰ –1.56 kW ³¹	110/220 V AC	–
	Health-care waste management			
	Small waste autoclave (35–178 L)	2–6 kW ³²	220 V AC ^{3a}	–
	Autoclave grinder	1400 W	–	–
	Small water pump – clinic	50–200 W ³³	–	15–30 V DC
	Water pump – district health centre	400–1000 W ³⁴	110/220 V AC	–
	UV water purifier	10–40 W ^{35,36}	–	12 V DC
	Reverse osmosis/other water purifier	264 W ³⁷ –570 W ³⁸	110/220 V AC	–
	General outpatient services			
	Micro-nebulizer	2.5 ³⁹ –36 W ⁴⁰	100–240 V AC	9–12 V DC
	Nebulizer	80–90 W ⁴¹	110/220 V AC	–
	Oxygen concentrator ⁴²	270–310 W	110/220 V AC	–
		70 W	–	12–18 V DC
	Pulse oximeter	50 W ⁴³	110/220 V AC	–
	Pulse oximeter (AA battery-operated)	2–3 W ⁴⁴	–	1.5–3 V DC

Continues

^{vii} Note: This table does not consider electricity demands for dentistry services, which also are important to primary health-care, and deserve further consideration in the energy context. All values are calculated for use in the "active" mode unless otherwise stated. Total daily power consumption (Wh/day) would normally be a function of watt hours of active use plus any standby power requirement. Wherever possible, indicative power requirements have been compiled from data contained in reports and supply catalogues offered by recognized UN or national health and energy research agencies, including: (UNICEF, 2014; World Health Organization, 2013; United States Agency for International Development, 2012; African Renewable Energy Access Program, 2010; National Renewable Energy Laboratory, 1998). References to other indicative values are noted individually in Annex. Reference to performance specifications of specific products or manufacturers does not imply any endorsement or recommendation by the World Bank or WHO, or that they are preferred to others of a similar nature not mentioned.

^{viii} Note: Regarding lighting options: Incandescent bulbs are very inefficient and generate a lot of heat. Such lamps are progressively being banned in some countries. CFLs contain volatile mercury and should be avoided when a strong recycling service is not in place. In addition, CFLs produce electromagnetic and UV emissions. Thus whenever possible LED is preferred. Linear fluorescent tubes, common in developed-country health facilities, have an additional problem insofar as they break easily in settings with electrical perturbations that occur frequently in the unstable grids of developing countries. As an alternative to fluorescent tubes, LED tubelights (9–18 W) with dimming option and running with both AC and DC power are now available in the market.

^{ix} Note: Power varies widely for desktop computers, from 15 W for very efficient, new models, plus another 15 W for the monitor display, and up to 200 W for older ones.

^x Daily electricity requirement for AC refrigerator: 600 Wh–1.44 kWh at ambient temperature of 21.1–32.2 °C

^{xi} Daily electricity requirement for DC refrigerator: 77–168 Wh at ambient temperature of 21.1–32.2 °C

^{xii} Larger models or models with faster cycles often require 440 VAC.

Health services	Electrical devices (features and characteristics)	Indicative power rating [W] operation mode	AC power supply	DC power supply or battery port	
SPECIFIC SERVICES	Antenatal, child and adolescent health	Vaccine refrigerator (polio, measles, DPT-Hib+HepB, BCG & tetanus toxoid) ^{xiii} designed to perform at 43° C:			
		Vestfrost VLS200 AC (electric mains) refrigerator, 100 litres (WHO/PQS: E003/031)	115 W ^{xiv}	110/220 V AC	N/A
		Dometic TCW 3000 DC (solar-charged, battery-driven) vaccine refrigerator, 110 litres (WHO/PQS-E003/008)	250 W solar array ^{xv}	N/A	12/24 V DC
		Sure Chill BLF100 DC (solar direct-drive) vaccine refrigerator, 99 litres (WHO/PQS: E003/019) ^{xv}	370 W +/- solar array ^{xv}	N/A	12/24 V DC
	Obstetric and newborn	LED light for phototherapy treatment of neo-natal jaundice ^{xvi}	440 W	110/220 V AC	–
		Suction apparatus ^{xvii}	90–200 W 33 W	110/220 V AC	± 12 V DC
		Vacuum aspirator or D&C kit ^{xv}	36–96 W	110/220 V AC	± 3–6 V DC
		Neo-natal incubator	800–1035 W ^{xviii}	110/220 V AC	–
		Neo-natal infant warmer ^{xviii}	125/550 W ^{xix}	110/230 V AC	–
		Fetal heart monitor (Doppler)	1.5–3 W (AA battery) ^{xx}	–	1.5–3 V DC
		Ultrasound	800–1000 W ^{xx}	110/220 V AC	–
		Portable ultrasound	6 W (idle) – 22–28 W (active-charging) ^{xix,xxi}	100–240 V AC ^{xxi}	11–15 V DC ^{xxii}
		General diagnostics, blood analysis and laboratory equipment	Laboratory refrigerator	60–160 W ^{xxiii} 40–80 W (165 L) ^{xxiii}	110/220 V AC
	Centrifuge		250 – 400 W (low-medium speeds) ^{xxiv}	110/220 V AC	–
	Mini-centrifuge		25 W ^{xxv}	–	12 V DC
	Haematology analyser		230–400 W ^{xxvi}	–	–
	Blood chemistry analyser		45–88 W ^{xxvii}	–	–
	Blood chemistry analyser (hand-held) ^{xxviii}		–	–	18 V DC battery ^{xxix}
	CD4 counter		200 W ^{xxxi}	110/220 V AC	12 V DC
	Brightfield white light microscope (with LED light)		20–30 W ^{xxxii}	110/220 V AC	3–6 V DC
	LED microscope (for fluorescence smear microscopy (halogen or LED light) ^{xxxiii}		70 W ^{xxxiii}	110/220 V AC	12 V DC
	Mercury/xenon fluorescence microscope ^{xxxiv}		75–200 W	220–240 V AC	–
	X-ray machine ^{xxxv}		15–20 kW	120 V AC	–
			30–40 kW	1Φ/108–230 V AC	–
			50–80 kW	3Φ/400–480 V AC	–
	Portable X-ray machine		3–4 kW ^{xxxvi}	90–264 V AC	–
	Laboratory incubator		200 W ^{xxxvii}	110/220 V AC	12 V DC
	Vortex mixer		18 W ^{xxxviii}	90/220 V AC	6 V DC
			70–90 W ^{xxxix}	120/230 VAC	–
	TB diagnosis	Sputum-smear microscopy (LED microscope w/fluorescent smear) ^{xl}	30 W (+ 6 W LED bulb) ^{xl} 20–30 W ^{xl} (+6 W LED bulbs)	110/230 V AC –	– 6 V DC
		GeneXpert MTB/RIF diagnostic	190 W ^{xli}	110/220 V AC	12/24 V DC
	HIV diagnosis	ELISA test reader	500–650 W ^{xlii}	110/220 V AC	48 V DC
	Cardiovascular diagnosis/ treatment	Portable electrocardiograph (ECG)	1.2 W ^{xliii} –45/70 W ^{xliii}	100/240 V AC	3–12 V DC
		Defibrillator with ECG	130–200 W ^{xliiii}	110/220 V AC	14–15 V DC
			100–130 W ^{xliiii}	–	11.1 V DC
	Diabetes	Blood glucose monitor	<1 W	–	3.3–5 V DC ^{xlv}
	Basic surgical services ^{xvii}	Suction apparatus (AC)	90–200 W	110/220 V AC	–
		Suction apparatus (DC)	33 W	–	± 12 V DC
		Anaesthesia machine	1440 W ^{xlv}	110/220 V AC	
Low-energy anaesthesia machine with DC monitor backup ^{lv}		480 W – oxygen concentrator 20 W – monitor ^{lv}	220 V	12 V DC backup (for monitor)	

^{xiii} Note: Vaccine refrigerators are designed to keep vaccines in a stable +2° C – +8° C range; vaccine cold packs require freezers.

^{xiv} Note: In a well-designed refrigerator, the cooling compressor only operates intermittently so total daily demand would be estimated at about 710 Wh/day

^{xv} At solar radiation reference period average = 3.5 kWh/m²/day – (approximating average solar radiation in less-than-optimal sunlight, e.g. cloudy, rainy and cool-weather days).

^{xvi} These values refer to the power supply for the x-ray generator; 150 kVp is the maximum voltage across the x-ray tube itself.

^{xvii} Including basic procedures such as: tracheotomy, tubal ligation, vasectomy, dilatation and curettage, obstetric fistula repair, episiotomy, appendectomy, neonatal surgery, skin grafting, open treatment of fracture, amputation, cataract surgery. Note: Dental surgery procedures can impose significant load requirements including: dental compressor (~750 W–2.2 KW); dental sterilizer (~850 W); and dental chair & exam light (200 W); as well as x-ray and other specialized devices.

Continued from previous page

Appendix M Summary of Modelling Inputs for a Typical Location in HOMER

Input Summary

Input Summary

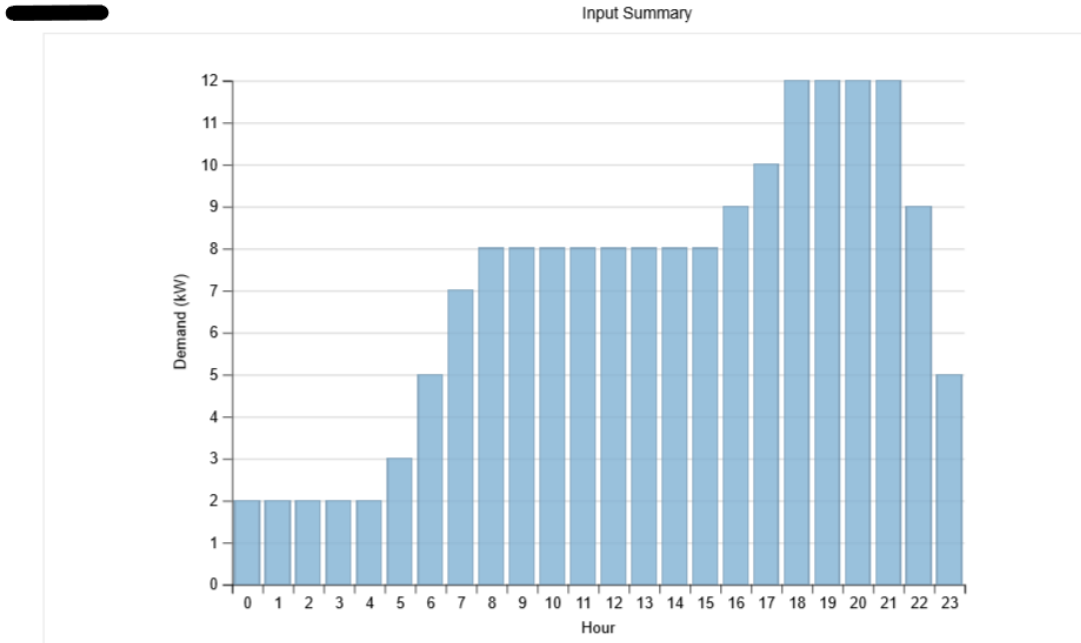
Project title	PH SS10kW Hydrokinetic, Solar and Wind turbine
Author	Adekunle Adewole
Notes	This model is conducted for a healthcare facility in Port Harcourt, South South Nigeria. This model considers a 20kW Guinard P154 hydrokinetic turbine, solar PV modules, 10kW wind turbine and inflation rate of 17% (2016).

Project Location

Location	4 Close D, Trans-Amadi, Port Harcourt, Nigeria
Latitude	4 degrees 48.93 minutes North
Longitude	7 degrees 2.99 minutes East
Time zone	Africa/Lagos

Load: Electric1

Data source	Synthetic
Daily noise	10%
Hourly noise	20%
Scaled annual average	21.530 kWh/d
Scaled peak load	2.6625 kW
Load factor	0.3369



Microgrid Controller: HOMER Cycle Charging

Quantity	Capital	Replacement	O&M
1	\$0.00	\$0.00	\$0.00

Minimization strategy	Economic
Setpoint state of charge	80
Allow multiple generators to operate simultaneously	Yes
Allow systems with generator capacity less than peak load	Yes
Allow diesel off operation	Yes

Microgrid Controller: HOMER Load Following

Quantity	Capital	Replacement	O&M
1	\$0.00	\$0.00	\$0.00

Minimization strategy	Economic
-----------------------	----------

Input Summary

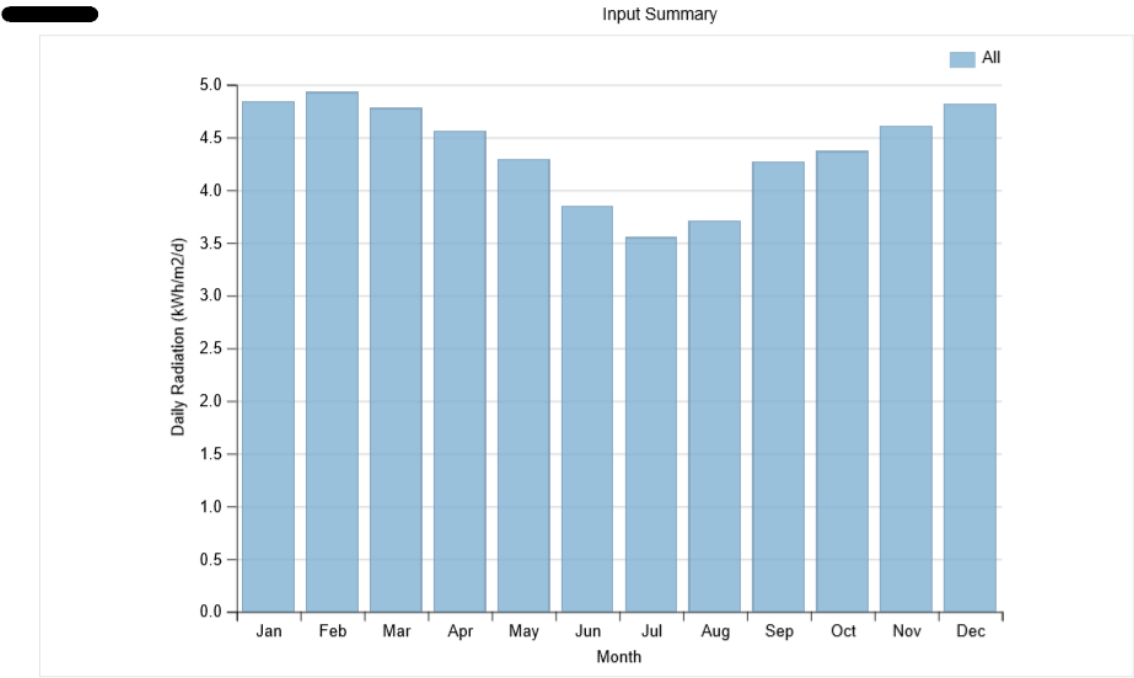
Allow multiple generators to operate simultaneously	Yes
Allow systems with generator capacity less than peak load	Yes
Allow diesel off operation	Yes

PV:Generic flat plate PV

Size	Capital	Replacement	O&M
Sizes to consider	0,5,10,22		
Lifetime	25 yr		
Derating factor	80%		
Tracking system	No Tracking		
Slope	4.816 deg		
Azimuth	0.000 deg		
Ground reflectance	20.0%		

Solar Resource

Scaled annual average	4.38 kWh/m2/d
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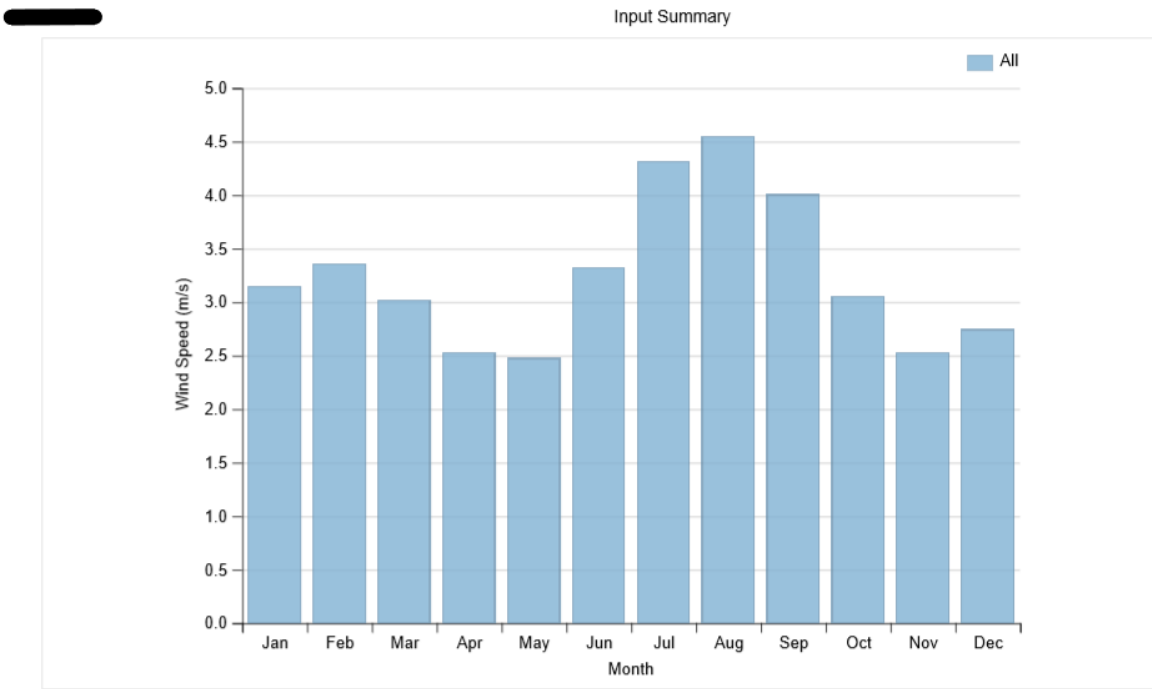
;

Wind Turbine:Generic 10 kW

Quantity	Capital	Replacement	O&M
1	\$50,000.00	\$50,000.00	\$500.00

Wind Resource

Scaled annual average	3.25
-----------------------	------



;

Generator:Generic 10kW Fixed Capacity Genset

Size	Capital	Replacement	O&M
10.00	\$7,500.00	\$7,500.00	\$0.30

Sizes to consider	0,10
Lifetime	15,000 hrs
Min. load ratio	25%
Heat recovery ratio	0%
Fuel used	Diesel
Fuel curve intercept	0.0480 L/hr/kW
Fuel curve slope	0.2860 L/hr/kW

Fuel: Diesel

Price	\$ 0.73/L
-------	-----------

Input Summary

Lower heating value	43.2 MJ/kg
Density	820.00 kg/m3
Carbon content	88.0%
Sulfur content	0.3%

Battery:Generic 1kWh Li-Ion

Quantity	Capital	Replacement	O&M
1	\$200.00	\$160.00	\$10.00
2	\$400.00	\$320.00	\$20.00
5	\$1,000.00	\$800.00	\$50.00
10	\$2,000.00	\$1,600.00	\$100.00
15	\$3,000.00	\$2,400.00	\$150.00
25	\$5,000.00	\$4,000.00	\$250.00

Quantities to consider	0,5,10,22
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Hydrokinetic:Guinard - P154 [20kW]

Quantity	Capital	Replacement	O&M
1	\$14,000.00	\$14,000.00	\$100.00

Quantities to consider	0,1
Rated Power	20 V

Converter

Input Summary

Size	Capital	Replacement	O&M
1.00	\$350.00	\$350.00	\$0.00

Sizes to consider	0,5,10,22 kW
Lifetime	15 yr
Inverter can parallel with AC generator	Yes

Economics

Annual real interest rate	-3%
Project lifetime	25 yr
Capacity shortage penalty	\$0/kWh
System fixed capital cost	0
System fixed O&M cost	0

System control

Timestep length in minutes	60
Multi-Year enabled	No
Allow systems with multiple generators	Yes
Allow systems with multiple wind turbine types	Yes
Battery autonomy threshold	2
Maximum renewable penetration threshold	55
Warn about renewable penetration	Yes

Optimizer

Input Summary

Maximum simulations	10000
System design precision	0.01
NPC precision	0.01
Minimum spacing	0
Focus factor	50
Optimize category winners	Yes
Use base case	No

Emissions

Carbon dioxide penalty	\$ 0/t
Carbon monoxide penalty	\$ 0/t
Unburned hydrocarbons penalty	\$ 0/t
Particulate matter penalty	\$ 0/t
Sulfur dioxide penalty	\$ 0/t
Nitrogen oxides penalty	\$ 0/t

Constraints

Maximum annual capacity shortage	5
Minimum renewable fraction	0
Operating reserve as percentage of hourly load	10
Operating reserve as percentage of peak load	0
Operating reserve as percentage of solar power output	25
Operating reserve as percentage of wind power output	50

Appendix N Power Quality Indicators, Definitions and Causes (IEEE, 2009; Seymour and Horsley, 2011)

Power Quality Problem	Definition	Causes
Transients	<p>Impulsive transients are sudden high peak events that raise the voltage and/or current levels in either a positive or a negative direction.</p> <p>Oscillatory transient is a sudden change in the steady-state condition of a signal's voltage, current, or both. This transient causes the power signal to alternately swell and then shrink, very rapidly</p>	<p>Causes of impulsive transients include lightning, poor grounding, the switching of inductive loads, utility fault clearing, and Electrostatic Discharge.</p> <p>Oscillatory transients occur when an inductive or capacitive load, such as a motor or capacitor bank, is turned off. This transient results because the load resists the change.</p>
Interruptions	An interruption is defined as the complete loss of supply voltage or load current. Depending on its duration, an interruption is categorized as instantaneous, momentary, temporary, or sustained.	The causes of interruptions can vary but are usually the result of some type of electrical supply grid damage, such as lightning strikes, animals, trees, vehicle accidents, destructive weather (high winds, heavy snow or ice on lines, etc.), equipment failure, or a basic circuit breaker tripping.
Under-voltage/sag	<p>A sag is a reduction of AC voltage at a given frequency for the duration of 0.5 cycles to 1 minute's time.</p> <p>Under-voltages are the result of long-term problems that create sags.</p>	Common causes of sags include starting large loads and remote fault clearing performed by utility equipment. E.g. a motor can draw six times its normal running current, or more, while starting.
Over-voltage/swell	<p>A swell is the reverse form of a sag, having an increase in AC voltage for a duration of 0.5 cycles to 1 minute's time.</p> <p>Over-voltages can be the result of long-term problems that create swells. An overvoltage can be regarded as an extended swell.</p>	<p>High-impedance neutral connections, sudden (especially large) load reductions, and a single-phase fault on a three-phase system are common sources of swells.</p> <p>Over-voltages are also common in areas where supply transformer tap settings are set incorrectly and loads have been reduced. This</p>

Waveform distortion	<ul style="list-style-type: none"> • DC offset: occurs when direct current traverses the ac power system and adds unwanted current to devices already operating at their rated level. • Harmonics: Harmonic distortion is the corruption of the fundamental sine wave at frequencies that are multiples of the fundamental. • Interharmonics: are a type of waveform distortion that are usually the result of a signal imposed on the supply voltage by electrical equipment such as static frequency converters, induction motors and arcing devices. • Notching: is a periodic voltage disturbance. This problem could be described as a transient impulse problem, but because the notches are periodic over each $\frac{1}{2}$ cycle, notching is considered a waveform distortion problem. • Noise: unwanted voltage or current superimposed on the power system voltage or current waveform. 	<ul style="list-style-type: none"> • Direct current (DC) can be induced into an AC distribution system, often due to failure of rectifiers within the many AC to DC conversion technologies that have proliferated modern equipment. • Symptoms of harmonic problems include overheated transformers, neutral conductors, and other electrical distribution equipment, as well as the tripping of circuit breakers and loss of synchronization on timing circuits that are dependent upon a clean sine wave trigger at the zero crossover point. • Cycloconverters (which control large linear motors used in rolling mill, cement, and mining equipment), create some of the most significant interharmonic supply power problems. These devices transform the supply voltage into an AC voltage of a frequency lower or higher than that of the supply frequency. • Notching is caused by electronic devices, such as variable speed drives, light dimmers and arc welders under normal operation. • Noise can be generated by power electronic devices, control circuits, arc welders, switching power supplies, radio transmitters and so on. Poorly grounded sites make the system more susceptible to noise.
Voltage fluctuations	A voltage fluctuation is a systematic variation of the voltage waveform or a series of random voltage changes, of small dimensions, namely 95 to 105% of nominal at a low frequency, generally below 25 Hz.	Any load exhibiting significant current variations can cause voltage fluctuations. Arc furnaces are the most common cause of voltage fluctuation on the transmission and distribution system.
Frequency variation	This is typically associated with unstable frequency of input power. Frequency variations may cause a motor to run faster or slower to match the frequency of the input power.	Where sites have dedicated standby generators or poor power infrastructure, frequency variation is more common especially if the generator is heavily loaded.

Appendix O Energy Demand Focus Group Design

Determination of Most Critical Emergency Treatment Case and Critical Energy Demand Profile at a Secondary Health Facility in Ibadan, Nigeria

Goal Clarification

To identify the most suitable energy system solution for critical applications in a health facility, it is important to carry out an energy assessment of critical equipment and devices. It is also important to base this assessment on the most common critical events. In order to identify a suitable critical treatment case and create an energy demand profile for the health facility, a focus group of two clinician and two medical facility managers are selected and tasked with achieving the following objectives:

- i. Identify the three most common emergency cases in the hospital using expert judgement.
- ii. determine the most critical of these cases using the triaging and GCS methodologies.
- iii. determine the critical energy use profile of health facility using the provided WHO health facility energy demand profile template.

Overall study design and selection criteria

Four focus group participants comprising of two medical doctors and two health facility managers from a hospital in Ibadan Nigeria will be recruited. The participants will be selected through the judgement of the facility's medical director based on availability, qualification and experience. Each of the participants will have at least a graduate degree and minimum of ten years' experience as clinician or facility management personnel. They will meet face-to-face three times, once for each focus group objective. The main method of contact with the focus group is via email and telephone. The above objectives will be achieved through the expert judgment of the selected focus group participants.

The use of expert judgement on a subject requires that judgement be made based on a specific set of criteria or expertise in a particular knowledge area or discipline. Expert judgement is typically required when a group or team requires an expertise that is not present within it. Therefore, an external group or person with the required skill or expertise is usually brought in for consultation. Since the researcher is not a clinical expert, the members of the focus group employed in this study are selected for their expertise on clinical emergencies and the treatment processes and devices used in these emergencies. The expert focus group were allowed a high level of independence in achieving the objectives within the limits of a set of criteria.

The treatment case selection criteria presented to the focus group are as follows:

- i. The condition of the patient is life-threatening and is categorised as high priority for treatment;
- ii. The treatment process of the patient is heavily reliant on the use of electrical medical devices.

Both criteria are designed to ensure that the most commonly occurring medical emergency requiring the highest level of energy demand is selected for intervention. By providing alternative power supply solutions that can cater to a treatment case that fits these two criteria, a health facility should be capable of ensuring positive outcomes for its most vulnerable patients. Furthermore, making the most essential medical devices the focus of early energy interventions will make energy provision more economically sustainable while providing desired patient outcomes.

Data Collection and Analysis

The processes employed in determining the treatment case are to be recorded on a Microsoft Word file and the energy demand profile recorded on the template presented as an Appendix A to this file. The movement of the patient through the clinical spaces in the facility will be mapped using the United Kingdom's NHS format for spaces in emergency facilities – presented in Appendix B.

No further analysis is expected after focus group objectives i) and ii) have been achieved. Using an Excel spreadsheet, the energy demand profile developed from objective iii) will be collected and analysed as follows:

- 1 Determine daily and hourly noise in demand (10% daily, 20% hourly variance proposed by energy demand focus group)
- 2 Create initial load profile (quantity and power rating) for two scenarios, conventional and energy-efficient medical devices
- 3 Create load profile (quantity and power rating) for conventional and energy-efficient medical devices
- 4 Determine daily distribution of hours of operation of medical devices across day, evening and night-time
- 5 Estimate total daily energy required based on focus group's analysis of load profile and distribution of daily load demands for both scenarios in step 2 and characterise the loads
- 6 Pause to determine most critical loads and then create a reduced second load profile for the two scenarios in step 2

These steps are based on WHO (2015)'s prescribed energy assessment methodology.

Instructions on how to complete the files will be given through a cover letter and through telephone conversations. The completed files will be collected by email. The energy demand profile assessment requires the collated power ratings, and daily hours of operation (early, daytime and night hours) to

calculate the total energy demand per day in kWh/day. A desk search of energy-efficient alternatives to each medical device and equipment will be conducted to provide a minimum and maximum load profile for the facility.

Ethical Considerations and Limitations of Focus Group

According to (WHO, 2017b), research ethics govern the standards of conduct for scientific researchers. Although the Focus Group activity is a medical-based, the use of human subjects or specific cases that can be traced to a particular patient of the facility is strictly prohibited. The set objectives will be achieved only through the expert judgement of the participants without relinquishing their identities.

Although the judgement sampling method saves time, it is unscientific and requires no special knowledge of statistics. A key limitation of the Focus Group method is the small sample size which is not a good representation of doctors and facility managers in Nigerian secondary hospitals. However, every hospital will normally present its own unique nature of emergency patients based on the demography of its locality, available services and accessibility among other factors.

Furthermore, the use of judgement sampling presents potential for bias from the medical director's professional perspective. Nevertheless, since the aim is to get expert judgements relating to emergency cases in the participant's place of work, the need to eliminate selection biases and sampling errors is settled by judgement.

Appendix P Energy Demand Focus Group Cover Letter

Dear Sir/Madam,

Invitation to Participate in A Focus Group to Determine the Most Common Emergency Case and Critical Energy Demand Profile for the Treatment of the Case at Your Facility

My name is Adekunle Adewole, a doctoral researcher at Cranfield University in the United Kingdom.

This Focus Group study is part of an ongoing doctoral research into the optimisation of renewable energy technologies to increase their potential for reliable deployment in health facilities in resource-constrained areas. The main objectives of this Focus Group are to:

- i. identify the three most common emergency cases in the hospital using expert judgement.
- ii. determine the most critical of these cases using the triaging and GCS methodologies.
- iii. determine the critical energy use profile of health facility using the provided WHO health facility energy demand profile template.

The eventual emergency case selected is required to meet the following criteria:

- i. The condition of the patient is life-threatening and is categorised as high priority for treatment;
- ii. The treatment process of the patient is heavily reliant on the use of electrical medical devices (please use the *spaces in emergency facilities* chart to evaluate the treatment equipment and devices).

For the objective, please follow the steps below in filling the attached energy demand profile template:

- 1 Determine daily and hourly noise in demand (10% daily, 20% hourly variance proposed by energy demand focus group)
- 2 Create initial load profile (quantity and power rating) for two scenarios, conventional and energy-efficient medical devices
- 3 Create load profile (quantity and power rating) for conventional and energy-efficient medical devices
- 4 Determine daily distribution of hours of operation of medical devices across day, evening and night-time
- 5 Estimate total daily energy required based on focus group's analysis of load profile and distribution of daily load demands for both scenarios in step 2 and characterise the loads
- 6 Pause to determine most critical loads and then create a reduced second load profile for the two scenarios in step 2

Please note that you are free to withdraw from participation and your contributions at any point in the rounds if you so desire. The Focus Group is completely anonymous, and every information provided will be handled with utmost confidentiality. The use of human subjects is completely prohibited in this study. All answers directed to the achievement of the Focus Group's objectives must be based only on expert judgement and opinion.

The outcome of this Focus Group activity will help create the basis for evaluating the different levels of critical services that can be provided in an economically and environmentally sustainable manner and powered using reliable electricity supply.

If you have any questions relating to this study, please do not hesitate to contact me or the research supervisor. Please see details below.

Yours faithfully,

Adekunle Adewole

Doctoral Researcher

Cranfield University

United Kingdom

Email: k.o.adewole@cranfield.ac.uk

Tel: +44 (0) 74 0295 2006

Research supervisor

Prof. Philip Longhurst

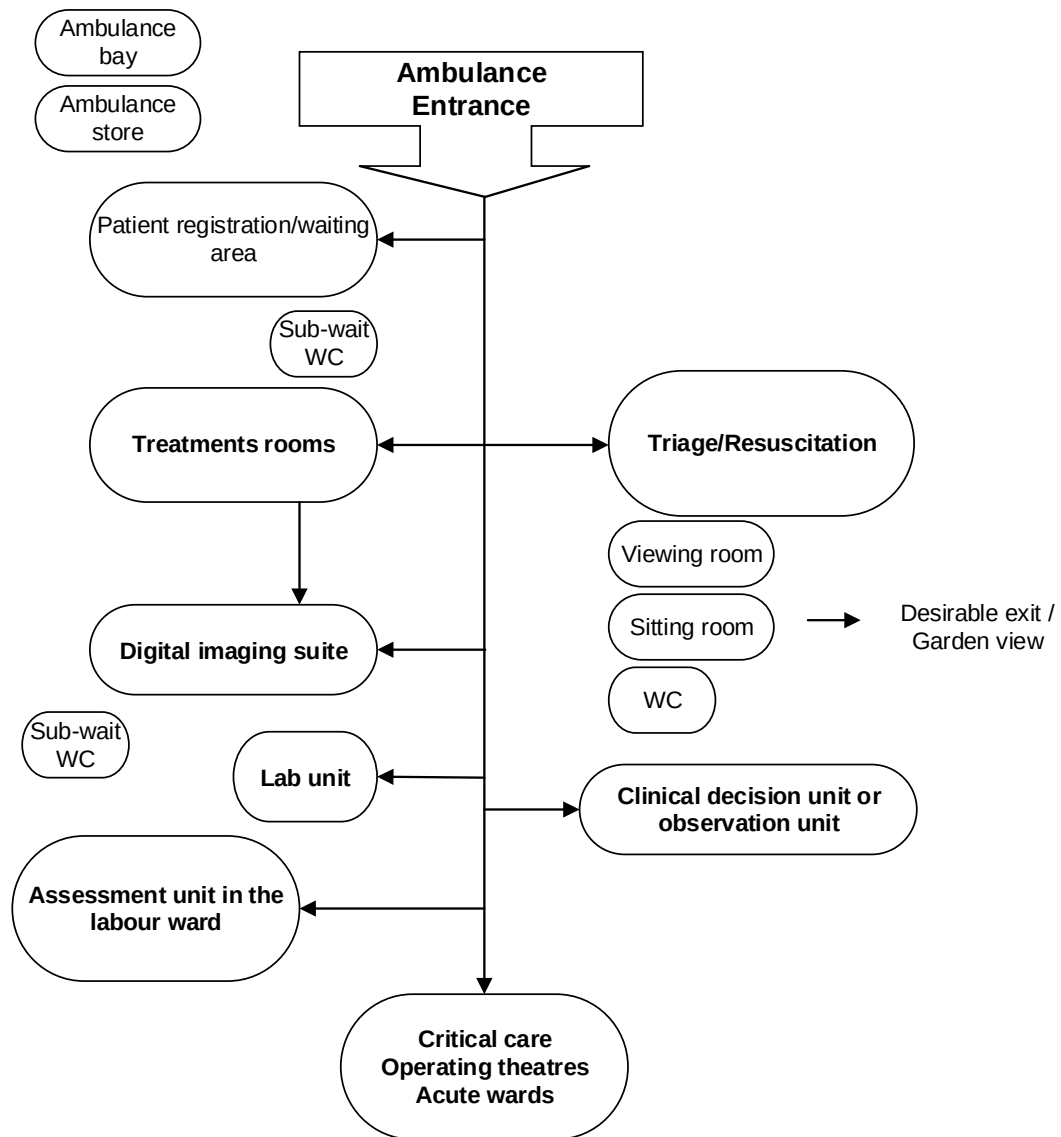
Email: p.j.longhurst@cranfield.ac.uk

Appendix A

Energy demand profile template (Source: WHO, 2015)

Area	Equipment/load	Qty	Rating (W)		Early hours	Daytime hours	Night hours	Total hours / day	Total Energy kWh/day		Non-critical / Contact / No-contact	DC Alternative?
			Min	Max	(0000-0759)	(0800-1759)	(1800-1159)		Min	Max		
e.g. Operating room												

Appendix B



Spaces in emergency facilities (NHS Estates, 2013)

Appendix Q Spatial Analysis

Ambulance Entrance (12.0m²)

Patient A is rushed in through the ambulance entrance. It is regulatory that there are two entrances to an A&E department, and this is often the case in primary healthcare facilities. The main entrance is designated for people arriving on their own and the ambulance entrance for patients arriving by ambulance. Both entrances are expected to be canopied and well-lit to aid access. Critical appliances in this space are the lighting equipment.

Triage / resuscitation Room (3 bays, 89.0 m²)

The resuscitation room is expected to have easy and unimpeded access to the ambulance entrance. The reason is so that patients in critical conditions can be admitted, assessed and treated without delay. The resuscitation room is also easily accessible from other treatment rooms.

Because of her semi-conscious state and advanced pregnancy, she is assumed to be wheeled directly to the resuscitation room from the ambulance entrance without registration. While she is transferred to a trolley stretcher, IV fluid is passed intravenously through her hand. Her blood samples are collected for testing while she is triaged and resuscitated. It is at this point that a leg bone fracture and vaginal bleeding are discovered.

Medical staffs perform clinical procedures from all sides of the trolley using various equipment. Surgical procedures may be necessary for some patients in the resuscitation room. Staff will also need to take and view x-rays and digital images, view monitors, obtain and input data into a computer. Therefore, lighting in the resuscitation room is critical. Devices in use at this stage include a fetal heart monitor for the baby, portable ultrasound device to monitor the status of the pregnancy, internal organs, portable electrocardiograph (ECG) and pulse oximeter to monitor the patient's heartbeat.

Imaging suite (15.0m²)

A general imaging room is required in every emergency department, with an associated sub-waiting area. The imaging room is able to accommodate both trolley and mobile patients. In the event of high influx of patients, a mobile imaging unit may be necessary for use in the resuscitation and treatment rooms.

After resuscitation, Patient A continued to relapse into unconsciousness, and it was decided that she is to be operated upon due to her declining GCS score. She is sent to the imaging suite to determine the cause of continuous bleeding from one of her orifices, examine if there are other fractures, check the status of internal organs and to continuously monitor the pregnancy. It is normal that imaging rooms allow blood pressure monitors, ECG equipment and other monitoring equipment to be connected to the patients. Resuscitation equipment should also be easily accessible including an alarm system should the assistance of the resuscitation team be necessary.

Equipment required in the imaging suite for Patient A include x-ray machine to check for the extent of fracture and other fractures, ultrasound scanner for detailed assessment of internal organs and ECG to monitor the heart.

Lab unit (8.5m²)

Although emergency patients in critical conditions like Patient A do not get to pass through the lab unit, the results of various tests carried out on their blood samples will almost certainly contribute to their chances of survival. This is especially crucial for patients who do not have a registration at the health centre and their medical records are not immediately accessible.

Testing in the lab unit for Patient A requiring the use of electric devices includes full blood count, grouping and cross matching, HIV, Hepatitis and Syphilis tests. Other crucial electric devices in the lab unit include laboratory refrigerator, centrifuge and mini-centrifuge, laboratory incubator and vortex mixer.

Operating theatre (38m²)

Operating theatres vary in size and their number of support spaces according to the level of provision of the hospital. It is not uncommon for primary provisions to have a rectangular hall partitioned into an anaesthetic room, operating room and recovery

room. This analysis focuses on the operating room and its devices because treatment rooms can sometimes double up as recovery rooms in primary provisions. The set of devices required in the operating theatre for this patient include anaesthesia machine, suction apparatus, defibrillator with ECG and fetal heart monitor.

Appendix R Wind Speed Data Algorithm and Sources in HOMER (Source: HOMER Energy, 2017)

Algorithm

HOMER follows a five-step process to synthesize one year of time series wind speed data.

Step 1

In the first step of the algorithm, HOMER generates a sequence of autocorrelated numbers, one for each time step of the year, using the first-order, autoregressive model:

$$z_t = a \cdot z_{t-1} + f(t)$$

where:

z_t = the value in time step i

z_{t-1} = the value in time step $i-1$

a = the autoregressive parameter

$f(t)$ = a "white noise" function that returns a random number drawn from a normal distribution with a mean of zero and a standard deviation of 1

HOMER sets the autoregressive parameter equal to the one-time-step autocorrelation coefficient:

$$a = r_1$$

On the Wind Resource page, enter the *one-hour autocorrelation coefficient*, which is different from the one-time-step autocorrelation coefficient if the time step is not 60 minutes.

To calculate the one-time-step autocorrelation coefficient from the one-hour autocorrelation factor, HOMER assumes logarithmic decay in the autocorrelation function, in which case the following equation gives the autocorrelation parameter for a lag of k time steps:

$$r_k = r_1^k$$

Solving that for r_1 gives:

$$r_1 = \exp\left[\frac{\ln(r_k)}{k}\right]$$

The one-hour autocorrelation factor is r_k where k is the number of time steps that fit in one hour, meaning:

$$k = \frac{60}{t}$$

Where t is the time step in minutes.

This first step of the algorithm produces a series of numbers that conform to a normal distribution with a mean of zero and a standard deviation of 1.

Step 2

In the second step of the algorithm, HOMER creates a full year of data by piecing together the desired average diurnal wind speed profile, repeated every day. Because the average wind speed varies by month, the average diurnal wind speed profile scales to a different value each month, but within each month the diurnal pattern simply repeats over and over.

Step 3

In the third step, HOMER performs a probability transformation on the sequence of numbers generated in Step 2 so that it conforms to the same normal distribution as the sequence generated in Step 1.

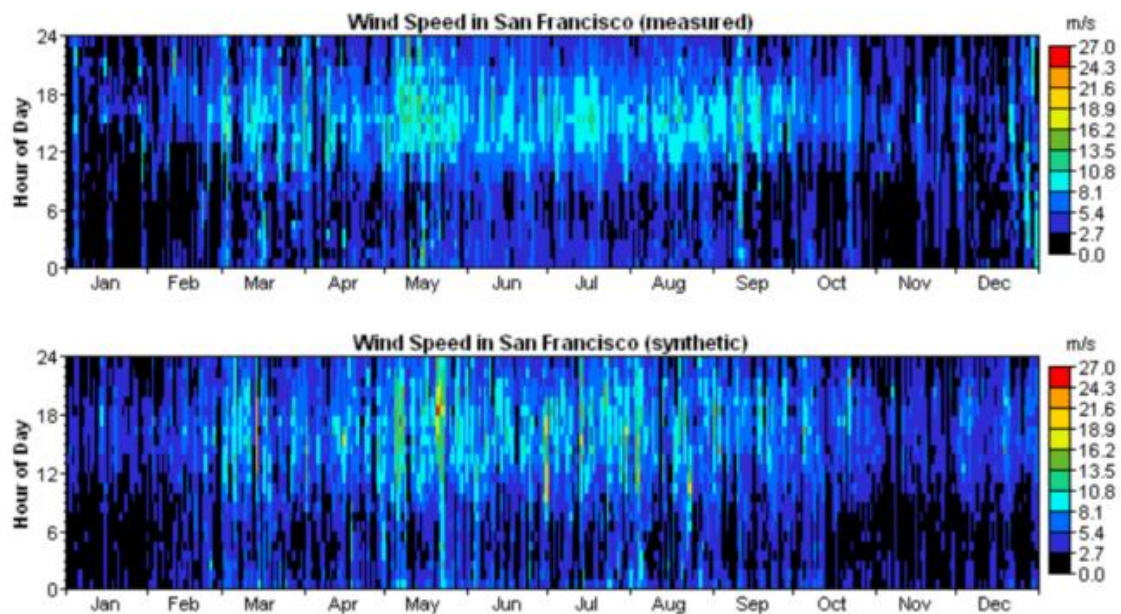
Step 4

In the fourth step, HOMER adds the sequence generated in Step 3 to the sequence generated in Step 1. The resulting sequence conforms to a normal distribution, but exhibits the desired degree of autocorrelation.

Step 5

In the fifth and final step, HOMER performs a probability transformation on the sequence generated in Step 4 to make it conform to the desired Weibull distribution.

The two [DMaps](#) below demonstrate the results of the synthetic wind data generation algorithm. The first shows the measured wind speed data for San Francisco, California from the TMY2 data set. The second shows the synthetic wind speed data that HOMER generated from the monthly average wind speeds and the four wind data parameters measured from the real data.



Wind Speed Data Sources

Many countries have published wind atlases:

- Wind maps for many US states are available at apps2.eere.energy.gov/wind/windexchange/windmaps/.
- The Canadian Wind Atlas is available at www.windatlas.ca.
- The Brazilian Wind Atlas is available at www.cresesb.cepel.br/publicacoes/index.php?task=livro&cid=1.

A number of other websites provide wind speed data:

- The US Renewable Resource Data Center provides information on wind data at http://www.nrel.gov/rredc/wind_resource.html.
- The www.weatherbase.com website provides monthly average wind speed data for many cities around the world.
- The Windustry website maintains a list of US wind data resources at www.windustry.com/resources/windmaps.htm.
- The US National Climatic Data Center provides monthly average wind speed data for many US cities at <http://www1.ncdc.noaa.gov/pub/data/ccd-data/wndspd12.txt>. To convert from mph to m/s, divide by 2.23694.
- The Technical University of Denmark maintains a database of wind characteristics at www.winddata.com.