Performance Evaluation of Off-Grid Power Supply for Rural Electrification in Kenya: The Case of Habaswein Hybrid Minigrid

Isaac Nzue Kiva

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DECLARATION

This research is my original work and has not been submitted for the award of a degree in any other University.

Signature ……………………………… Date …………………….

Isaac Nzue Kiva

This research study report has been submitted for examination with our approval as the University supervisors.

Signature ……………………………… Date …………………….

Dr. Jeremiah K. Kiplagat

KPLC, Kenya

Signature ……………………………… Date …………………….

Prof. Robert Kinyua

JKUAT, Kenya

DEDICATION

I would like to dedicate this thesis to my family, who have always supported and encouraged me in my personal, professional and academic pursuits, and remain my most important source of inspiration as I look forward to more opportunities and challenges in the future.

This work is especially dedicated to my children, who I am very proud of, and for whom I would like to set an example of working hard to achieve the best they can.

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LIST OF ABBREVIATIONS AND ACRONYMS

EPRA	Energy and Petroleum Regulatory Authority
ESIA	Environmental and Social Impact Assessment
FiT	Feed-in Tariff
GOK	Government of Kenya
HOMER	Hybrid Optimization of Multiple Energy Resources
IEA	International Energy Agency
IEET	Institute of Energy and Environmental Technology
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KenGen	Kenya Electricity Generating Company
KPLC	Kenya Power & Lighting Company Ltd. (also abbreviated as Kenya Power)
kWh	kilowatt hour (unit of electrical energy)
kWp	peak capacity in kW
LCPDP	Least Cost Power Development Plan
LPG	Liquefied Petroleum Gas
LRMC	Long Run Marginal Cost
MoE	Ministry of Energy
MoEP	Ministry of Energy and Petroleum
MWe	Megawatts applying to electrical capacity

MWh	Megawatt hour (unit of electrical energy)
O&M	Operation and Maintenance
PPA	Power Purchase Agreement
PV	(Solar) Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RE	Renewable Energy
REREC	Rural Electrification and Renewable Energy Corporation
REP	Rural Electrification Programme
RES	Renewable Energy Sources
RET	Renewable Energy Technology
SHS	Solar Home System
SPP	Small Power Producer
SPPA	Standard/Small Power Purchase Agreement
WEO	World Economic Outlook

ABSTRACT

To save money spent on diesel and reduce environmental impacts, the Kenyan government started a program of integrating wind and solar in off-grid power generation stations. This initiative commenced in the year 2010, however, detailed performance and sustainability studies of the hybrid stations have not been conducted. This research sought to evaluate and address this problem using Habaswein hybrid power generation station as a case study. The power station comprised of three diesel generation units of 410 kW, 360 kW and 280 kW capacity, 30 kW solar PV and 60 kW wind power systems. The study methodology was inductive research to build a theory, using quantitative data from Kenya Power and Lighting Company (KPLC) and Ministry of Energy, and qualitative data from interviews with KPLC staff and customers. Photovoltaic Geographical information System (PVGIS), Excel and Hybrid Optimization of Multiple Energy Resources (HOMER) PRO software were used for the analysis. The electricity access is currently not 100% in Habaswein Division, but electricity is equitably distributed to all categories of consumers across multiple villages. Further, reliability of power supply is fair, with relatively high frequency of power outages which lasts for short durations as a result of switching between diesel generators. Secondly, the study found that solar and wind energy potential in Habaswein was high. WindyCator showed wind speeds averaging 6.04 m/s, at a 20 m height, while irradiation was 6.28 kWh/m^2/day. Lastly, in order to ensure maximum utilization of renewable energy resources and enhanced performance, the optimal hybrid design mix consists of: 100 kW diesel generator to meet the base load, 410 kW diesel generator to meet the peak load (switch over from 100 kW), and 578 kW solar PV. It is recommended that the 360 kW and 280 kW diesel generators be decommissioned and replaced with a new 100 kW generator and an additional 548 kW solar PV. In addition, proper training and capacity building of KPLC’s personnel in operation and maintenance (O&M) is required.

CHAPTER ONE

INTRODUCTION

1.1. Background of the Study

Reliable and affordable energy is recognized as an essential ingredient for socio-economic development and economic growth of any country. Energy is critical in enabling the population to meet the basic human requirements such as cooking, lighting and safe drinking water as well as aiding in the provision of services such as education, and communication.

It is estimated that about 1.2 billion people, which amounts to 16% of the global population do not have access to electricity, and more than 95% of those living without electricity are in countries in Sub-Saharan Africa and developing Asia (IEA WEO 2016). Among these countries, Kenya has accelerated its national electrification rate which has increased the access rate to 75% as at February 2018 (GOK, 2018).

However, looking at the current energy situation, there are still a few challenges and weaknesses that affect the energy supply sector in Kenya. The main ones identified are as follows: (i) high cost of energy, (ii) high cost of rural electrification through grid extension due to the scattered nature of settlements, (iii) frequent power outages and high system losses and (iv) high dependence on imported petroleum fuels (Kiplagat et al., 2011).

The Kenya Government has developed the Kenya Vision 2030 as the country's new development blueprint. The vision aims at transforming Kenya into a newly industrializing, middle-income country providing a high quality of life to all its citizens by the year 2030. Energy provision has been identified as a key enabler in attaining the goals of vision 2030. Therefore, in line with this government strategy, Kenya has implemented the Energy Policy 2004, with a target to reach electricity connectivity of 40% in the rural population by the year 2020. The country electricity connectivity has also received impetus from the UN Sustainable Energy for All Initiative and the manifesto of Jubilee Coalition (Kenyatta et al, 2013). The government has also developed the national electrification strategy, which is intended to provide a roadmap to the achievement of universal access to electricity by the year 2022 (GOK, 2018)

The main challenge hindering the pursuance of universal energy access has been the capital requirements for expanding energy transmission and distribution infrastructure as well as power generation. In Kenya, energy transmission network development is capital intensive and has hitherto concentrated mainly in high population density and high economic areas. The Kenya Government has installed off-grid diesel power stations and distribution mini-grids covering some rural areas remote from the transmission grid. Currently there are over 10 off-grid stations as indicated in Appendix I. The geographical spread of the stations is presented in Appendix II.

These off-grid power supply systems based on diesel generation installed by the Ministry of Energy (formerly Ministry of Energy and Petroleum) to supply electricity to areas which are far from the national grid have experienced a number of challenges, such as (i) the cost of transporting fuel increases with the remoteness of the location, (ii) on-site storage challenges, (iii) high operation and maintenance costs, and (iv) the CO_2 emissions contribute to environmental pollution and global warming.

In order to make the cost of power affordable in off-grid areas, the government has been providing fuel subsidies. The provision of subsidies has appeared to be unsustainable in the long run. In efforts to lower the cost of generation, the Ministry of Energy commenced a hybridization programme in the year 2010. In this programme, Kenya Power and Lighting Company (KPLC) and Rural Electrification and Renewable Energy Corporation (REREC) (formerly Rural Electrification Authority), undertook pilot programmes to hybridize the off-grid power stations by installing renewable energy power sources, particularly wind and solar PV.

Currently, there are a few existing off-grid diesel power stations which have been retrofitted with hybrid systems (solar or wind or both), and further installation works is being undertaken by REREC. One of such operational station is Habaswein, which consists of a 410 kW diesel, 60 kW wind and 30 kWp PV-solar generators.

Hybrid stand-alone electricity generation systems are often considered more reliable and less costly than systems that rely on a single source of energy (Bernal-Agustín and Dufo-López 2009). Several research papers e.g. Shaahid and El-Amin (2009) and Al-Karaghouli and Kazmerski (2010) have shown that hybrid renewable energy based off-grid systems are economically viable especially in remote locations. In the recent past, the combined use of renewable energy sources, especially wind and solar has become increasingly attractive and is being widely used as an alternative to fossil fuel energy (Nema et al., 2009). It is therefore advisable for Governments to regularly evaluate the renewable power development policies in order to effectively promote the application of renewable energy sources (IRENA 2014).

Another important aspect of evaluation of energy systems is sustainability. Sustainable development has been defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Burton 1987). Sustainability encompasses not only ecological, but also economic and social aspects. It is imperative, therefore, that any development or action, which might affect the environment or socio-economic bearing on both the present and future, needs to be undertaken sustainably. Energy plays a crucial role in sustainable development. Its availability, exploitation, development and use practically influences all fields of social, economic and political activities, environment and climate and often, determines whether nations will live in peace or in conflict with each other. The use of energy is only sustainable if sufficient and permanent availability of suitable energy resources is assured, while at the same time limiting the detrimental effects of its supply, transportation and utilization.

1.2. Statement of the Problem

As part of its mandate, REREC has been installing diesel fired generators to supply electricity to areas which are far from the national grid. These are then handed over to KPLC to operate and maintain. However, these systems have experienced a few challenges. The unit cost of generation is high, high fuel transportations costs as well as on-site storage challenges. The operation and maintenance costs are high, and the emissions contribute to environmental pollution and global warming.

Hybrid off grid power generation and minigrid distribution systems in Kenya have been developed on a pilot basis, and mainly as retrofit to the original pure diesel generation sets. In 2010, REREC and KPLC commenced a pilot programme of installing renewable energy, particularly wind and solar, to hybridize these power stations. Habaswein power station is one of the successful pilots off-grid hybrid stations. The total installed generation capacity from renewable energy resources of solar and wind is 30 kW and 60 kW respectively, accounting for 11.6% and 6.8% of the total installed generation capacity respectively. Diesel accounts for the remaining installed generation capacity at 81.8%.

However, the installation of such systems was done without proper study and optimization, to determine the appropriate capacity of each renewable energy source installed and their configuration for maximum contribution. Moreover, no detailed studies have been done in the Kenyan situation to establish the performance, reliability and sustainability of the hybrid power stations. This study is thus geared towards contributing to this existing knowledge gap in relation to sustainable operations and optimization of hybrid off grid power stations in Kenya.

The study is aimed at establishing their sustainability and feasibility of hybrid minigrids in Kenya in meeting rural electrification objectives, as well as determine the optimization criteria and levels with the aim of reducing the unit cost of power generation.

1.3. Justification of the Study

As REREC and KPLC promote the installation of hybrid stations in remote areas, there is need to undertake this exercise in a well-structured and pragmatic manner. This is necessary to ensure the reliability of the systems, value for the investments, and optimum use of local renewable energy resources to ensure sustainability clean environment. The outcome of this study will inform the policy adjustments required in order to support successful implementation of hybrid power systems.

This will also fill the shortfall in research on policy of hybrid systems in Kenya. The result will provide additional knowledge on design optimization of renewable energy integrated off-grid power stations. This work contributes to the bridging of research gap currently existing in this area, and it will be a vital tool for researchers, implementers and more particularly policy makers in the energy sector.

The study will also provide lessons on performance of mini-grids and show potential for reducing unit cost of generation through integration of wind and solar systems. This information is required to provide impetus for up scaling the installation of the mini-grids and hybrid systems.

1.4. Objectives of the Study

1.4.1. Main Objective

The main objective of this research is to evaluate the performance of Habaswein wind/solar/diesel hybrid station, assess the potential of solar and wind energy resources and optimize the existing hybrid system to enhance reliability.

1.4.2. Specific Objectives

The specific objectives of the research are to:

a) Evaluate the performance of the wind/solar/diesel hybrid power generation system at Habaswein power station

b) Assess the potential of solar and wind energy resources for power generation in Habaswein.

c) Optimize Habaswein hybrid power station for maximum utilization of renewable energy resources and enhanced performance.

d) Determine the sustainability of the Habswein hybrid power generation station.

1.5. Research Questions

The research questions addressed by the study are:

a) How is the performance of Habaswein hybrid power station in meeting the power demand of the community?

b) What amount of solar and wind energy resources are available for use at Habaswein power station?

c) What is the optimum solar/wind/diesel hybrid system which can make maximum use of the available renewable energy resources and provide a lower cost of generation?

d) Is the performance of the Habaswein hybrid power generation sustainable?

1.6. Scope of the Study

The study is limited to Habaswein off-grid hybrid power generation station in Wajir County, Kenya. Habaswein’s geographical coordinates are 1° 0' 33" North, 39° 29' 17" East.

1.7. Thesis Structure

The thesis comprises of five chapters as summarized in Figure 1.1.

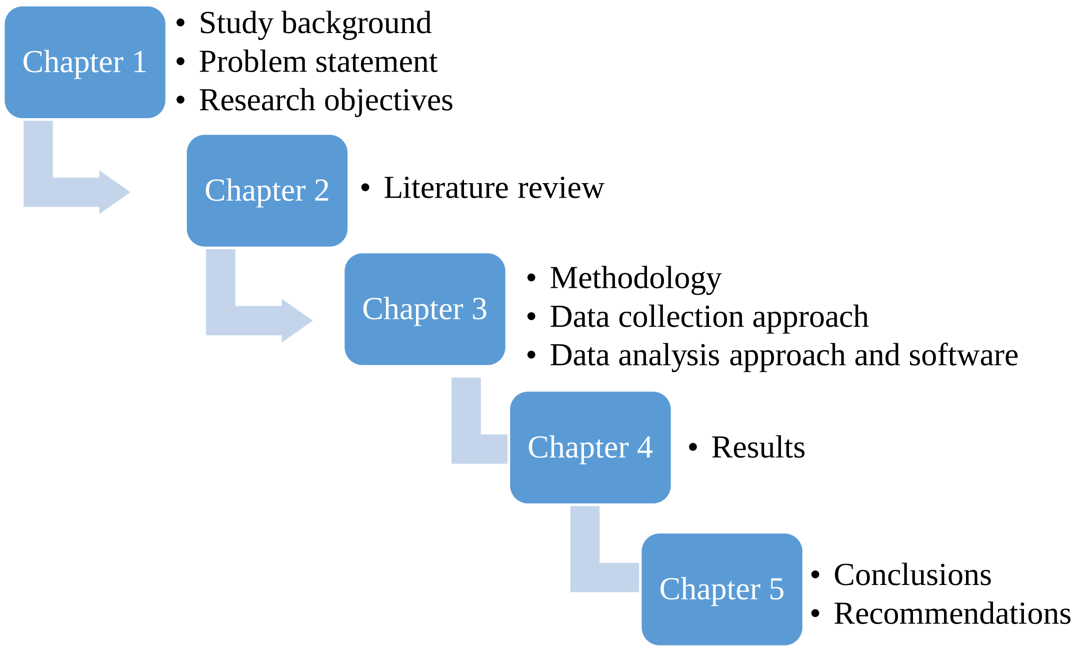

Figure 0.1 Flow Chart Illustrating Thesis Structure

Chapter 1 provides the overall introduction of the thesis and points out the research problem and objectives of the study. Chapter 2 presents the literature review that informed the design of the study. It includes aspects such as: the relevance of hybrid off-grid systems in electrification, methodologies for assessing performance of these systems, the approaches to determining renewable energy resource potential and the concept of sustainable development. Further, the chapter summarizes how to optimize the performance of the off-grid system.

Chapter 3 discusses the research methodology, summarizing key points such as the geographical focus of the study, and the approach to data collection and analysis including description of the PVGIS and HOMER PRO software used in the study to optimize the off-grid system.

Chapter 4 gives the results of the study which are presented in a few sections each focusing on a key aspect of performance of the system. First, the chapter explains how the mini-grid is operated by KPLC, and the perspective of staff involved in these operations. Second, the chapter describes the characteristics of electricity services, such as the number, type and evolution of consumers over time, as well as highlights of their consumption patterns. Further, the chapter presents the assessment of the technical performance of the system looking at the electricity generated vis a vis the installed capacity of the system, and solar and wind resource potential in the areas. Lastly, the chapter presents the findings of the optimization modelling, showing how electricity generation can be improved with some changes to the configuration of the system. Lastly, Chapter 5 provides the conclusions and recommendations derived from the findings of the study.

CHAPTER TWO

LITERATURE REVIEW

This chapter provides a review of the key and important aspects of the research and provides lessons and methodologies that have been applied by other researchers. The relevance and justification of use of hybrid systems for off grid electrification as well as alternative technology combinations is presented. In addition, design optimization techniques of off-grid hybrid systems have been reviewed as well as studies on renewable energy resource potential in Kenya.

2.1. The Concept of Sustainable Development

The World Commission on Environment and Development defined sustainable development as that which meets the needs of the present without compromising the ability of future generations to meet their own needs (Burton 1987). This Commission argued that time had come to couple the economy and ecology, so that the wider community would take responsibility for both the causes and consequences of environmental damage. The 6th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES Conference) identified three pillars of sustainability of development, namely economic, environmental and social pillars Duic, N and Urbaniec, K (2012). The concept of sustainable development has its origin in fundamental crises, which were essentially crises of the energy system developed in specific historical eras to stabilize the specific energy systems during its crises and thus defend the boundaries of the energy system until a new energy system emerged to replace the old one (Schlor, H., Fischer, W., Hake, J., 2012).

The idea of sustainability originated during the energy crises of the medieval agrarian solar energy system, when this system could no longer satisfy the growing energy demands of the emerging industrial age at the end of the 18th century and thus reached its ecological boundaries. The concept of sustainable development then originated afterwards at the end of the 20th century when the fossil energy system reached its ecological limits and the society was in search of a concept to reconcile ecological, economic, and social goals at the global level taking into consideration the interests of the present generations as well as of future generations.

Currently, we are witnessing a slow transition to a new, probably post-fossil energy age, whose limits are formed by the available energy. This new post-fossil energy system must develop its own sustainability system to defend its boundaries and thereby avoid energy crises and stabilize society. The future design of the concept of sustainable development will depend on the character of the specific crises of the new post-fossil energy system. Ilskog (2008) presented a set of 39 indicators for assessing sustainability of rural electrification projects. These indicators considered five sustainability dimensions- technical sustainability, economic sustainability, social/ethical sustainability, environmental sustainability and institutional sustainability (Ilskog 2008).

2.2. Solar and Wind Energy Resource Potential

Kenya is endowed with vast solar and wind energy resource potential. This has been confirmed through various studies. In 2001, the Ministry of Energy and Petroleum developed a Wind and Solar Resources atlas, using synoptic weather data. In 2008, in collaboration with UNDP and other partners, this Atlas was improved with use of the existing data, satellite and ground validation, which saw the production of high-resolution Solar and Wind Energy Resource Atlas (SWERA). This Atlas which was launched in May 2008 provided reliable high-resolution resource information for planners, policy makers and investors in solar and wind energy. It showed that wind regimes in certain parts of Kenya such as Marsabit, Turkana, Ngong and the Coastal region can support commercial electricity generation as they enjoy wind speeds ranging from 8 to 14 metres per second. The total area with speeds rated "good" and above is 22,000 square kilometers (SWERA UNEP, 2008). While SWERA contained solar and wind resource data on a general area it is necessary to use site-specific data in order to make good investment decisions. This is especially pertinent for small generation systems deployed in off-grid electrification projects.

Buoyed by the positive outcome of SWERA, the Ministry of Energy thus commenced wind data logging in specific high potential areas in December 2009. Installation of 95 wind masts and data loggers has so far been installed in three phases. In 2013, this data was analyzed, leading to higher resolution wind maps. These confirmed the huge potential for wind energy development. Incidentally, the areas with good wind speeds are in the remote areas in northern Kenya, which are not served by grid connected electricity. Appendix III show the wind and solar energy resource potential in the whole country. However, there are no solar and wind data loggers installed in Habaswein, or near the Habaswein off-grid station.

2.3. The Relevance of Hybrid Systems in Off-Grid Electrification Projects

Planning for universal electricity access in countries currently with a low electrification level will entail large numbers of new grid connections. This may require the reinforcement or expansion of the transmission network and the addition of new generation, therefore demanding a complete appraisal of the power system (Perez-Arriaga, 2017), with a focus on both off-grid and on-grid markets across generation, transmission, distribution, and retail. The growing concerted efforts towards the target of universal access to energy has emphasized the role of rural electrification, and off-grid small-scale generation represents one of the most appropriate options (Mandelli et al., 2016).

Hybrid stand-alone electricity generating systems are often considered more reliable and less costly than systems that rely on single source of energy (Bernal-Agustín and Dufo-López, 2016) and those based on renewable energy are economically viable especially in remote locations (Shaahid and El-Amin, 2009) (Al-Kharaghouli and Kazmerski, 2010). In the recent years, the combined use of renewable energy sources, especially wind and solar, has become increasingly attractive and being widely used as an alternative to fossil fuel energy (Nema et al., 2009). Governments therefore ought to regularly evaluate renewable power development policies in order to effectively promote the application of renewable energy sources (IRENA, 2017), especially for off-grid power plants, since fuel procurement can be a serious issue in rural areas, due to lack of good infrastructure, combined with long distances existing between the mini-grid and the fuel station; however, this aspect is usually disregarded in designing the mini-grid (Fioriti et al., 2017). Another important aspect of evaluation of energy systems is the project sustainability and its impact on sustainable development, in which energy plays a crucial role.

Most of the existing off-grid solutions, whilst having a very positive impact in delivering basic energy services, are not focused on productive uses of energy-the main driver of job creation and economic growth. It is therefore necessary to upscale the ambition of off-grid electrification efforts. This could be helped by the ongoing trend of cost reduction and performance improvement of technologies for electricity supply and demand, which now allow for addressing electrification in different ways (Perez-Arriaga, 2017). The energy availability, exploitation, development and use influences practically all fields of social, economic and political activities, environment and climate and often determines whether nations will live in peace or conflict with each other.

2.4. Brief History of Habaswein Power Generation Station

Habaswein Power Generation Station is an off-grid diesel, solar and wind hybrid installation owned by the Kenya government and operated by KPLC, and located in Habaswein Division of Wajir County, Kenya. The plant was initially established with an 80 kVA diesel generator in Habaswein Town in December 2007, it provided electricity to 2 customers, and consisted of 3 general staff and 3-line maintenance staff. In July 2008, the current station site was identified and allocated to the local community. The plant was then moved to the current site and a 500 kVA diesel generator (and generator house) were immediately installed. Alongside these, 4 fuel storage tanks with a total capacity of 204,000 litres were also installed. Over the past years the configuration of the system has been changing as summarized in Figure 2.1. Most notable however were the additions of a 30 kW solar PV system without battery storage in the year 2011 and a 60 kW wind system consisting of 3 wind turbines rated at 20 kW in the year 2012. Figure 2.1 provides a summary of the historical context of the Habaswein power generation station

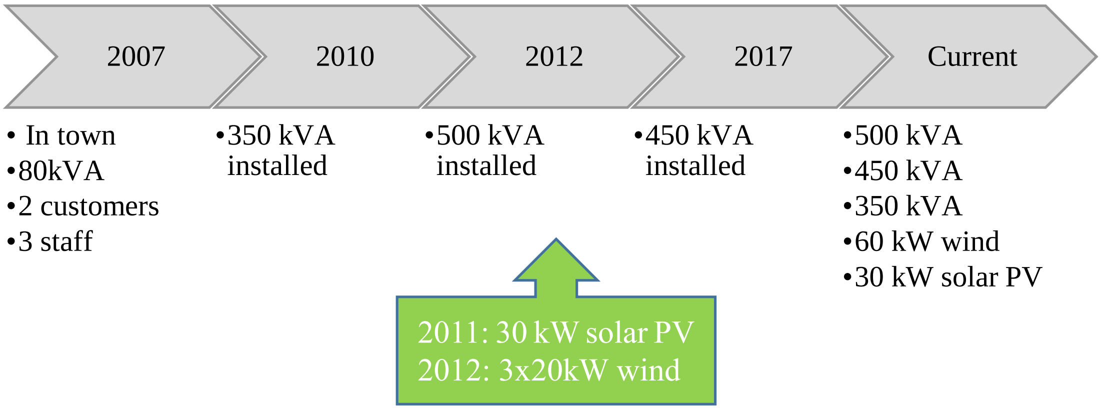

Figure 0.1 Historical Context of the Habaswein Power Generation Station

2.5. Methodologies for Evaluating Off-Grid Electrification Projects

Bhattacharyya (2012) reviewed alternative methodologies that are used for off-grid electrification projects to identify the features of each methodological approach and to present their strengths and weaknesses. He focused on techno-economic feasibility studies, analytical works highlighting methodological applications and practice-oriented literature. The review identified five methodological options, namely: worksheet-based tools, optimization tools, multi-criteria decision-making tools, system-based participatory tools and hybrid approaches. He recommended a hybrid approach that combines two or more options to take advantage of their strengths and weaknesses as well as to verify results from alternative approaches, but this can be resource intensive and will therefore require careful consideration on a case-by-case basis.

Rojas-Zerpa and Yusta (2015) have focused their studies on social and environmental criteria, stating that they have not been fully integrated in rural electrification projects design and play often an opposing role to technical and economic criteria. They have therefore elaborated multi-criteria decision-making methods, such as, the Analytical Hierarchy Process (AHP) and Compromise Ranking method (VIKOR), to facilitate the selection of the best solution for electrical supply of remote rural locations, involving technical, economic, environmental and social criteria. A similar approach was taken by Domenech et al., (2015) who published a hierarchical methodology based on a novel three-stage structure: Stage 1 consists of three assessments to define the target community; Stage 2 is the design process itself that groups the alternatives generation and selection phases identified in literature; and Stage 3, which is optional, allows trying to diminish the cost of the solution, maintaining the technical and social design considerations decided in the previous stage.

2.6. Design Optimization of Hybrid Systems

The optimum design of a hybrid system becomes complicated due to uncertain renewable energy supplies and load demand, non-linear characteristics of the components, high number of variables and parameters that have to be considered for the optimum design, and the fact that the optimum configuration and optimum control strategy of the system are interdependent (Zhou et al., 2010). This complexity makes the hybrid systems more difficult to be designed and analyzed.

Optimizing the plant size is necessary in order to efficiently and economically utilize the renewable energy resources. The optimizing method can help guarantee the lowest investment with full use of the technologies, so that the hybrid system can work at the optimum conditions in terms for investment band system reliability. This type of optimization requires the assessment of the system's long-term performance in order to reach the best compromise for both reliability and cost. In order to select an optimum combination for a hybrid system to meet the load demand, evaluation must be carried out on the basis of power reliability and system life-cycle cost (Zhou et al., 2010).

According to Akikur et al., (2013), the design, optimization and operation control of hybrid energy systems with two or more energy sources are complex and the risk of failure is high. Researchers have studied a wide variety of methods to reduce the complexity of designing hybrid energy systems. Some useful methods include Probabilistic, Analytical, Iterative and Hybrid methods (Luna-Rubio et al., 2012). A few studies have used these methods to design optimal hybrid systems combining two or more energy sources.

Simulation and modeling programs are the most common tools for evaluating the performance of the hybrid systems. By using computer simulation, the optimum configuration can be found by comparing the performance and energy production cost of different system configurations. Several software tools are available for designing of hybrid systems, such as HOMER, HYBRID2, HOGA and HYBRIDS.

Bekele and Tadesse (2012) in their feasibility study of small hydro/PV/wind hybrid system for rural electrification in Ethiopia assessed the solar, hydro and wind power potential available in Dejen District and proposed the optimal hybrid combinations for electrification of the District inhabited by 10,500 families. HOMER software was used for optimization and sensitivity analysis of the small hydro/PV/wind hybrid system. The study inputs of HOMER included the hydro, wind and solar data. The size, cost and lifetime of the wind turbine, PV modules, converter, battery and diesel generators are defined. The installation cost, design flow rate and the head of hydropower source were all inputted to the software and the HOMER algorithm considered each possible combination of the resource and determined the feasible combination that could meet the required system load and constraints.

Kenfack et al., (2009) proposed a Micro hydro-PV-Hybrid system which was sized according to the seasonal variation of the solar and hydro resources. The yearly simulation of the system operation was made via HOMER software making it possible to analyze the complementary contributions of both parts of the system, the best way of storing energy and the necessity to introduce a diesel generator as back-up.

Kanase-Patil et al., (2010) studied off-grid electrification of seven villages in the Almora District of Uttarakhand state, India. In the study, biomass, solar, hydro and wind energy sources were considered and analyzed using LINGO and HOMER software. Four different scenarios were considered during modeling and optimization of the Integrated Renewable Energy System (IRES) to ensure reliability parameters such as energy index ratio (EIR) and expected energy not supplied (EENS).

The optimum system reliability, total system cost and cost of energy (COE) were worked out by introducing the customer interruption cost (CIC). The renewable energy scenario accounting 44.99% micro hydropower (MHP), 30.07% biomass, 5.19% biogas and 4.16% solar energy along with the additional resources of wind (1.27%) and energy plantation (12.33%) was found to be the best among the different options considered.

Furthermore, Connolly et al., (2010), did a comparative study of 68 computer tools for integration of renewable resource in various energy systems. Accordingly, HOMER was evaluated as one of the most applicable for optimization, feasibility and sensitivity analysis of both off-grid and grid connected micro power systems. Akikur et al., (2013) also pointed out that HOMER is the most used and best known of all the software tools so far developed.

2.7. The Hybrid Optimization Model and Problem Formulation

The configuration of the system is studied when designing a power system in terms of the components, and size, selecting from numerous technology options and various energy resources. The HOMER was developed by the U.S. National Renewable

Energy Laboratory to simplify the task of designing multisource power systems and evaluating the maximum number of possible system configurations (Lambert, Gilman, & Lilienthal, 2006). The optimal system with the lowest net present cost (NPC) is determined using this micro power optimization model.

The total annualized cost (C_{ann_tot}) represents the cost of the project in a given year ($/year), which includes the initial costs (C_{capann}), replacement costs (C_{repann}), and O & M costs ($C_{O\&Mann}$), and is expressed mathematically as (Lambert, Gilman, & Lilienthal, 2006):

$$C_{ann\_tot} = C_{capann} + C_{repann} + C_{O\&Mann}. \tag{1}$$

On the other hand, total annualized cost can be defined as the annualized value of the total net present cost, and is expressed mathematically as (Lambert, Gilman, & Lilienthal, 2006):

$$C_{ann\_tot} = C_{NPC} \times CRF(i,N). \tag{2}$$

The capital recovery factor (CRF) converts a net present cost (C_{NPC}) into a flow of equal annual payments over a specified time, and calculates this value based on the annual interest rate (i) and number of years (N), and is expressed mathematically as (Lambert, Gilman, & Lilienthal, 2006):

$$CRF(i,N) = i(1 + i)_N(1 + i)_N - 1 \tag{3}$$

The C_{NPC} represents all the costs that occur within the project lifecycle, with future cash flows discounted to the present using the discount rate. NPC includes the initial costs (IC), replacement costs, and O & M costs. Besides, salvage value that occurs at the end of the project lifetime that reduces the total NPC. The salvage value (S) is the value remaining for each component after a project's lifetime is completed and is computed using (Lambert, Gilman, & Lilienthal, 2006):

$$\boldsymbol{S = C_{rep} R_{rem} R_{comp},} \tag{4}$$

where R_{comp} is the lifetime of the component (years), R_{rem} is the remaining lifetime of the component (years), and C_{rep} is the replacement cost of the component ($).

The NPC objective function for system optimization based on Equation (2) is (Lambert, Gilman, & Lilienthal, 2006):

$$\text{minimize } \boldsymbol{(C_{NPC} = C_{ann\_tot} CRF(i,N)),} \tag{5}$$

which is subject to:

$$0 < E_{PV}, \tag{6}$$

$$E_{annual\text{-}demand} < E_{PV}, \tag{7}$$

$$E_{Battery} + E_{PV} = E_{BS} + E_{Losses}. \tag{8}$$

(i) The energy output of the PV array (E_{PV}) must always be positive, as given in Equation (6), and must be at least 10% of the total annual demand ($E_{annual\text{-}demand}$). The factors influencing the solar energy generation are the peak capacity of the PV array (Y_{PV}) in kW, the peak sun hour (PSH) in hours, and PV efficiency, which represents the relationship between the target yields (f_{PV}) and the actual target. The mathematical modeling in HOMER calculates the total annual energy contribution of the solar array and is expressed as (Lambert, Gilman, & Lilienthal, 2006):

$$E_{PV} = Y_{PV} \times PSH \times f_{PV} \times 365\ day/year. \tag{9}$$

(ii) To ensure a balance between demand and production power, the energy production of the sources (PV array and battery ($E_{Battery}$)) should cover the needs of the battery storage (BS) (E_{BS}) plus the losses (E_{Losses}) incurred by a DC-DC regulator, inverter, and active cooling.

The discharging and charging limits of a battery depend on its power rating and vary between the values (P_{min}, P_{max}), where P_{min} is the minimum state of charge and P_{max} is the maximum state of charge of the battery, which is also the nominal capacity of the battery bank. Moreover, the depth of discharge (*DOD)*, efficiency, days of autonomy (A_B), and lifetime of the battery (L_B) are important, as they significantly affect the system's total cost. The *DOD* refers to the maximum energy delivered from the battery and is defined using equation (Lambert, Gilman, & Lilienthal, 2006)

$$DOD = 1 - SOC_{min}100, \tag{10}$$

where minimum state of charge (SOC_{min}) is the lower limit provided in the battery datasheet so that the battery does not discharge below the minimum state of charge.

In the case of a PV array malfunction, the battery bank feeds the required energy load. Thus, the battery bank autonomy (B_{aut}) is a critical factor representing the potential number of days that the battery bank can supply the required energy load without any PV array contribution. This value is expressed as the ratio of the battery bank size to the BS load (Lambert, Gilman, & Lilienthal, 2006):

$$A_B = N_{bat} \times B_V \times B_Q \times B_{DOD} \times (24\ h/d)L_{BS}. \tag{11}$$

where B_V is the nominal voltage of a single battery in V, N_{bat} is the number of batteries in the battery bank, L_{BS} is the average daily B_S load in kWh, and B_Q is the nominal capacity of a single battery in Ah.

Using HOMER, the battery lifecycle is calculated based on (Lambert, Gilman, & Lilienthal, 2006):

$$L_B = min(N_{bat} \times Q_{lifetime} Q_{thrpt}, R_{batt,f}). \tag{12}$$

where $R_{batt,f}$ is the battery float life in years, Q_{thrpt} is the annual battery throughput in kWh, and $Q_{lifetime}$ is the lifetime throughput of a single battery in kWh.

The number of batteries in series is equal to the DC bus-bar voltage (V_{b-b}) divided by the voltage rating (B_V) of one of the batteries selected (Lambert, Gilman, & Lilienthal, 2006):

$$\boldsymbol{N_{seriesbatt} = V_{b-b}B_V.} \tag{13}$$

The number of parallel paths is obtained by dividing the total number of batteries by the number of batteries connected in series.

HOMER initiates the hourly simulation of every possible configuration, uses the PV array (P_{PV}) to compute the available power, compares it with the electric load (P_{Load}) and losses (P_{Losses}), and finally decides how the additional power should be generated during deficits (battery discharging) or how the surplus power should be managed in times of excess (battery charging).

2.7.1. The Solar System Optimization Parameters

The considered PV system and replacement cost is 2,200 US$/kWp. The O & M cost is set to 10 US$/kWp/year. The solar module type is a polycrystalline PV panel with efficiency 15%. The costs include purchase, transportation and installation of modules, all balance of system components like cables and structures (excluding the inverter) and the security system. The Inverter size is calculated using the Homer Optimizer™ algorithm. The cost is set to be 300 US$/kW, and the efficiency of the inverter is assumed to be 95%.

2.7.2. The Wind System Optimization Parameters

The wind turbine component (Layer Electronics GE-200 20 kW wind turbine) was not present in the HOMER component library. A custom component was created starting from the 'Generic 10 kW' turbine present in HOMER. The power curve of the turbine, available in pdf form from the manufacturer[1], see Figure 0.2, has been digitized to be inserted in HOMER's component library, Figure 0.3.

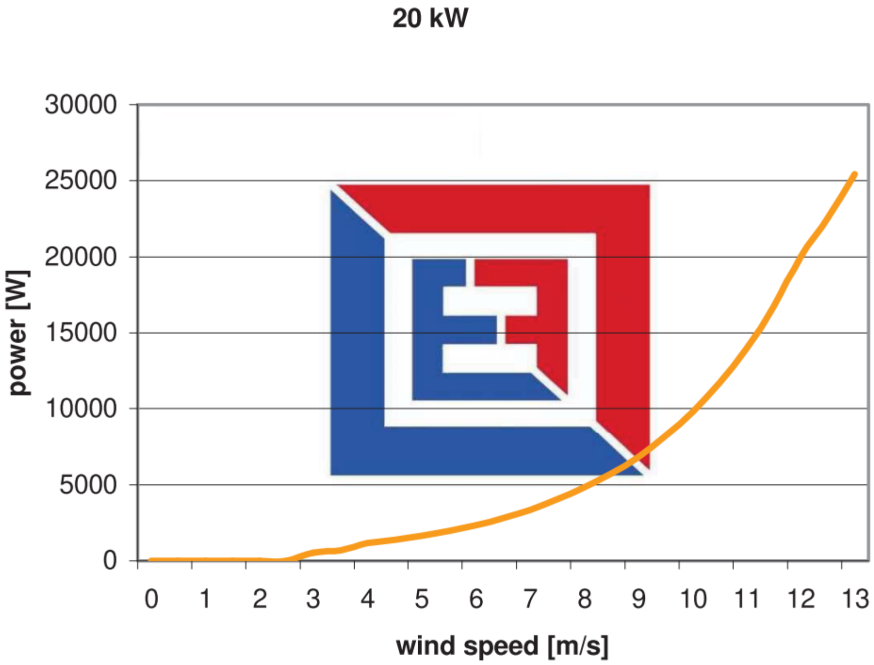

Figure 0.2 GE-200 Wind Turbine Load Profile, From the Datasheet

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[1] https://www.layer.it/main/media/2018/11/GE-eng.pdf

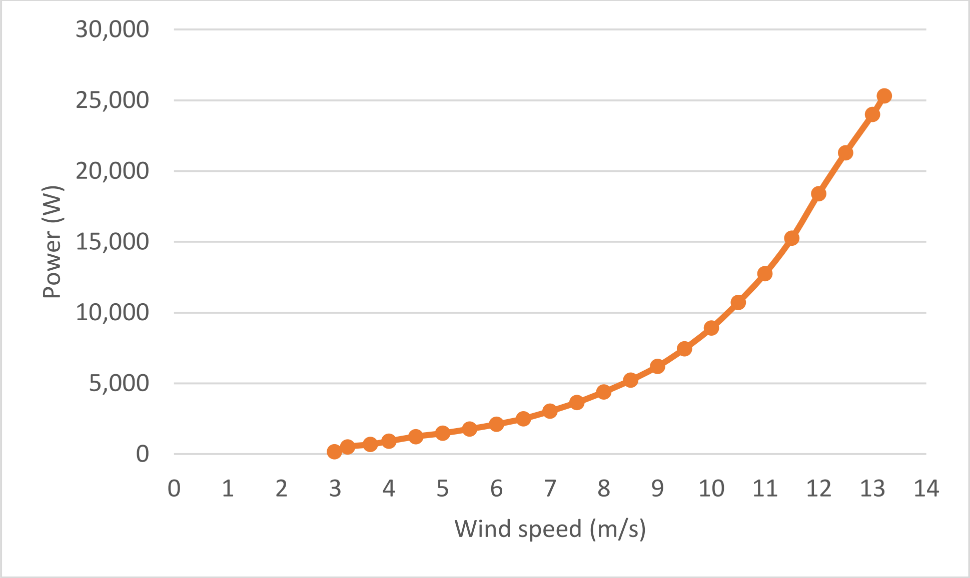

Figure 0.3 GE-200 Wind Turbine Power Curve, Digitized Load Profile

The losses and maintenance sheets were kept identical to the ‘Generic 10 kW’ turbine. As for the costs, the generic 10 kW featured US$ 50,000 capital costs, US$ 50,000 replacement cost, and US$ 500 annual O&M cost. We considered, very roughly, that the costs for a 20 kW system increase linearly with the rated power, so that the replacement cost for the GE-200 turbine is US$ 100,000 and the O&M is US$ 1,000. Considering that the three turbines are de-facto already present on-site but must be ‘fixed’ in order to produce energy as per their nominal capacity, their capital cost was halved, as a ‘revamping’ cost.

2.7.3. The Diesel System Optimization Parameters

For the 410 kW diesel generator it has not considered a capital cost because it is working, the replacement cost is $90,000, the O &M cost is 2 US$/h. The diesel cost is set to 1.28 $/L which is the average cost of the diesel in Habaswein in 2014.

2.7.4. The Battery Energy Storage System Optimization Parameters

For the battery energy storage system (BESS) we consider a Li-Ion battery, with round trip losses of 8% [Bradbury et al., 2014], an estimated cost of 600 US$/kWh, an O&M cost of 10 US$/kWh/year, and a connection on the DC bus. For the limited BESS solution, the size of the BESS is varied from 500 kWh to 1,300 kWh with a step of 50 kWh.

2.7.5. The Overall Diesel System Optimization Parameters

The lifetime of the plant used in the economic evaluation is 25 years. The main factors to evaluate the economic optimal solution for the optimization of the Habaswein power plant are Net Present Cost (NPC) and the cost of electricity (COE). The assumed lifetimes of the PV panels and inverter are 25 years and 15 years respectively. The discount rate of this study is set to 10% (Central Bank of Kenya, 2018) and the inflation rate is assumed to be 8% (World Bank, 2018).

CHAPTER THREE

METHODOLGY

3.1. Chapter Overview

This chapter outlines the methodology used to achieve the research objectives. The research was conducted through an inductive approach where multiple data sets were collected and analyzed in order to build a theory. Quantitative data on KPLC electricity generation and sales from Habaswein mini-grid was obtained from KPLC and analyzed to determine operation and performance parameters. Qualitative data on community views was obtained through Key Informant Interviews and Focus Group Discussions. Renewable energy resource data was obtained from the Ministry of Energy (wind) and PVGIS (solar). This was analyzed to determine the renewable energy resource potential in Habaswein. Lastly, all the above data was used to undertake system optimization using HOMER PRO software.

3.2. Study Area

The area covered by the study was in Wajir County. Wajir County is one of the 47 counties of Kenya and is located in the North Eastern region of the country (refer to Figure. 3.1 shaded in red colour). The county is significant in size, covering an area of 56,686 km^2, which is equivalent to about 10% of Kenya’s total land area. It borders four counties namely Mandera, Isiolo, Garissa and Marsabit, as well as the neighbouring countries of Ethiopia and Somalia.

Figure 0.1 Map of Kenya Showing the Location of Wajir County[2]

Wajir has an estimated population of 852,963 (as per 2017 data), of which 45% of the population are female while 55% are male. The labour force in the county constitutes 30% of the population, and it is primarily engaged in pastrolism. Wajir is semi-arid with seasonal, unpredictable and short rainfall which limits the potential for vegetation based socio-economic activity. The county experiences drought around June, which is the driest month with average rainfall of 1 mm, while it normally experiences the most rainfall which can be as high as 68 mm in April.

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[2] http://learn.e-limu.org/topic/view/?t=1531&c=468

3.2.1. Habaswein Ward

The study was undertaken at Habaswein hybrid off grid power station, whose geographical coordinates are 1° 0' 33" North, 39° 29' 17" East. Habaswein is the fourth largest settlement in size in the County and is almost exclusively inhabited by ethnic Somalis. The name Habaswein literally means a lot of dust. Wajir South Constituency (in which Habaswein Ward is located), has the lowest population density in Wajir County at 8 people per km^2 as compared to the county average of 13 people per km^2. In 2017, the population in the urban areas of Habaswein consisted of 10,953 people, 5,920 of whom were males while 5,033 females. This population accounts for 9% of the total urban population of Wajir County. Due to lack of diverse socio – economic activities the urban areas are primarily market centers while the rural areas are watering and grazing points for livestock.

3.3. Data Collection

Raw primary data for the hybrid station performance for the last five years was obtained from the Kenya Power and Lighting Company in regard to the energy generated by the diesel, wind and solar components, the fuel consumption, and the power loads. The data was based on observations/readings of meters and was manually documented by Kenya Power personnel at the station, who were filling data log sheets every 30 minutes over 24 hours. Additional data was obtained from Kenya Power which included electricity meter readings and revenues (kWh consumption and KSh revenue, respectively) per connected user, as well as the amount of fuel consumed (in litres) at the station as well as the cost of the fuel (KSh.) on a monthly basis. More data on technical and social issues was also collected through face to face interviews and focused group discussions with Engineers, technicians, installers, consumers and communities regarding social, environmental and health issues as regards the hybrid power stations.

3.3.1. Quantitative Data

Quantitative data was collected and analysed in order to determine the characteristics of the electricity load. Although the minigrid was deployed in 2010, load data was available for the period 2012 – 2017. The load data was based on kWh meter readings of the various generators - solar output, wind output, and diesel output in kW. These parameters were logged manually every 30 minutes over 24-hour periods, for all the days of the year, between 2012 and 2016. In total approximately 87,600 data points were obtained and analysed to determine the load characteristics of the station based on the energy generation technology and time (of day and year), as shown in Table 3.1.

Table 0.1 Template for Quantitative Data Collection

	01/01/2012				…	31/12/2012	…	31/12/2016
Time	Diesel (kW)	Solar (kW)	Wind (kW)	Total (kW)	…	…	…	…
00.30	…	…	…	…	…	…	…	…
01.00	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
24.00	…	…	…	…	…	…	…	…

Data on solar and wind energy resource potential was obtained from a few sources. Although there was an anemometer at the site the anemometer readings were not available as there was no monitoring or recording system in place. Hence, the study utilized the data from a wind mast installed in Habaswein town by the Ministry of Energy, which was the closest to Habswein off-grid station. While the study established that solar and wind energy resource data collected by the mast was available, it was for a limited duration of time, from July 2011 to November 2012. From the data collected, a WindyCator report on wind energy resource potential was generated for use in this study. A second source of data was therefore considered in order to obtain historical data which could be broadly applied to the timeframe of the data obtained from KPLC (2012 to 2016). Solar energy resource potential data was therefore obtained from an online application Photovoltaic Geographical Information System (PVGIS)[3].

3.3.2. Qualitative Data

Since the study's focus was on quantitative analysis, the qualitative analysis was conducted for the sole purpose of providing contextual information and a reference point for the findings of the quantitative research. Qualitative data was collected using informant interviews with key personnel of Kenya Power and Lighting Company, and interviews with residents who were leaders and representatives (chiefs) of the localities. A total of 12 one on one interviews were conducted. Four of the interviews involved village elders in Habaswein Division, one village elder selected from each of

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[3] An online application available a http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=en

the 4 villages located within proximity of the Habaswein power station and which are electrified by the mini-grid: Adamasajida, Bulandege, Bulajuu and Central (The 4 villages are located in the area indicated ★ in Figure 3.2).

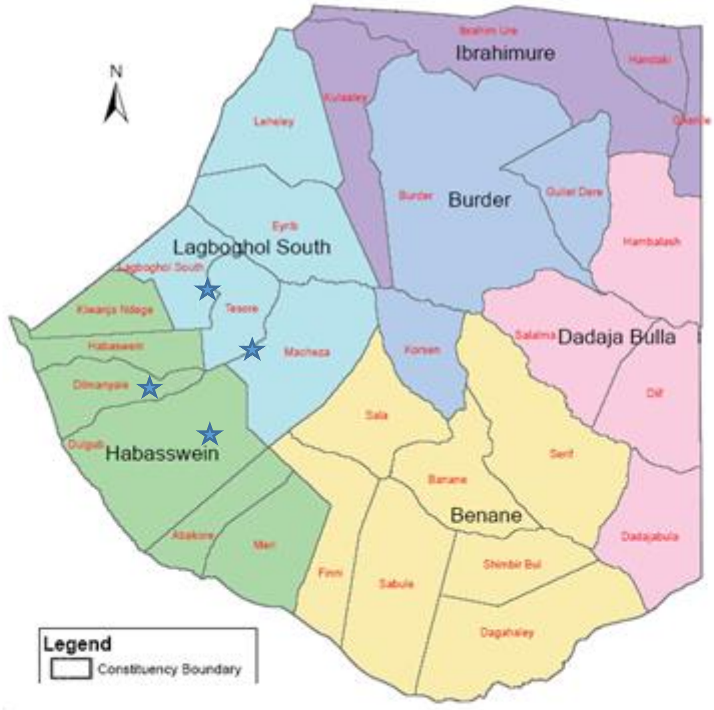

Figure 0.2 Map Showing Villages Where Interviews Were Conducted

The remaining 8 interviews were conducted with available Kenya Power personnel who were conversant with functions of electricity supply primarily generation, maintenance and billing. These included 5 KPLC personnel at the power station, 1 KPLC personnel at the Habaswein KPLC office, and 2 KPLC personnel at the Wajir County KPLC office. The questionnaires administered to village representatives and businesses are shown in Appendix IV.

Focused group Discussions (FGDs) were conducted with Kenya Power personnel - operations and maintenance teams - based in Habaswein, with the aim of understanding the operation and performance aspects of the power generation station. This feedback was documented and analyzed in the results alongside the quantitative data. In addition to the FGDs, key informant interviews were conducted with the Kenya Power Area Manager for Habaswein, and Kenya Power County Manager for Wajir County with the aim of obtaining detailed data on electricity connection and growth over time. A detailed list of the respondents is provided in Appendix V.

3.4. Simulation and Optimization

3.4.1. Simulation and Optimization with HOMER PRO Software

HOMER software was used to model and simulate different mix scenarios with the aim of establishing the optimal penetration levels of renewable energy. HOMER is a computer- based model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation applications. It has been developed by United States National Renewable Energy Laboratory since 1993. It is developed specifically to meet the needs of renewable energy industry's system analysis and optimization. There are three main tasks that can be performed by HOMER: simulation, optimization and sensitivity analysis. In the simulation process, HOMER models a system and determines its technical feasibility and life cycle. In the optimization process, HOMER performs simulation on different system configurations to come out with the optimal selection. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of inputs to account for uncertainty in the model inputs. Detailed description on HOMER software can be found on the HOMER website (Lilienthal, Lambert, & Gilman, 2004) (Lambert, Gilman, & Lilienthal, 2006)

HOMER Pro Microgrid Analysis Tool 3.9.2 (HOMER Energy LLC, 2018) is the simulation tool adopted for the optimization of the plant. This simulation tool assists in the planning and design of renewable energy based micro-grid. The physical behavior of each power plant configuration, their life-cycle (excluding dismantling) cost and the energetic and economic comparison were made using the three main operations of the software: Simulation, Optimization and Sensitivity Analysis.

In the simulation area, HOMER Pro determines technical behavior, feasibility and life-cycle cost of a system for every hour of the year. The assessment is made not only for the entire system: the operation of each component is simulated to examine how the components work in relationship with the entire system. In the Optimization section HOMER displays each feasible system and its configuration in a search space sorted by the minimum cost depending on the total net present cost. In this way, we can find the optimal configuration which satisfies the constraints imposed in the model. In the section of Sensitivity Analysis, the user can analyze the effects of parameter variations in time and the behavior of the sensitivity variables. The sensitivity variables are those parameters entered by the user and having different values.

Before the construction of the model, the first step needed is the evaluation of the load, which could be electric, thermal or both, although in this study we focused on the electric load. In this study, the yearly electric load profile adopted was the measured load of 2014 with 30-min step.

3.5. Limitations and Treatment of Data

The specific limitation in data collection is in the quantitative dataset on electricity generated described in Table 3.3. This data was based on observation, reading, and documenting meter readings into the log sheets, a process which was subject to human error. While there were some instances of incorrect data entries (where the data was out of the range of expected data in a category) these were fewer than 100 instances in total. For such instances the immediately preceding record was used to replace the data with the error.

3.5.1. Assumptions in the Analysis

The analysis assumed that:

(i) Instances where the quantitative data in the manual logs of power output (kW) for diesel, solar PV and wind generation systems were blank indicated 0 kW output, rather than a missed data entry

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1. Chapter Overview

The chapter presents the overall operation of the Habaswein hybrid power generation station in order to provide a background for the technical system performance. In addition, the findings of the study are presented in line with the specific objectives as was presented in Chapter 1.

4.2. General Operation Parameters of the Habaswein Hybrid Minigrid

The general operation parameters of the mini-grid were determined which include power generation plant history, staffing levels, mode of operation and maintenance, characteristics of customers connected, customer growth patterns, demand growth. This was necessary in order to understand the plant and hence be able to make reasonable conclusions as pertaining the plant performance.

4.2.1. Current Status of Habaswein Power Generation Station

The station – as at July 2017 – had diesel, solar and wind generation systems onsite, all of which were in use. The general parameters of the systems are summarized in Table 4.1.

Table 0.1 General Parameters of Diesel Generators

Generation System	Capacity
Diesel generator - Perkins	500 kVA (410 kW)
Diesel generator - Perkins	350 kVA (280 kW)
Diesel generator - Cummins	450 kVA (360 kW)
Wind System	60 kW (3 x 20 kW)
Solar PV System	30 kW

A photograph of the station showing the various components is shown in Figure 4.1.

Figure 0.1 Photograph of Habaswein Power Generation Station

Each of the 3 diesel generators was connected to two storage battery banks, rated at 12V 200Ah. The batteries are primarily used for starting the diesel generators. The diesel, solar and wind generators are all synchronized in the same bus bar.

4.2.2. Modalities of Operation of the Power Generation Station

The station is operated by 6 personnel employed by Kenya Power and Lighting Company (KPLC) who are responsible for all the generation systems. The station typically uses one diesel generator at a time, especially during off peak hours. In some instances, two generators are operated at a time, specifically to meet peak demand, especially if the lower capacity generators are in operation. The decision on which generator to run is primarily dependent on the generator's availability and whether in good working condition. The decision to operate a 2nd generator in addition to the one in operation is based on the performance trend observed during the half-hour intervals readings. If there is an unexpected increase in demand which could potentially increase to levels that may not be met by the generator in operation, then the 2nd generator is switched on.

The diesel generator in use at a given time could be any of the three generators availability as at times a generator could break down or undergo scheduled maintenance as shown in Figure. 4.2. The generator in use is operated for a 24-hour period, after which it is shut off for a 30-minute break to check the cooling system. It is then restarted repeatedly until the runtime for a complete service is reached.

Figure 0.2 Kenya Power Personnel Repairing a Diesel Generator After Break-down[4]

There are relatively many incidences of break downs of at least 1 generator at a time. This is the most common operational status of the station. In July 2017 during the site visit to the power station, 2 of the 3 generators had broken down. The personnel were unable to fix the generators because spare parts were not available. Spare parts are cross-shared amongst generation stations and may be borrowed from other off grid stations. However, time, distance and transportation logistics are main constraints that affect the ability to undertake repairs where spare parts need to be brought from other areas. This contributes to delays in restoring power, and inability to meet peak demand in the meantime. The personnel report peak demand of approximately 300 kW, while

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[4] July 2017

the available installed generation capacity varies from 280 kW - 410 kW, meaning that at least 2 generators must be in operation to meet peak demand depending on renewable energy generation.

Typically, when break downs occur, the cause is unknown, and the personnel dismantle the generator to make an assessment and troubleshoot if there is no obvious cause of failure. The personnel are well equipped to undertake repairs and have not had an incidence in which they were unable to identify the problem.

From the perspective of the power generation station personnel, there are some key challenges experienced in operation of the minigrid as follows:

1) There may be inductive loads particularly the boreholes, which affect the grid as in the case of three-phase connections.
2) The minigrid experiences frequent blackouts, typically around 7 pm when the demand increases significantly and sharply.
3) Now there is only one feeder whereas the station personnel recommend that at least four feeders are installed.
4) The station alternates between multiple generators, which have different levels of output. The station personnel recommend:
    a. Each generator to have a feeder installed
    b. Load balancing to be implemented per machine
    c. Ensure good protection on feeders
    d. Ensure good protection on the distribution lines due to long distances
5) It may be useful to have a range of spare parts available on site based on the frequently required parts

4.2.3. Maintenance of the Power Generation Station

Maintenance of the station varies with the technology, except for the case of generators which have a maintenance program which requires scheduled maintenance after a specific number of operating hours. The output from the solar photovoltaic system is monitored at the inverters in a cursory manner daily. In some instances, when the output of the solar system is considered of concern, the terminals of the system are checked. The solar panels are normally cleaned twice a year on average, approximately every 6 months.

Maintenance of the diesel generators is typically in the form of scheduled service after a specific number of operating hours. This consists of dismantling of the generator to assess the wear and tear of components and replace worn out parts. More frequently, lubrication of the generator parts is conducted, approximately once a month. Figure 4.3 shows a truck transporting lubricants.

Figure 0.3 Transportation of Lubricants to Generation Stations in Oil Barrels

The status of the batteries is similarly observed during routine daily activities at the station. On average, one check is done every month, to verify the battery level, and add distilled water when it is below the required level. The battery charging system connected to the wind power generation has an automatic alarm system which indicates when there is an error. In this case, the local staff inform the KPLC HQ in Nairobi, which in turn works with the contractor to address the problem.

4.2.4. Fuel Procurement

4.2.4.1. Tank Storage on Site

There are four tanks installed at the site with a total installed capacity of 204,000 litres. The individual tank capacities are: 1 tank of 104,000 litres, 2 tanks of 36,000 litres each and 1 tank of 28,000 litres. These tanks are all interconnected so that 1 tank is in use at a time, with a second one coming online once the first tank's fuel supply is drained.

4.2.4.2. Tank Refilling

The tank refilling is done periodically (without a fixed schedule). On a day to day basis, the personnel eyeball the level of fuel in the tank in use and notes the remaining tanks to see whether they are empty or full. The station personnel measure the fuel levels in the tank using a dipping stick, once a week. They then include the fuel levels readings in weekly and monthly reports on the operations of the station, which they submit to Kenya Power headquarters. The decision to refill the tank and place the order with the supplier is made at the Kenya Power headquarters. This is based on the fuel balance at the start of the week in comparison to the fuel balance at the end of the week, and in line with the historical fuel consumption pattern of the station. Typically, fuel suppliers are delivered when the level of available fuel is approximately 50,000 litres. The personnel consider 40,000 – 50,000 as the minimum reorder level where when reached they are able to escalate the issue to headquarters for immediate action. To date there has been no incidence where station operations were limited or shut down due to fuel supply issues.

4.2.4.3. Fuel Delivery

According to the delivery notes signed by the receiving personnel at the station, it takes approximately 2-3 days for the fuel to arrive at the generation station from the time of loading at the point of origin. The fuel is provided by Kenol Kobil based along Lunga Lunga Road in Nairobi County. The distance covered by the trailer, assuming a direct route from Nairobi to Habaswein, is approximately 515 km. Approximately 30,000 to 33,000 litres are delivered using a trailer, and in almost all instances only 1 trailer is delivered at a time. Typically, deliveries are done in 4-6 weeks' windows.

4.2.5. Characteristics of Customers Connected to the Minigrid

4.2.5.1. Minigrid Customer Profile[5]

The customers connected to the Habaswein minigrid are varied, comprising of residential, business, community and public facilities. The majority of premises in all the categories are connected to the minigrid. Those that are not connected are primarily due to limitations such as safety and security concerns in electrifying traditional houses, for which internal wiring presents a hazard. As summarized in Table 4.2, based on the perception of village elders, the electrification rate in Habaswein minigrid coverage is relatively high.

Table 0.2 Electrification Status by Villages in Habaswein Division

Type of Consumer	Village	Adamasajida	Bulandege	Bulajuu	Central
Households	Total	>300 estimate, over 25% of the population	>970	250	421

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[5] Based on key informant interviews

Type of Consumer	Village	Adamasajida	Bulandege	Bulajuu	Central
		leaves during drought			
	Connected	<50	All except traditional houses	200	Almost all
Businesses	Total	>10	25	15	130
	Connected	Majority	25	15	Almost all
Places of Worship	Total	3	8 (7 mosques, 1 church)	1	25 (24 mosques, 1 church)
	Connected	3, includes water supply	8	1	Almost all
Health Centers	Total	1	1 sub-county hospital	0	1

Type of Consumer	**Village**	**Adamasajida**	**Bulandege**	**Bulajuu**	**Central**
	Connected	1	1	0	1
Schools	Total	3 (2 primary and 1 secondary)	5 (3 public and 2 private)	2	2
	Connected	3	5	2	2

The residents of Habaswein primarily use a household energy mix of electricity from the mini-grid, and charcoal and firewood for cooking. Indicative range of the monthly cost of electricity varies from KES. 600 – 2,000 where respondents who spend between KES. 600 – 1,000 may represent the average connected household, while those who spend between KES. 1,000 – 2,000 have higher socio-economic standing such as teachers and administrative officers.

There is insignificant penetration of Solar Home Systems (SHS) at the household level as it is predominantly used as a backup in community facilities. The penetration of alternative energy sources such as LPG for cooking are insignificant, with households spending approximately KES. 2,000 on firewood. Expenditure on charcoal is primarily during seasons in which firewood availability is limited, such as rainy seasons when firewood is not adequately dry for use.

Table 4.3 highlights some of the indicative energy sources and costs for residents in Habaswein.

Table 0.3 Indicative Energy Use Characteristics in Habaswein Division

Village	**Adamasajida**		**Bulajuu**	**Central**		
Household electricity (mini-grid)	KES 2,035 per month for 1st household	KES 1,680 per month for 2nd household	-	KES 640 – 1,000 per month for household	KES 1,600 per month for business premise on average	-
Household charcoal	2 X 50 kg per month (@KES 800)	KES 1,600 per month	-	<25% of households	4 X 50 kg per month	KES 3,200

Village	**Adamasajida**		**Bulajuu**	**Central**
Household firewood	KES 2,000 per crate	KES 2,000 per month	-	<75% of households
Household LPG	-		-	6 kg cylinder @KES 2,500
Businesses	-		Generator to pump water, 5 shops and 2 refrigerators, Average KES. 3,000 per month, KES.	-

Village	Adamasajida	Bulajuu		Central	
		2,800 in July 2017			
Solar Home Systems	-	3 (Mosque, household, as back up)	Schools have SHS alongside grid connection as a backup	<25 households have SHS	-
Diesel	-	2 (Borehole, petrol station)	<50 households use kerosene	Diesel generators used as backup by about 10	Generators rated at approximately[6] run @KES 500 per day

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[6] Author's estimate based on purchase price of KES. 10,000 for the generator

Village	Adamasajida	Bulajuu	Central
			businesses and 24 mosques

In the business category, indicative expenditure is KES. 1,600 – 3,000 per month. Further, this category includes water pumping activities majority of which are operated as a business. Boreholes are powered by diesel generators in most instances, though there are some grid-connected and solar PV/grid-connected boreholes as well.

4.2.6. Customer Growth Trends

The number of customers connected to the Habaswein Power Generation Station has grown significantly over time, from 106 customers in 2008 to 1,249 customers in 2016. Of the 1,249 connections, 851 (68%) are postpaid. This represents an average increase of 37% per year over the period 2008 to 2016, with a peak 74% increase in the number of customers in 2011/2 and a low of 12% between 2015/6. When cumulative electricity connections are considered without considering the constituent customer types, it could be considered that growth in electricity connections has generally tended to be exponential.

4.2.6.1. Customer Growth based on Electricity Tariff

There are four categories of consumers connected to the Habaswein Power Generation Station aligned with the national categories of Kenya Power and Lighting Company customers.

1) A0 – Domestic consumers, also referred to as DC in other literature
2) A1 – Small commercial consumers, also referred to as SC in other literature
3) P0 – Commercial and industrial consumers, also referred to as CI1
4) P1 – Commercial and industrial consumers, also referred to as CI2

Between 2008 and 2012, new customers connected to the minigrid were limited to domestic consumers and small commercial consumers, with domestic consumers accounting for most of the new connections up to 2014. This changed in 2012 when small commercial and industrial customers started to be connected. The trend in later years has been a reduction in domestic connections and an increase in small and large commercial and industrial customers, with the latter accounting for majority of new connections in 2015 and 2016. However, when Kenya Power customers are disaggregated by customer types as shown in Figure 4.4, growth in domestic consumers and small commercial has been minimal over the past 3 years.

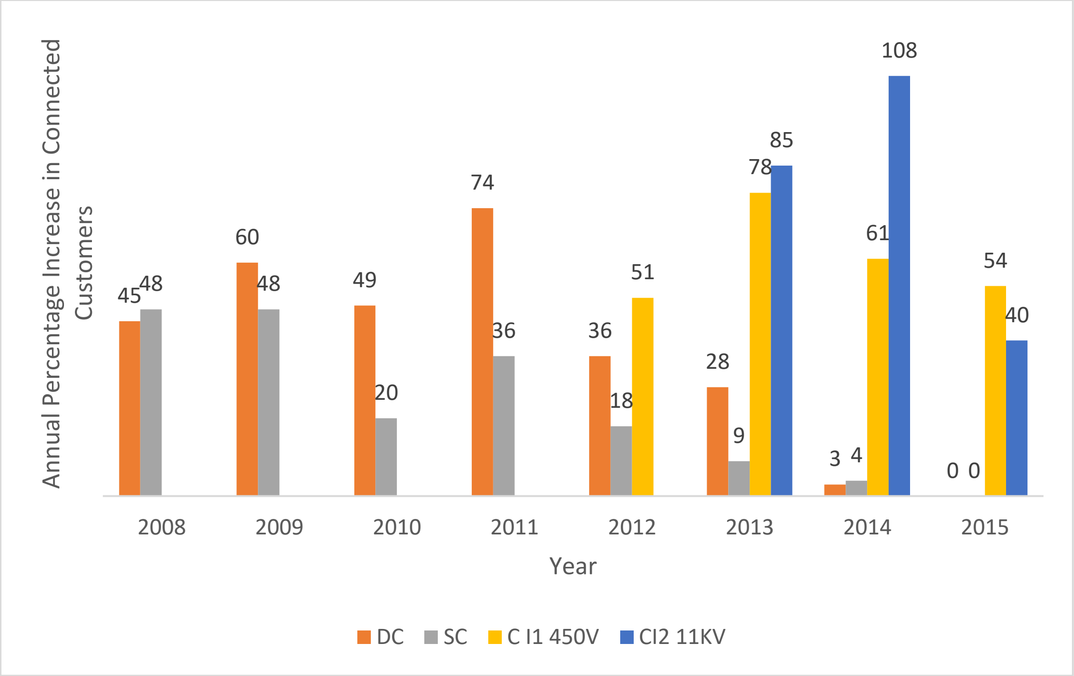

Figure 0.4 Annual Growth in KPLC Customers (%) from 2008 to 2016 by Tariff

Since 2012, the trend in commercial and industrial customers' categories shows that P0 and P1 are taking an increasingly larger share of the connections. Perhaps the greatest potential for growth may be in the small and large commercial and industrial customers' categories assuming that number of businesses and industries grow in Habaswein.

4.2.6.2. Growth in Electricity Sales[7]

The evolution of the number of customers consuming 3 different brackets of electricity (kWh) were considered: lifeline tariff of 50 kWh per month or less, 50 kWh-1500 kWh per month, and above 1,500 kWh. As shown in Figure 4.5, growth in customers consuming between 0-50 kWh per month on average has been the highest. The number

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[7] Based only on pre-paid customers.

of customers consuming over 1,500 kWh per month are negligible, while those consuming 50 kWh-1,500 kWh per month have generally remained static.

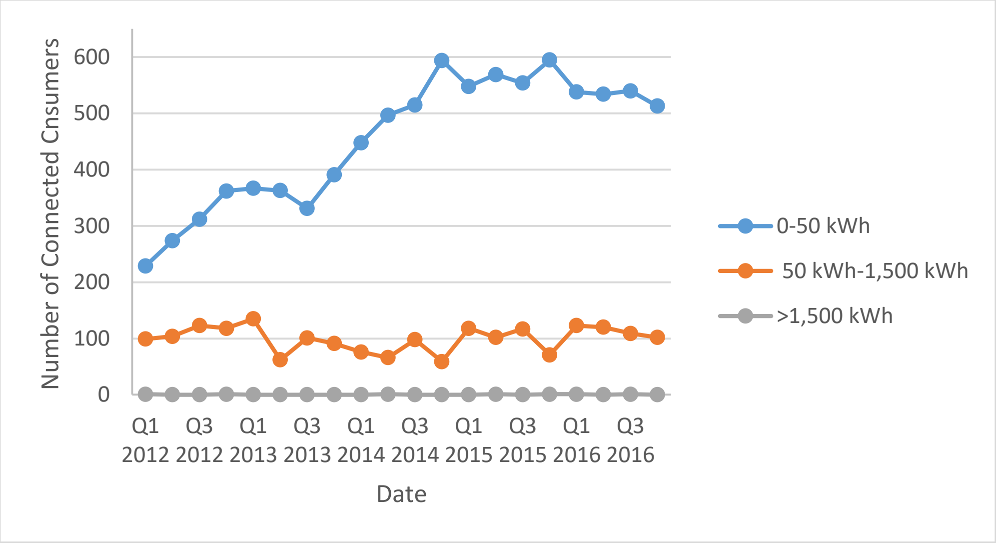

Figure 0.5 Electricity Consumption Categories from 2012 to 2016

While the total number of consumers in the lifeline tariff of <50 kWh per month has increased over time, the study found that there was no increase in the transition of <50 kWh consumers to >50 kWh as shown in Figure 4.6.

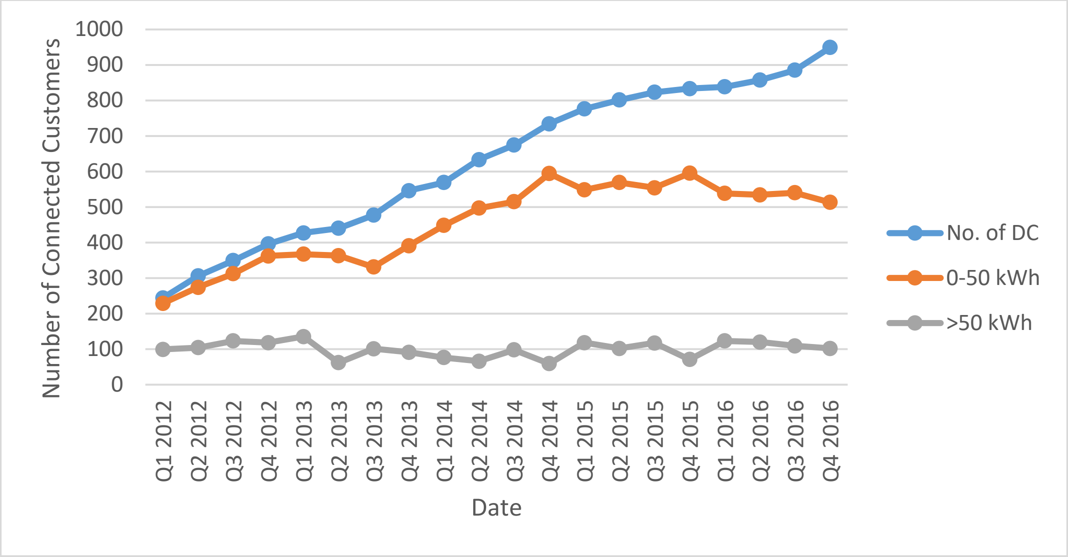

Figure 0.6 Redistribution of Domestic Consumers from 2012 to 2016

In fact, the rate at which consumers of >50 kWh per month were increasing was found to be lower than the rate for <50 kWh per month consumers. It can therefore be considered that the total number of consumers of >50 kWh per month are unlikely to surpass that consuming <50 kWh. The current gap in the rate of growth of consumers of >50 kWh per month is significant.

4.2.6.3. Growth in Electricity Demand

The average demand per customer (W)[8] is also low at 123 W with a peak of 182 W in Quarter 2 of 2015. Further, as shown in Figure 4.7, the demand per customer (W) has been declining over time and in fact fell to its lowest level in 2016.

Possible reasons for the decline in average electricity demand are:

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[8] Based on postpaid only

(i) Growth in the number of domestic customers who are low power users compared to commercial and industrial users who are large power consumers.

(ii) Low power usage for domestic, commercial and industrial users due to low ownership of electrical equipment and productive use appliances.

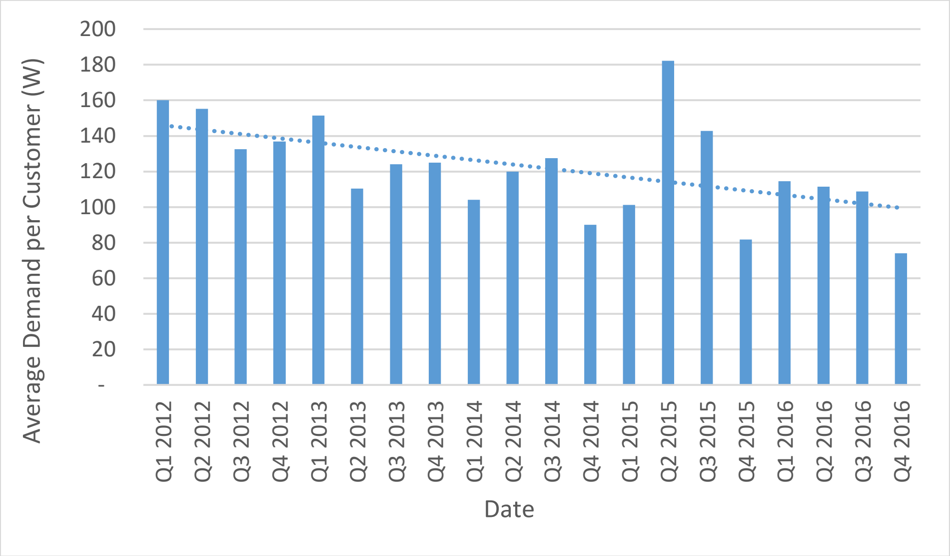

Figure 0.7 Demand Per Customer Connected to the Minigrid

4.2.6.4. Growth in Customer Electricity Consumption

Similar to demand (W), units of electricity sold to consumers is low and reducing over time. The average electricity units sold per customer (kWh)[9] is at 88 kWh per month with a peak of 131 kWh in Quarter 2 of 2015. Further, as shown in Figure 4.8, the electricity units sold per customer (kWh) has been declining over time and in fact fell to its lowest level in 2016.

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[9] Based on postpaid only

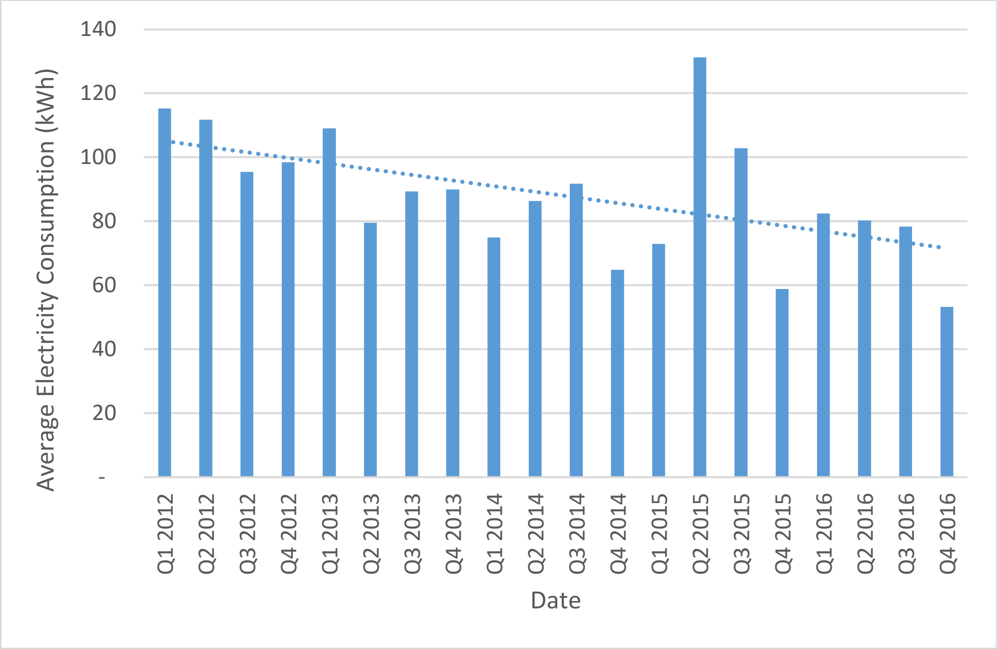


Figure 0.8 kWh Sales Per Customer Connected to the Minigrid

4.2.6.5. KPLC Considerations on Electricity Demand

The study found that there are a number of considerations for KPLC in regard to the characteristics of electricity demand for the Habaswein mini-grid, most notably demand per customer, and income per customer. The study established that average demand per customer was 123 W, while the average electricity sales to customers was 88 kWh per month per customer, and average gross sales revenue was KSh. 1,775 per month per customer. However, the study found that there were primarily two categories of consumers, domestic and boreholes and considered that the significant use of boreholes was likely to skew the findings toward higher demand and revenue per user. Most domestic consumers utilized 50 kWh per month or less; and domestic consumers accounted for about 79% of the kWh consumed and about 75% of the revenue collected.

The study found that economic impact of electricity supply in Habaswein was low, particularly due to limited socio-economic development of the general population. Electricity demand in Habaswein Division was consistently low. Moreover, all three parameters - average demand (W), average gross sales revenue (KSh) and average electricity sales (kWh) - were declining over time, reaching historical lows in the fourth quarter of 2016. It could therefore be considered that connections to small enterprises reached saturation.

4.3. Solar and Wind Energy Resource Potential for Power Generation in Habaswein

4.3.1. Solar Energy Resource Potential for Habaswein

The nearest meteorological stations to Habaswein are in Garissa and Wajir Towns. The theoretical performance for Habaswein is therefore geographically based on Wajir Town. The solar energy resource potential was determined using Wajir Town's solar resource data available in international databases; specifically, the Joint Research Center (JRC) of the European Union and National Aeronautics and Space Administration (NASA). As shown in Table 4.4 and Figure 4.9, the solar irradiation in Wajir is high, averaging between 5-6 kWh/m^2/day. The lowest solar irradiation is experienced in June and July, with a low of 5.5 kWh/m^2/day

Table 0.4 Incident Global Irradiation in Wajir (PVGIS)

Month	Irradiation on Horizontal Plane (Hh) (Wh/m^2/day)	Irradiation on Optimally Inclined Plane (Hopt) (Wh/m^2/day)	Irradiation on Plane at 90^0 angle (H90) (Wh/m^2/day)	Optimal Inclination (Iopt) (degrees)
January	6,610	6,720	4,230	30
February	6,930	7,000	3,180	20
March	7,130	7,140	1,900	4
April	6,350	6,310	863	-14
May	6,130	6,050	801	-28
June	5,690	5,600	835	-30
July	5,580	5,500	893	-30
August	5,980	5,920	917	-20

Month	Irradiation on Horizontal Plane (Hh) (Wh/m^2/day)	Irradiation on Optimally Inclined Plane (Hopt) (Wh/m^2/day)	Irradiation on Plane at 90^0 angle (H90) (Wh/m^2/day)	Optimal Inclination (Iopt) (degrees)
September	6,610	6,600	836	-3
October	6,310	6,340	2,580	14
November	5,900	5,970	3,510	27
December	6,130	6,230	4,240	33
Year	6,280	6,280	2,060	2

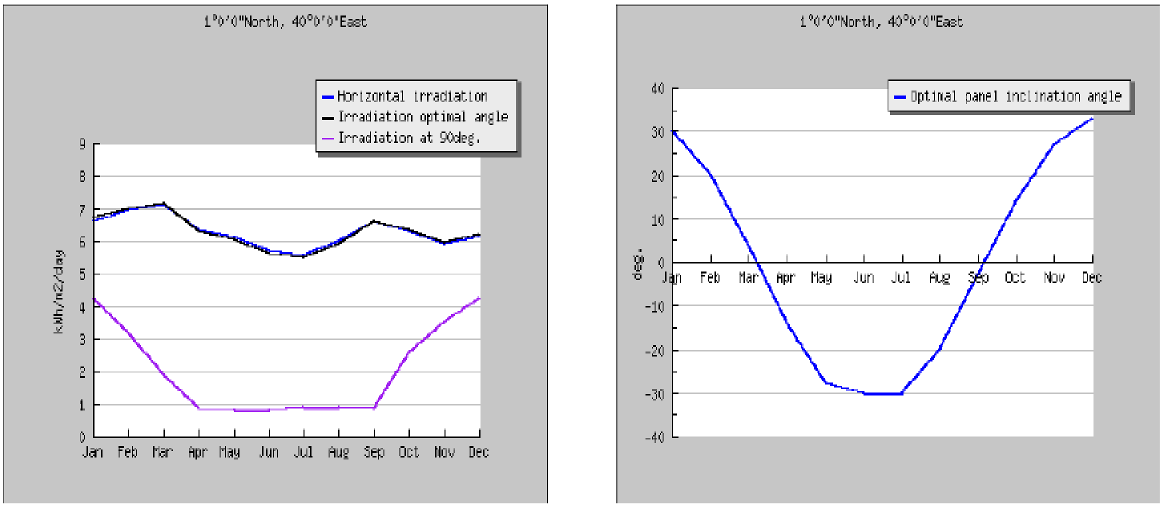
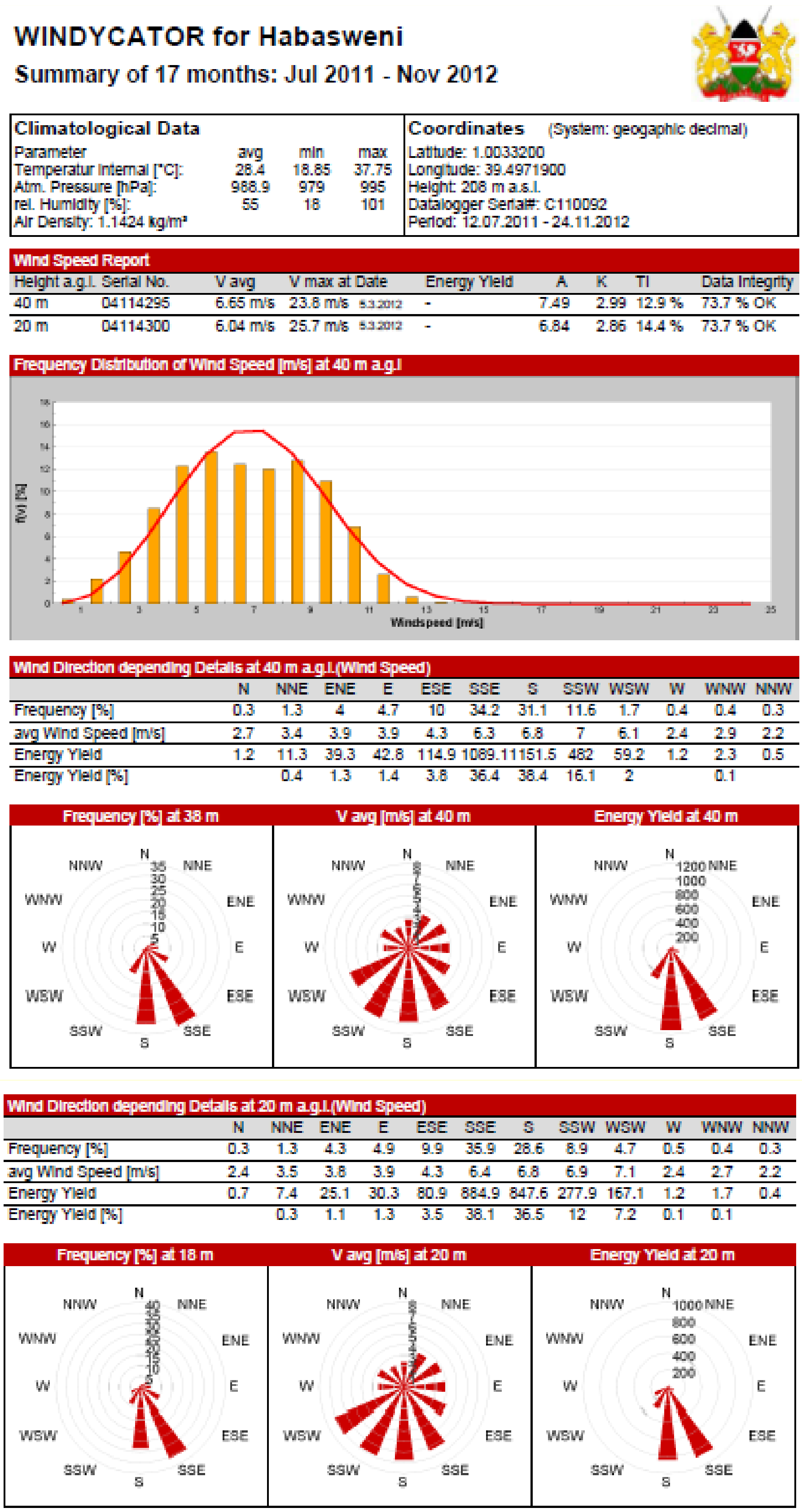


Figure 0.9 Irradiation (kWh) in Wajir (PVGIS)

4.3.2. Wind Energy Resource Potential for Habaswein

The wind resource potential in Habaswein was obtained from data collected at a meteorological station at proximity to the site. As shown in Figure 4.10 and Figure 4.11, the monthly mean wind speed in Habaswein varies from a low of 3.7 m/s to a high of 8.6 m/s.



WINDYCATOR for Habasweni

Summary of 17 months: Jul 2011 - Nov 2012

Climatological Data

Parameter	avg	min	max
Temperatur internal [°C]:	28.4	18.85	37.75
Atm. Pressure [hPa]:	988.9	979	995
rel. Humidity [%]:	55	18	101

Air Density: 1.1424 kg/m³

Coordinates (System: geogaphic decimal)

Latitude: 1.0033200
Longitude: 39.4971900
Height: 208 m a.s.l.
Datalogger Serial#: C110092
Period: 12.07.2011 - 24.11.2012

Wind Speed Report

Height a.g.l.	Serial No.	V avg	V max at Date		Energy Yield	A	K	TI	Data Integrity
40 m	04114295	6.65 m/s	23.8 m/s	5.3.2012	-	7.49	2.99	12.9 %	73.7 % OK
20 m	04114300	6.04 m/s	25.7 m/s	5.3.2012	-	6.84	2.86	14.4 %	73.7 % OK

Frequency Distribution of Wind Speed [m/s] at 40 m a.g.l

Wind Direction depending Details at 40 m a.g.l.(Wind Speed)

	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Frequency [%]	0.3	1.3	4	4.7	10	34.2	31.1	11.6	1.7	0.4	0.4	0.3
avg Wind Speed [m/s]	2.7	3.4	3.9	3.9	4.3	6.3	6.8	7	6.1	2.4	2.9	2.2
Energy Yield	1.2	11.3	39.3	42.8	114.9	1089.1	1151.5	482	59.2	1.2	2.3	0.5
Energy Yield [%]		0.4	1.3	1.4	3.8	36.4	38.4	16.1	2		0.1	

Frequency [%] at 38 m | **V avg [m/s] at 40 m** | **Energy Yield at 40 m**

Wind Direction depending Details at 20 m a.g.l.(Wind Speed)

	N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW
Frequency [%]	0.3	1.3	4.3	4.9	9.9	35.9	28.6	8.9	4.7	0.5	0.4	0.3
avg Wind Speed [m/s]	2.4	3.5	3.8	3.9	4.3	6.4	6.8	6.9	7.1	2.4	2.7	2.2
Energy Yield	0.7	7.4	25.1	30.3	80.9	884.9	847.6	277.9	167.1	1.2	1.7	0.4
Energy Yield [%]		0.3	1.1	1.3	3.5	38.1	36.5	12	7.2	0.1	0.1	

Frequency [%] at 18 m | **V avg [m/s] at 20 m** | **Energy Yield at 20 m**

Figure 0.10 Windycator for Habaswein: Between July 2011 and November 2012

WINDYCATOR for Habasweni

Summary of 17 months: Jul 2011 - Nov 2012

Monthly Mean Values

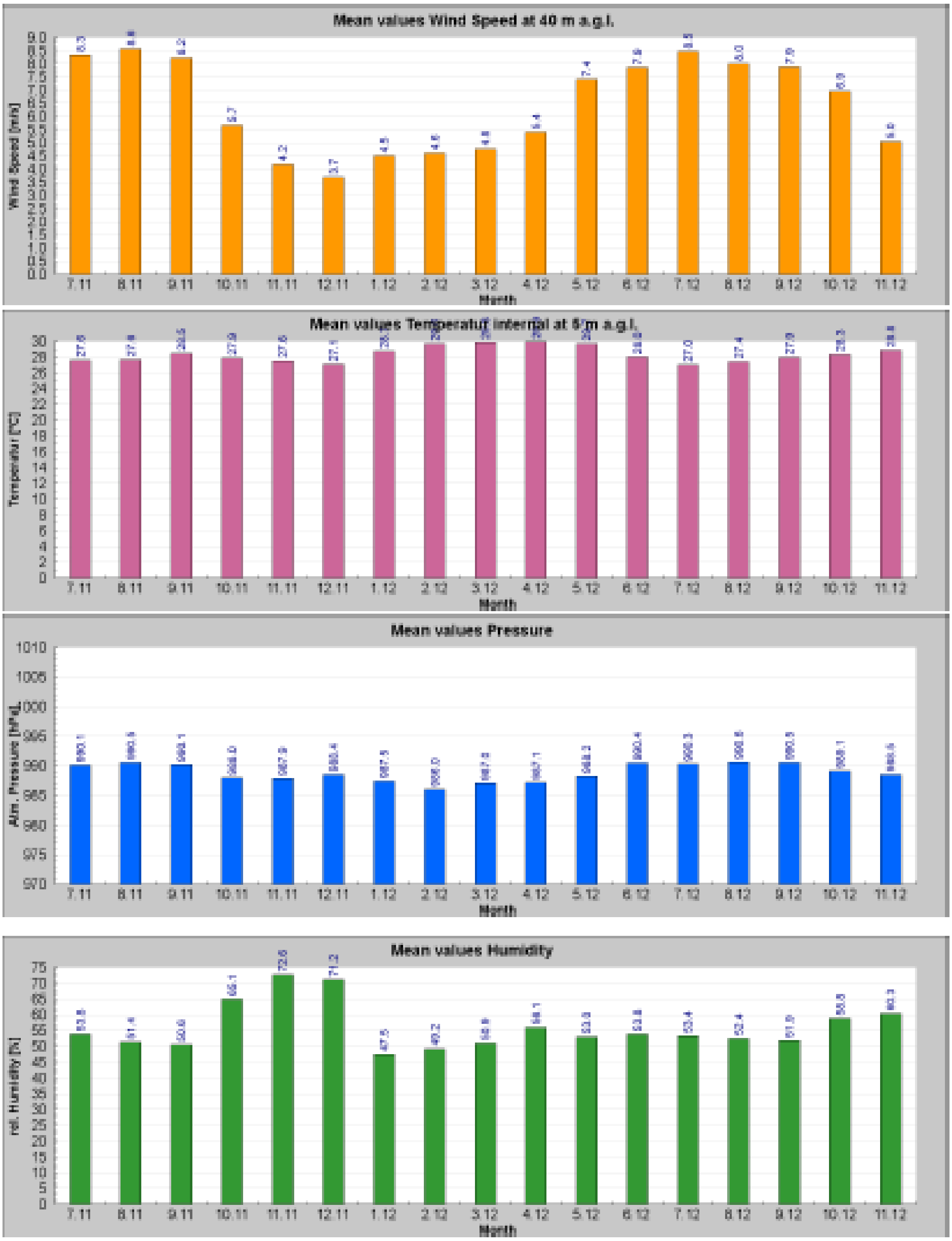


Figure 0.11 Wind Energy Resource Potential Data by Month

4.4. Performance Evaluation of Habaswein Diesel, Solar and Wind Hybrid System

4.4.1. Theoretical Performance of a 30 kW Solar PV System

The characteristics of Habaswein Power Generation Station in terms of installed capacity are as follows: 360 kW diesel, 60 kW wind and 30 kW solar PV. Determination of the theoretical solar and wind power output was based on PVGIS online solar photovoltaic calculator tool[10], and WindyCator, while actual electricity generation for both was based on periodic (ideally every 30 minutes) reading and manual logging from the respective kWh meters. In order to determine the expected theoretical output, the following known parameters were used: i) Solar PV system size of 30 kWp; and (ii) Wajir coordinates Latitude 1.749 and Longitude 40.059.

Results from the PVGIS solar PV calculator are summarized in Table 4.5, which shows the indicative theoretical monthly solar radiation and electricity generation from the system and their variation over the course of the year. as follows. The 30 kWp solar PV system is expected to generate approximately 101 – 158 kWh as average daily electricity production, and 3,080 kWh – 4,690 kWh as average monthly electricity production.

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[10] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa

Table 0.5 Theoretical Performance of a 30 kWp Solar PV system in Wajir

	Average daily electricity production (kWh)	Average monthly electricity production (kWh)	Average daily sum of global irradiation (kWh/m^2)	Average sum of daily global irradiation (kWh/m^2)
Jan	158	4890	7.48	232
Feb	158	4420	7.52	211
Mar	151	4690	7.17	222
Apr	126	3780	5.88	176
May	116	3590	5.39	167
Jun	103	3080	4.78	143
Jul	101	3120	4.67	145
Aug	115	3560	5.35	166

	Average daily electricity production (kWh)	**Average monthly electricity production (kWh)**	**Average daily sum of global irradiation (kWh/m^2)**	**Average sum of daily global irradiation (kWh/m^2)**
Sep	133	4000	6.24	187
Oct	129	4010	6.1	189
Nov	132	3960	6.17	185
Dec	148	4590	6.97	216
Year	131	3970	6.14	187
Total for year		**47700**		**2240**

4.4.2. Theoretical Performance of 60 kW Wind System[11]

The parameters used to calculate theoretical performance of the 60 kW wind power generation system are summarized in Table 4.6.

Table 0.6 Parameters Applied to Calculate Wind Power Output

Parameter	Estimate	Unit
Height of the turbine	39.62	Meters
Weibull K	1.8	
Wind Shear Exp.	0.180	
Turbulence Factor	15.00	%
Daily Energy Output	126.5	kWh
Annual Energy Output at Maximum Capacity	46,188	kWh
Average Monthly Energy Output	3,849	kWh
Turbulence Factor	15.00	%

---

[11] The actual performance (kWh produced per month) is based on the calculated maximum kWh output for that given month, in the period 2012 to 2016. It therefore accounts for the best turbine performance rather than average performance of the turbine during that period.

Parameter	Estimate	Unit
Hub average wind speed	6.91	m/s
Air density factor	-1.91	%

As shown in Table 4.7, the average monthly wind speed generated by WindyCator was used to estimate power output for each 20 kW wind turbine and the three (3) wind turbines assuming their power output was the same.

Table 0.7 Theoretical Power Output of the Wind System

Month	Wind speed (m/s)	kWh produced by 20 kW turbine	kWh produced by 3 X 20 kW turbine
January	4.5	1,729	5,187
February	4.6	1,647	4,941
March	4.8	2,019	6,057
April	5.4	2,548	7,644

Month	**Wind speed (m/s)**	**kWh produced by 20 kW turbine**	**kWh produced by 3 X 20 kW turbine**
May	7.4	4,612	13,836
June	7.9	4,849	14,547
July	8.4	5,355	16,065
August	8.3	5,291	15,873
September	8.05	4,955	14,865
October	6.3	3,573	10,719
November	4.6	1,765	5,295
December	3.7	1,051	3,153
Annual	6.65	39,394	118,182

4.4.3. Actual Performance of Habaswein 30 kW Solar PV System

The actual performance of the solar PV system was determined by analyzing data on electricity generation (kWh) as logged by KPLC personnel at the station as discussed in Chapter 3. Collected data was transferred from physical log sheets into excel spreadsheets as summarized in Table 4.8.

Table 0.8 Sample of KPLC Data Set Used to Determine Actual Electricity Generation

	1/24/2012			
Time	**Diesel (kW)**	**Solar (kW)**	**Wind (kW)**	**Total (kW)**
12:30:00 AM …				
8:00:00 AM	46	2.9		48.9
8:30:00 AM	42	3.5		45.5
9:00:00 AM	36	3.7		39.7
9:30:00 AM	37	7.2		44.2
6:00:00 PM	44	1.5		45.5

	1/24/2012			
Time	**Diesel (kW)**	**Solar (kW)**	**Wind (kW)**	**Total (kW)**
6:30:00 PM …	40	1.2		41.2
12:00:00 PM				
Total kWh/day				

The data set in Table 4.8 was on a 24-hour basis in 30-minute intervals (12:30:00 AM to 12:00:00 AM), and daily for 5 years (23/01/2012 to 31/12/2016). Based on the above data set, electricity output from diesel, solar and wind generation were determined individually, as well as the total electricity output, for each day, month and year. Further, the average daily electricity and monthly electricity output were determined, based on total annual production.

A sample of raw data on total electricity output from the solar PV system is included as Appendix VI.

4.3.1.1 Daily Total Solar PV Electricity Generation

A comparison of the actual average daily solar PV electricity generation and the theoretical values are shown in Figure 4.12. The study found that the solar PV system was operational for 3.5 years between January 2012 to July 2015. This is the period during which any electricity output data from the solar PV system was logged by the

KPLC staff. During this time the actual output could be considered generally in line with the expected output.

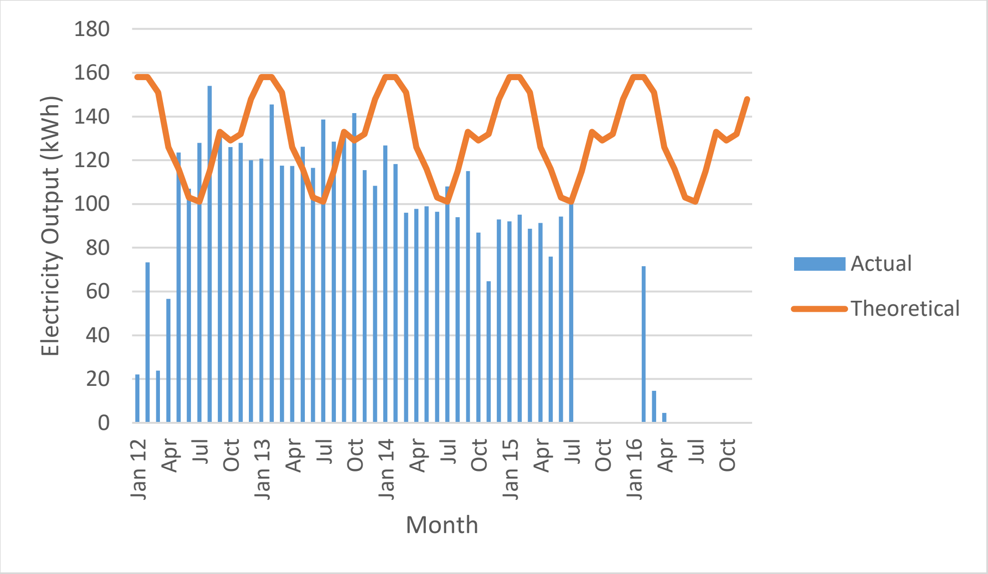

Figure 0.12 Comparison of Actual and Theoretical Daily Electricity Output of the 30 kWp Solar PV System From 2014 to 2016

Between August 2015 and December 2016, the solar PV system could be considered to have failed due to the drop in output to zero.

The deviation from theoretical is a result of several reasons:

1. Limited access to solar resource data at the time of design and installation of the system
2. Lack of detailed study to inform optimal design of the system
3. Lack of automated and remote monitoring systems
4. Malfunction of the system components

Figure 4.12 shows the electricity output during that time. Based on feedback from Kenya Power personnel on site, there has been limited maintenance of the system since installation, and the staff are not trained on solar PV system design or operation and are therefore unable to troubleshoot.

4.3.1.2 Monthly Total Solar PV Electricity Generation

The comparison of the average monthly solar PV electricity generation in the theoretical and actual scenarios is summarized in Figure 4.13. The report found that the actual output could be considered generally in line with the expected output.

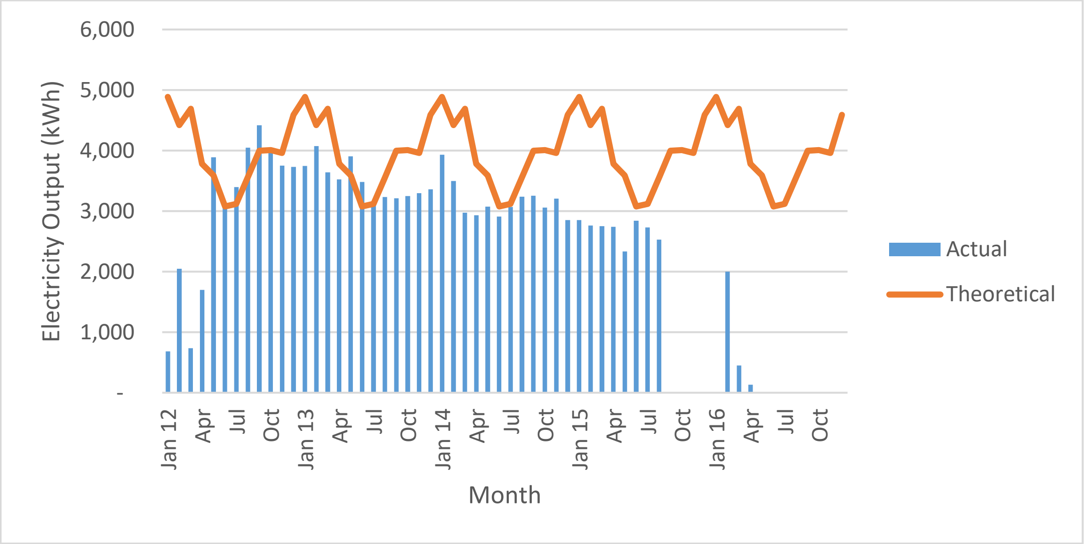

Figure 0.13 Comparison of Actual and Theoretical Monthly Electricity Output of the 30 kWp Solar PV System From 2012 to 2016

4.4.4. Performance of the Wind Power System

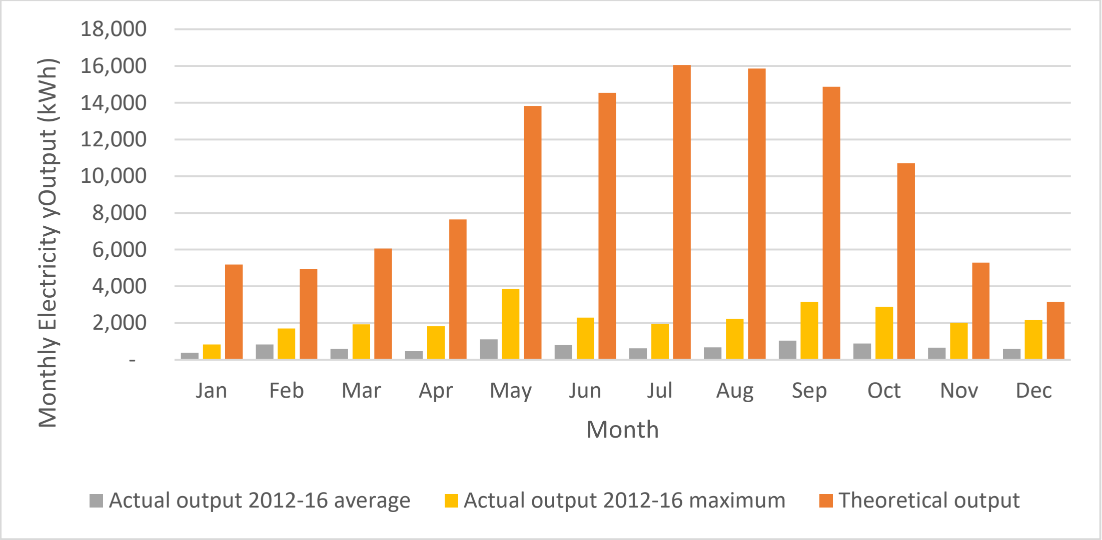

Figure 0.14 Theoretical Versus Actual Output of 60 kW Wind System

As shown in Figure 4.14 and Figure 4.15, the actual output of the Habaswein wind power system was far below the theoretical output expected of a generic 60 kW installation, based on the available wind resources. The actual output based on the monthly average over the 5 years, as well as the actual output based on the monthly maximum power output over the 5 year, were both far below the expected output of a 60 kW wind turbine. Considering the best performance of the system in each month over the 5 years (i.e. basing performance measurement on maximum output) the actual output ranged from 12 – 69% of the anticipated output.

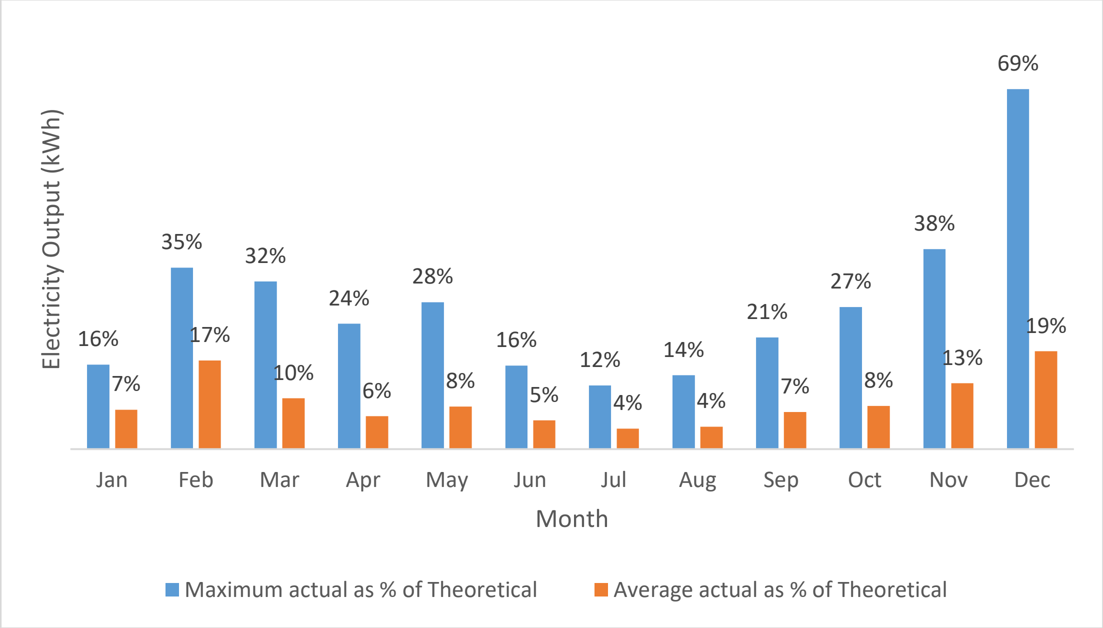

Figure 0.15 Actual Output as a % of Theoretical Output of a 60 kW Wind System

Considering the typical performance of the system in each month over the 5 years (i.e. basing performance measurement on average output) the actual output ranged from a low of 4 - 19% of the anticipated output. The comparison of theoretical versus actual performance of the 60 kW system shows that the performance of the wind system is far below the expected output. Further, as shown in Figure 4.16, when only one (1) 20 kW turbine is considered the actual output is still below the theoretical output expected. This non-satisfactory performance of the system is indicative of a system malfunction based on the nominal output of the system.

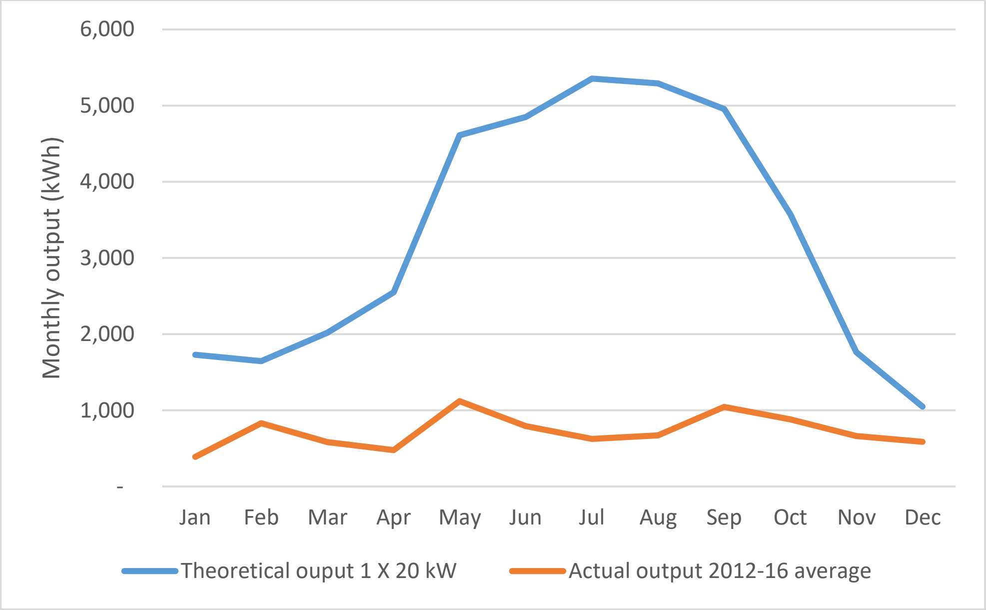

Figure 0.16 Theoretical Versus Actual Output of 1 x 20 kW Wind System

However, when only one (1) 20 kW turbine is considered, there are instances where the actual power output curve follows the theoretical output path (January to May, and September to December). Given the above comparisons, it is therefore considered likely that only one (1) turbine has been operational at the site, for the majority of the minigrids operations. Further, it can also be considered that any one (1) operational turbine has likely not been fully operational.

4.4.3 Electricity Generation

The annual total electricity generation (kWh) grew by an average of 21% per year between 2012 and 2016. The most significant growth was 45% in 2012 but between 2013 and 2016 the growth is declining as shown in Figure 4.17.

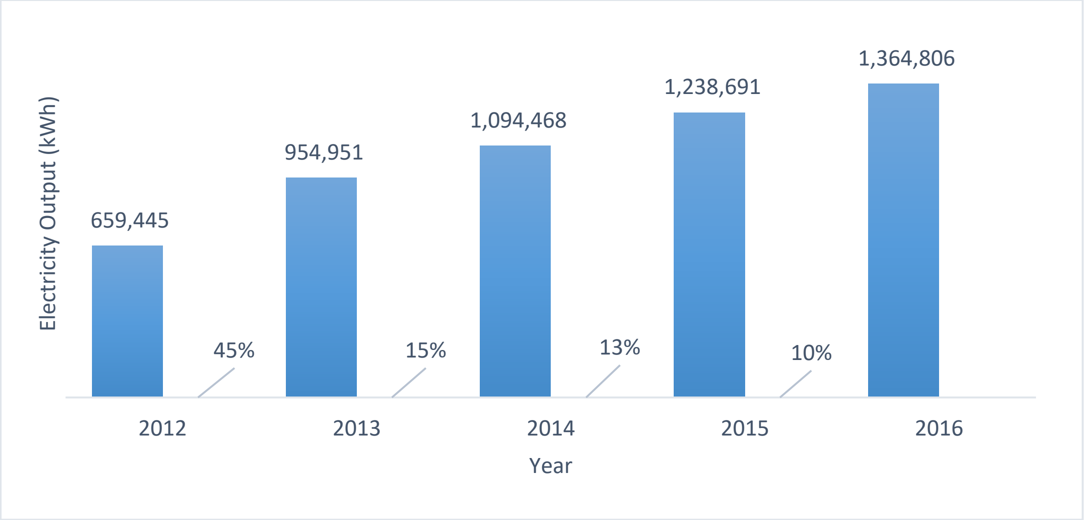

Figure 0.17 Year on Year Increase in Total Electricity Generation (kWh) Reduced From 2012 to 2016

This trend in total electricity generation could possibly be a result of early electricity connections being made to customers with high unmet energy demand – thereby providing a significant jump in electricity demand - while latter connections were to customers with low unmet demand.

4.4.3.1 Monthly Electricity Generation

The study found some variation in the monthly electricity generation as shown in Figure 4.18. However, there was no evident trend in the variation, when the lowest and highest months were considered.

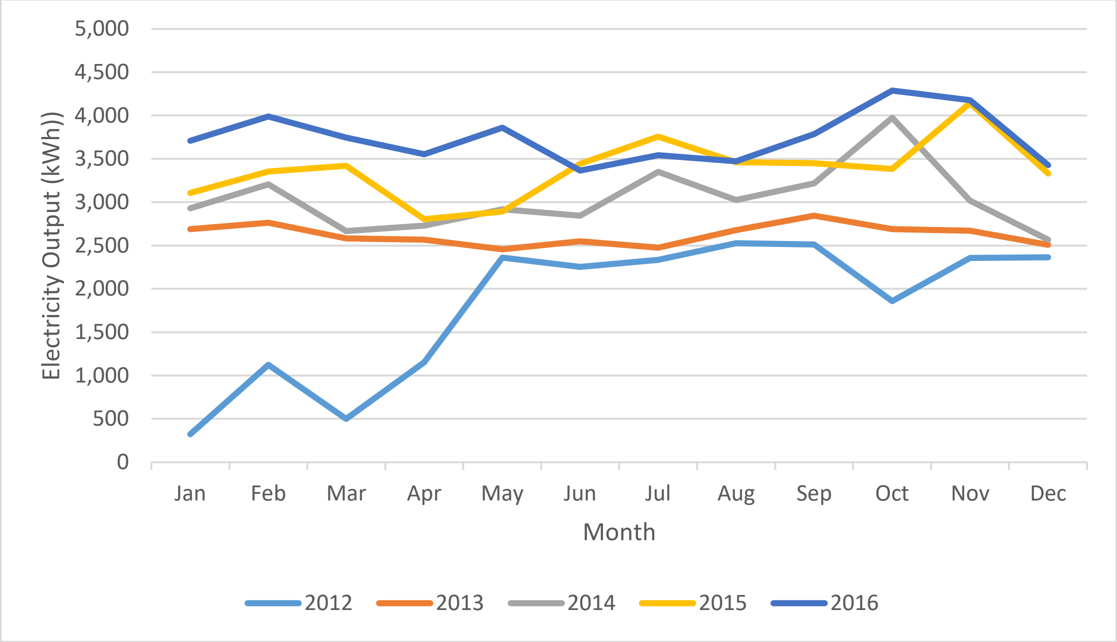

Figure 0.18 Variation of Monthly Average Electricity Generation (kWh) From 2012 to 2016

Figure 4.19 shows the total monthly electricity generation (kWh) from 2012 to 2016 in greater detail.

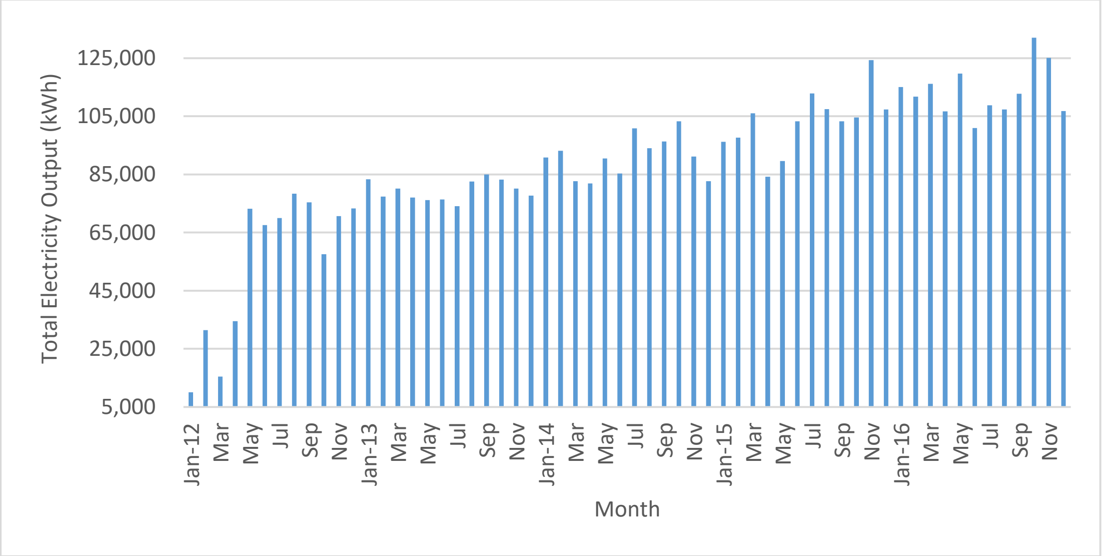

Figure 0.19 Total Monthly Electricity Generation (kWh) From 2012 to 2016

4.4.4 Peak Power Demand

The study found that peak power demand grew from 220 kW in 2012 to 364 kW in November 2015 (also experienced in November 2016). In comparison, the peak power demand was 256 kW and 270 kW, in 2013 and 2014, respectively. The peak load on a month to month basis was assessed in order to determine how the peak demand changes over the year as shown in Figure 4.20.

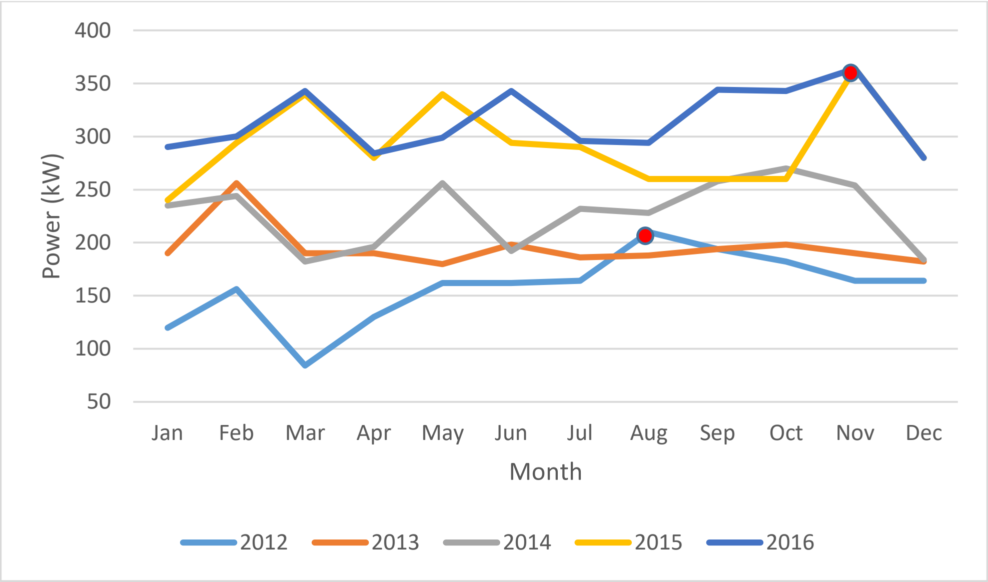

Figure 0.20 Peak Power Demand (kW) From 2012 to 2016

4.4.5 Daily Load Curve

The annual average load at Habaswein Power Generation Station has consistently increased in each year, while the load curve has maintained the same trend as shown in Figure 4.21. However, the percentage increase in daily average load has been reducing year on year, with the lowest increase observed between 2015 and 2016.

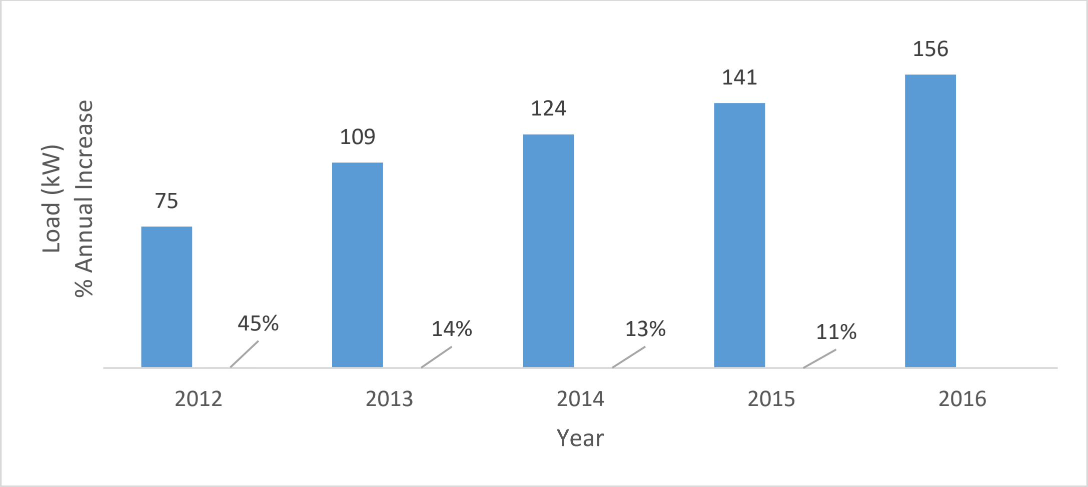

Figure 0.21 Daily Average Load (kW) From 2012 to 2016

4.4.6 Renewable Energy Penetration Levels

The electricity generation from the hybrid energy sources – diesel, solar and wind – were considered and compared to determine the renewable energy penetration level at the station. As shown in Figure 4.22 to Figure 4.25, renewable energy generation dropped to zero in September 2015 as a result of system failures for both solar and wind generation. This largely remained the same to date with some minimal output observed in January to April 2016.

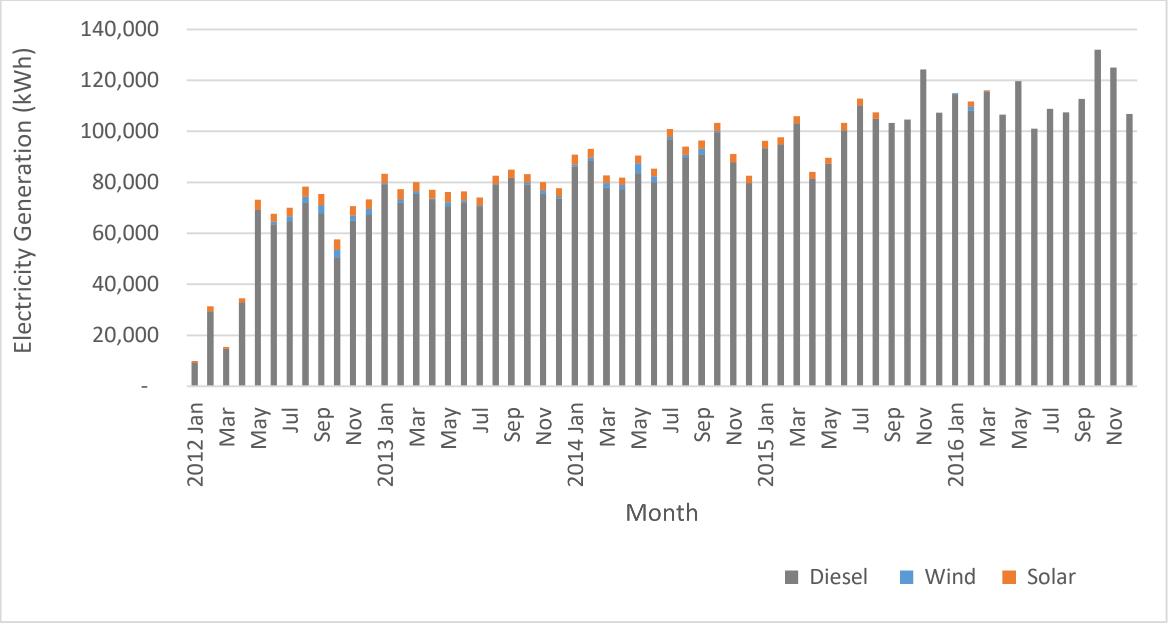

Figure 0.22 Electricity Generation (kWh) by Source From 2012 to 2016

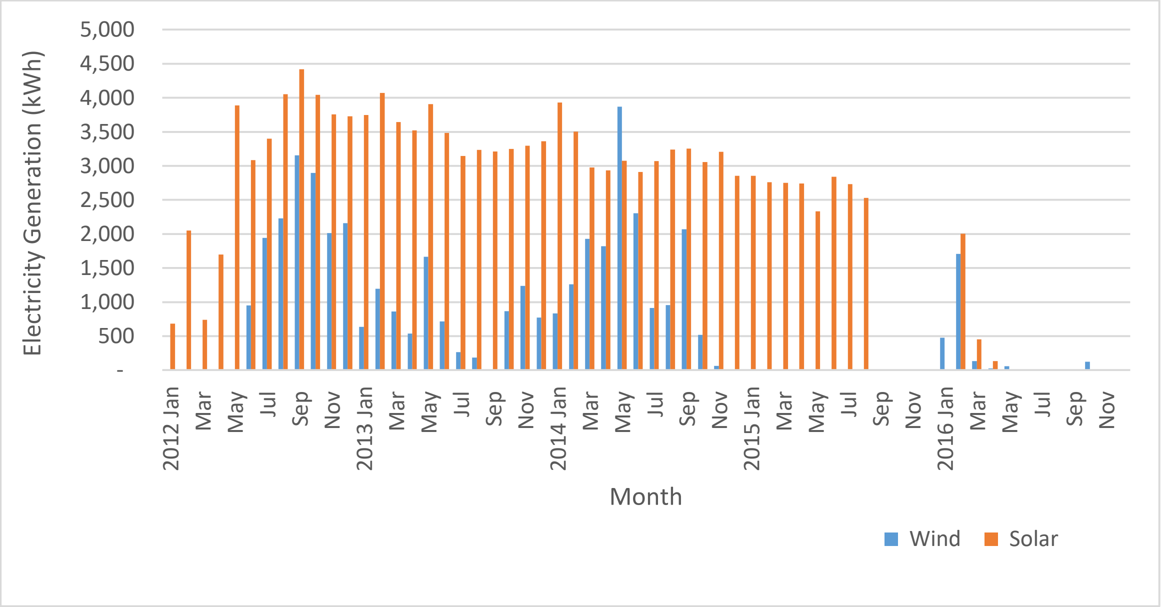

Figure 0.23 Electricity Generation (kWh) by Renewable Energy Sources From 2012 to 2016

Figure 4.24 show that the solar PV penetration peaked at 7% while the wind penetration peaked at 5%.

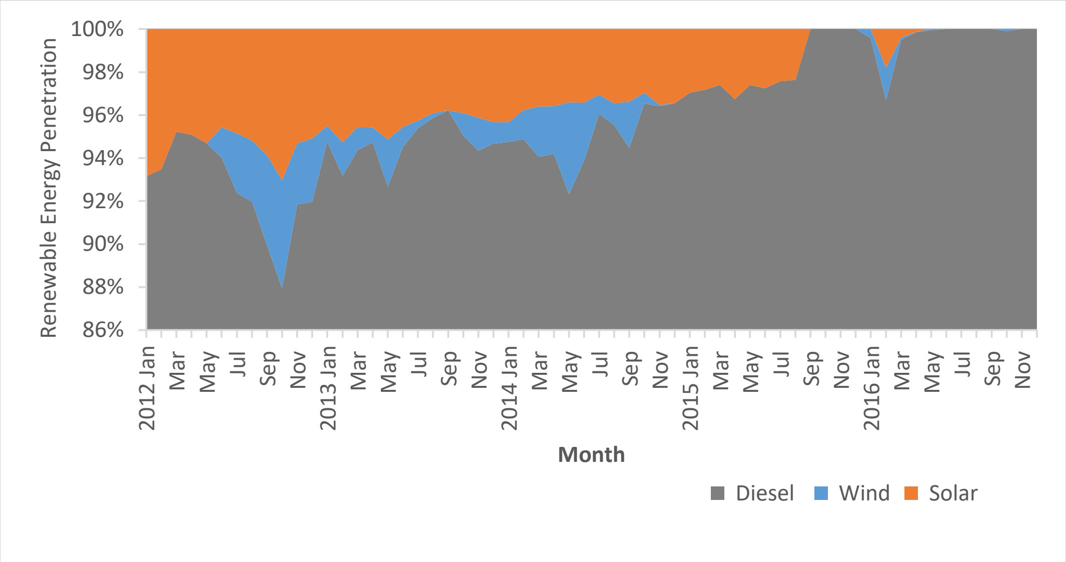

Figure 0.24 Renewable Energy Penetration From 2012 to 2016

Figure 0.25 Renewable Energy (Solar PV and Wind) Penetration From 2012 to 2016

Figure 4.25 show that the renewable energy penetration peaked at 12% but reduced over the years for several reasons:

(i) The installed diesel capacity at the station increased over time while the solar and wind capacity remained constant.

(ii) There were system malfunctions reducing the electricity output from the solar and wind power generation systems.

(iii) There were insufficient O&M arrangements in place for the solar and wind power generation systems.

4.4.7 Specific Fuel Consumption

The specific fuel consumption (SFC) of the Habaswein power station has been reducing over time. As shown in Figure 4.26, there was a significant reduction in SFC in July 2012 when the renewable energy penetration was at its peak (12%).

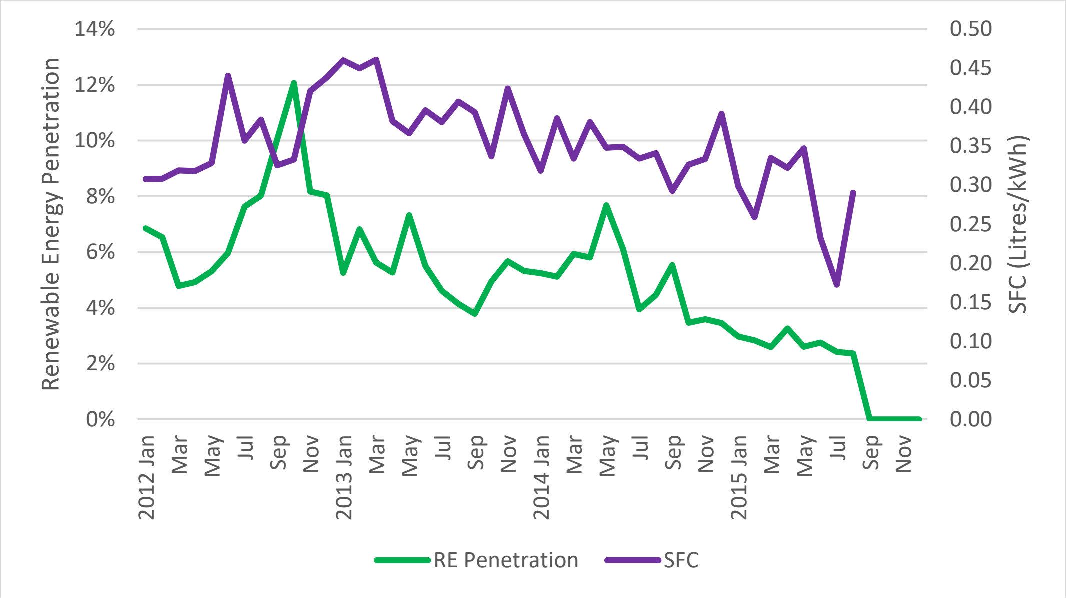

Figure 0.26 Specific Fuel Consumption (Litres/kWh) From 2012 to 2016

There are some instances of direct correlation between SFC and renewable energy penetration, as SFC has been seen to be lower when renewable energy generation is higher and vice versa. However, the overall reduction in SFC could not be a result of the renewable energy generation. In addition, given that 3 diesel generators with different performance characteristics are operated in different configurations at less than full load, there are variable generator efficiencies. Diesel power generation with better fuel efficiency at full load operation may possibly yield lower SFC.

Rather, as shown in Figure 4.27, SFC could be reducing only as a result of increase in total electricity demand (kWh).

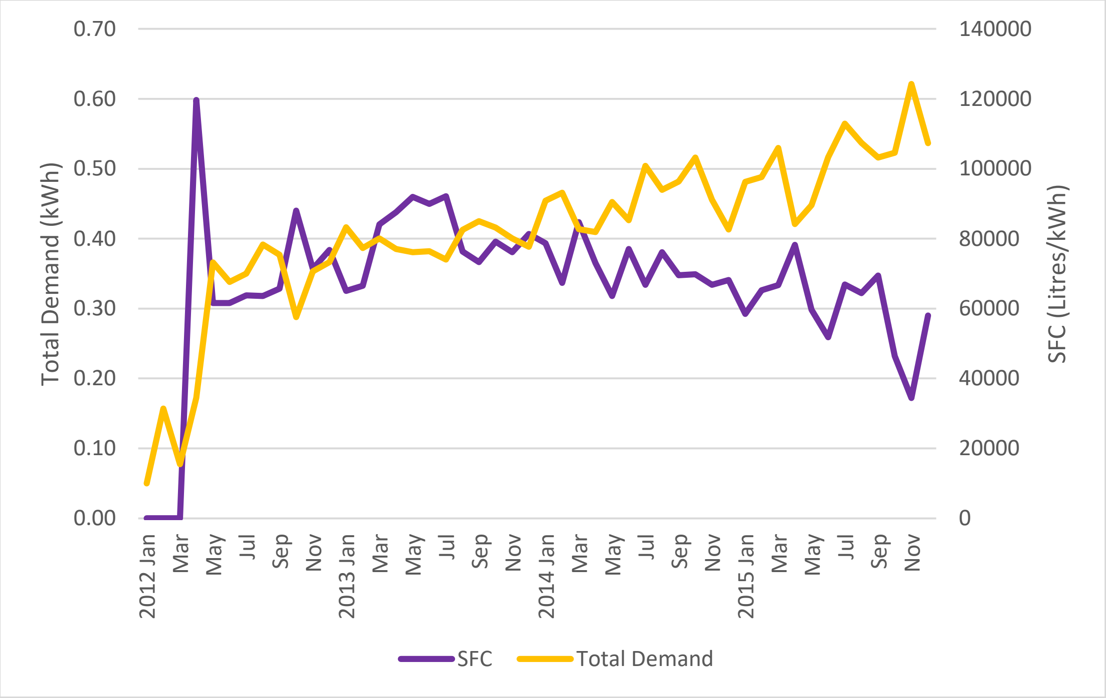

Figure 0.27 Specific Fuel Consumption (SFC) and Demand (kWh) From 2012 to 2015

The SFC has been reducing over time because of increase in the load, therefore allowing for more efficient operation of the diesel generators. The reduction in SFC is expected given that a closer match between the load and the generator capacity increases efficiency of operation.

4.5. Optimization of the Habaswein Power Station

The study further sought to establish the optimal design and performance of the system which currently comprises of 410 kW diesel, 30 kW solar and 60 kW wind (Base Case). The key findings of the study regarding optimization of power generation from the minigrid are discussed in this section. The HOMER analysis considered several variations from the Base Case including increase in the installed capacity of the diesel system, introduction of battery energy storage systems (BESS) and increase in the installed capacity of the solar PV system; which also resulted in changes in the system's converter size.

From the available data on performance of the wind system, the wind turbines have negligible energy output, not compatible with their rated power and available wind resource. Since they are malfunctioning, their inclusion in the optimal design has been treated separately, assuming an initial revamping cost to have them operating properly. The scenarios which consider the malfunctioning wind turbines as 0 kW effective capacity (Base Case). Specifically, the adjustments summarized in Table 4.9 were made in the design in order to determine the optimum configuration[12]:

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[12] The dispatch strategy is set as HOMER Cycle Charging in all scenarios

Table 0.9 Variables Adjusted in the Optimization Process

Scenario	Diesel	Solar	Wind		BESS Adjustment
Base Case	410 kW	30 kW	0 kW – 60 kW installed capacity is disregarded based on the current performance (malfunction)	Nil	500 kWh – 1,300 kWh
Case 1	410 kW	30 kW	60 kW – 60 kW installed capacity is revamped to establish performance at par with turbine specifications and available wind resource (operational)	Nil	Nil

When the Base Case was considered, the HOMER analysis resulted in an optimal design with an increased solar PV capacity and an increased diesel capacity as shown in Table 4.10. The HOMER analysis results in a total NPC of $7,568,600.45 and a Levelized Cost of Energy (US$/kWh) of US$0.354.

Table 0.10 Architecture of Optimized System – Without Wind Turbine Revamping (Diesel/Solar Hybrid)

Component	**Name**	**Base Case Size**	**Optimal Size**	**Unit**
Generator #1	Generic 100 kW Fixed Capacity Genset	0	100	kW
Generator #2	Kohler 410 kW Standby	410	410	kW
PV	Generic solar PV	30	569	kW
Wind (malfunctioning)	Layer electronics GE -200 (3x)	0	0	kW
System converter	System Converter	-	193	kW

The schematic diagram of the optimized system based on the Base Case scenario is shown in Fgure 4.28.

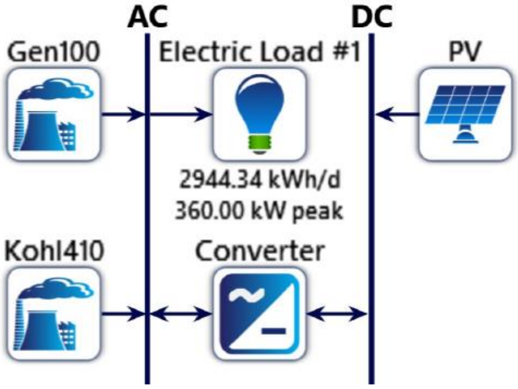

Figure 0.28 Schematic Diagram of Optimized System (Diesel/Solar Hybrid)

The HOMER analysis indicates that in the Base Case scenario with no battery energy storage system, no wind turbines revamping and the addition of a 100 kW diesel generator to meet base load, to the existing 410 kW diesel generator to meet peak load (switch over), that the optimal sizing of the hybrid system features a 569 kW solar PV system. The diesel generator is considered a back-up component, given that the 410 kW generator already in the system is oversized compared to the load curve, most of the time, because the maximum requested power is 292 kW and the average requested power is 122 kW. For the 100 kW diesel generator, the capital cost and replacement cost are set to $40,000 and the O & M cost is 2 US$/h. The diesel cost remains the same at 1.28 US$/L.

The cost summary of the Base Case is provided in Figure 4.29.

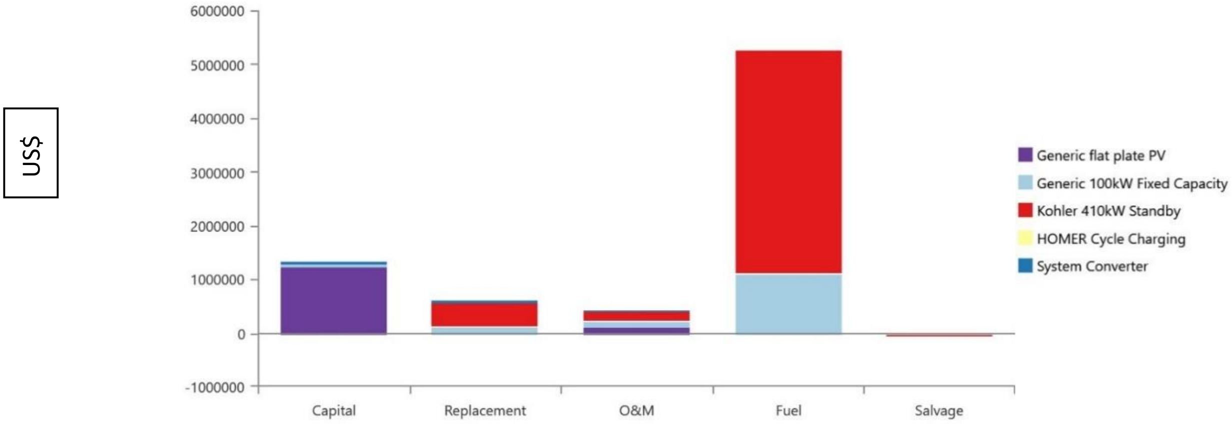

Figure 0.29 Cost Summary (US$) of Optimized System – Without Wind Turbine Revamping (Diesel/Solar Hybrid)

The NPC summary of the Base Case is provided in Table 4.11.

Table 0.11 Net Present Cost of Optimized System – Without Wind Turbine Revamping (Diesel/Solar Hybrid)

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic solar PV	$1.25M	$0.00	$113,073	$0.00	$0.00	$1.37M
Generic 100 kW Fixed	$40,000	$125,034	$108,078	$1.11M	-$11,799	$1.37M

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Capacity Genset Kohler 410 kW Standby	$0.00	$425,713	$156,276	$4.15M	-$25,315	$4.71M
System Converter	$57,806	$43,898	$38,282	$0.00	-$12,180	$127,807
System	$1.35M	$594,645	$415,710	$5.26M	-$49,294	$7.57M

The annualized cost summary of the Base Case is provided in Table 4.12.

Table 0.12 Annualized Cost of Optimized System – Without Wind Turbine Revamping (Diesel/Solar Hybrid)

Component Capital		Replacement	O&M	Fuel	Salvage	Total
Generic solar PV	$63,024	$0.00	$5,691	$0.00	$0.00	$68,715
Generic 100 kW Fixed Capacity Genset	$2,013	$6,293	$5,440	$55,689	-$593.89	$68,842
Kohler 410 kW Standby	$0.00	$21,428	$7,866	$208,948	-$1,274	$236,967
System Converter	$2,910	$2,210	$1,927	$0.00	-$613.05	$6,433
System	$67,947	$29,931	$20,924	$264,637	-$2,481	$380,957

In the second scenario (Case 1), the wind turbines are revamped and the installed capacity of 60 kW is reinstaated and included in the optimized design schematics and the optimized system architecture. When Case 1 was considered, the HOMER analysis resulted in an optimal design with an increased solar PV capacity and an increased diesel capacity as shown in Table 4.13. The HOMER analysis results in a total NPC of $7,700,013 and a Levelized Cost of Energy (US$/kWh) of US$0.361.

Table 0.13 Architecture of Optimized System – With Wind Turbine Revamping (Diesel/Solar/Wind Hybrid)

Component	Name	Base Case Size	Optimal Size	Unit
Generator #1	Generic 100 kW Fixed Capacity Genset	0	100	kW
Generator #2	Kohler 410 kW Standby	410	410	kW
PV	Generic solar PV	30	520	kW
Wind (malfunctioning)	Layer electronics GE -200 (3x)	0	60	kW
System converter	System Converter	-	189	kW

The schematic diagram of the optimized system based on Case 1 scenario is shown in Fgure 4.30.

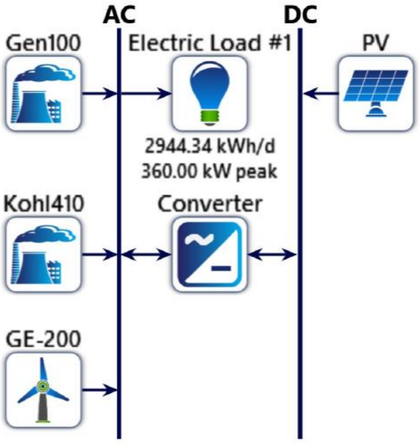

Figure 0.30 Schematic Diagram of Optimized System – With Wind Turbines Revamping (Diesel/Solar/Wind Hybrid)

The cost summary of Case 1 is provided in Figure 4.31.

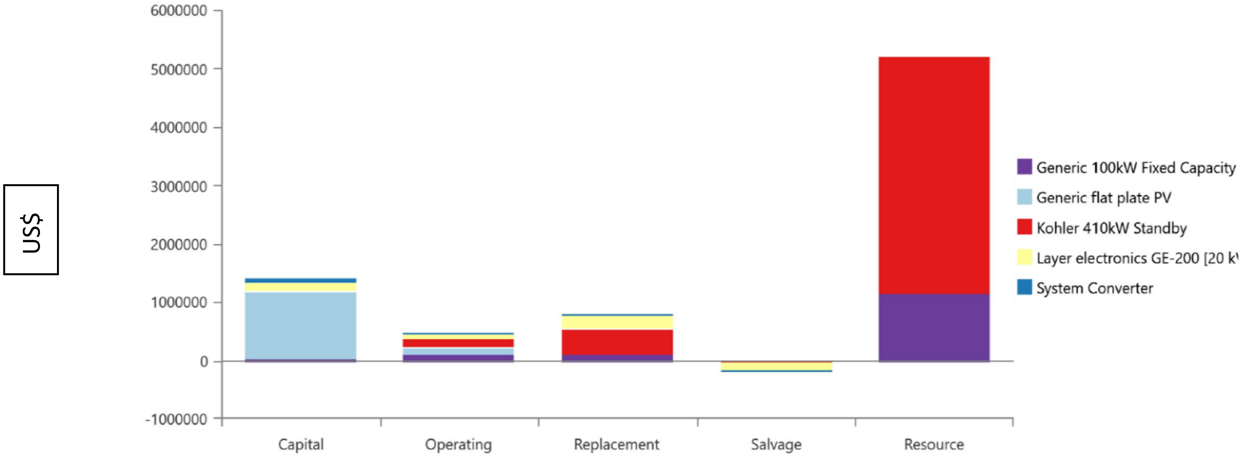

Figure 0.31 Cost Summary (US$) of Optimized System – With Wind Turbine Revamping (Diesel/Solar/Wind Hybrid)

The NPC summary of Case 1 is provided in Table 4.14.

Table 0.14 Net Present Cost of Optimized System – With Wind Turbine Revamping (Diesel/Solar/Wind Hybrid)

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic solar PV	$1.15M	$0.00	$103,407	$0.00	$0.00	$1.25M
Layer electronics GE -200 (3x)	$150,000	$207,846	$59,602	$0.00	-$142,220	$275,229
Generic 100 kW Fixed Capacity Genset	$40,000	$127,249	$116,581	$1.17M	-$2,781	$1.45M
Kohler 410 kW	$0.00	$424,425	$154,250	$4.05M	-$30,151	$4.60M

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Standby System Converter	$56,636	$43,009	$37,507	$0.00	-$11,933	$125,2197
System	$1.39M	$802,529	$471,347	$5.22M	-$187,084	$7.70M

The annualized cost summary of Case 1 is provided in Table 4.15.

Table 0.15 Annualized Cost of Optimized System – With Wind Turbine Revamping (Diesel/Solar/Wind Hybrid)

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic solar PV	$57,636	$0.00	$5,205	$0.00	$0.00	$62,841

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Layer electronics GE -200 (3x)	$7,550	$10,462	$3,000	$0.00	-$7,158	$13,853
Generic 100 kW Fixed Capacity Genset	$2,013	$6,405	$5,868	$58,998	-$139.99	$73,144
Kohler 410 kW Standby	$0.00	$21,363	$7,764	$203,821	-$1,518	$231,431
System Converter	$2,851	$2,165	$1,888	$0.00	-$600.63	$6,303

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
System	$70,050	$40,394	$23,725	$262,819	-$9,417	$387,572

HOMER analysis indicated that the economic results with the presence of the wind turbines are slightly worse than the ones with no wind turbine, because the added initial CAPEX does not result in proportionally improved fuel savings; the systems has to coordinate the dispatch of a variable renewable energy source and this may cause the diesel genset to work off their optimal generation conditions.

4.5.1. Effect of Battery Energy Storage Systems (BESS)

Since the wind turbines do not improve the economics of the system, further simulations to determine the effect of Battery Energy Storage Systems (BESS) on the optimization of the system were conducted based on the wind system being excluded. BESS integration was therefore based only on the optimal design of the Base Case comprising diesel/solar hybrid as summarized in Table 4.16.

Table 0.16 Introduction of BESS in the Optimization Process of the Diesel/Solar Hybrid

Scenario	**Diesel**	**Solar**	**Wind**	**BESS**
Base Case	410 kW	30 kW	0 kW – 60 kW installed capacity is disregarded based on the lower economic viability of the revamped option	500 kWh to 1,300 kWh with a step of 50 kWh.

The resulting optimal configuration is formed by a 578 kWp PV generator, with a 206 kW inverter, a 1,328 kWh BESS capacity, and two diesel generators of 100 kW and 410 kW. The diesel generators total production is 339,665 kWh/year with a fuel consumption of 109,927 L/year. PV total energy production is 882,471 kWh/year and satisfies 68.4% of the load energy consumption, thanks also to the energy stored in the BESS.

There is still an excess of energy produced by the PV plant, corresponding to the cases when BESS are already fully charged and the production exceeds the consumption (usually, during the afternoon). Such excess is 82,071 kWh/year, corresponding to 6.7% of the total electricity generation (1,222,136 kWh/year) as summarized in Table 4.17 and Table 4.18. Additional findings from HOMER optimization are included in Appendix VII.

Table 0.17 Excess and Unmet Electricity Load of Optimized System (Diesel/Solar/Wind Hybrid)

Quantity	Value	Units
Excess Electricity from System	408,305	kWh/yr
Excess Electricity from Solar PV	82,071	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

With a COE of 0.305 US$/kWh and a NPC of US$6,507,321.53 this optimization scenario, compared to the current situation, reduces: (i) the diesel consumption by 281,358 L/(ii) the CO_2 emissions by 738,656 kg/year; and (iii) the emissions of other pollutants by 5,681 kg/year.

For this optimized system, the diesel fuel consumption statistics are summarized in Table 4.18, electricity production in Table 4.19 and the pollutants which comprise the total emissions reductions are shown in Table 4.20.

Table 0.18 Electricity Production of Optimized System (Diesel/Solar/Wind Hybrid)

Quantity	Value	Units
Total fuel consumed	206,747	L
Avg fuel per day	566	L/day
Avg fuel per hour	23.6	L/hour

Table 0.19 Electricity Production of Optimized System (Diesel/Solar/Wind Hybrid)

Component	Production (kWh/yr)	Percent
Generic solar PV (First optimization cycle)[13]	868,391	57.7
Generic solar PV (Last optimization cycle)	882,471	68.4
Generic 100 kW Fixed Capacity Genset	141,861	9.42
Kohler 410 kW Standby	495,937	32.9
Total	1,506,189	100

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[13] HOMER analysis prioritizes optimization of the financial parameters of the project over the system design specifications. As a result, there are minor deviations in the system sizing such as solar PV capacity varying from 569 kW to 578 kW; and inverter sizing varying from 193 kW to 206 kW. The values in the last optimization cycle are the final design and optimization parameters.

Table 0.20 System Emissions Summary of the Optimal System by Pollutant

Pollutant	Quantity	Unit
Carbon Dioxide	542,179	kg/yr
Carbon Monoxide	2,779	kg/yr
Unburned Hydrocarbons	149	kg/yr
Particulate Matter	14.5	kg/yr
Sulfur Dioxide	1,325	kg/yr
Nitrogen Oxides	290	kg/yr

4.6. General Findings on Sustainability

Further, in line with the IRENA guidelines, the optimization will positively impact several aspects which will contribute to the sustainability and efficacy of the minigrid. Table 4.21 highlights the general findings from that perspective.

Table 0.21 Performance of Habaswein Regarding IRENA indicators

Performance Indicator	Objectives	Accomplishment	Rationale
Effectiveness	Installed renewable energy capacity	Yes, partially	60 kW wind and 50 kW solar were installed to hybridize the diesel generation system.
	Increase in the renewable energy share of total power generation	Yes, partially	Between 2012 and 2016, 182,938 kWh of electricity was generated from solar and wind resources. There was electricity generation from the

Performance Indicator	Objectives	Accomplishment	Rationale
			renewable energy sources. However, the renewable energy penetration peaked at 12% and was as low as 0%
	Amount of diesel avoided	Yes	At an SFC of 0.43 litres per kWh[14], 78,663 litres of diesel were avoided.
	CO_2 emissions avoided as a result of the renewable energy solutions	Yes	At a CO_2 emissions factor of 2.32 Kg CO_2 per litre of diesel, 182.5 tons CO_2 were avoided.
Efficiency	Cost of fuel displaced by	Yes	At a cost of diesel of KSh. 106.2882[15], KSh. 8.36 million was saved.

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[14] Actual average SFC between January 2012 and December 2016

[15] Actual average cost of diesel between January 2012 and December 2015

Performance Indicator	Objectives	Accomplishment	Rationale
	renewable energy solutions		
Equity	Connection and distribution	Yes	All villages, households and businesses within proximity to the minigrid have been connected. Kenya Power is constructing more distribution networks
	Load shedding/rationing	Yes	Every village experiences scheduled rationing on a needs – basis when demand exceeds supply.
Institutional Feasibility	Acceptability of minigrid and hybridization policy	Yes	Minigrid electrification is viewed as fair and acceptable to locals

Performance Indicator	Objectives	Accomplishment	Rationale
			particularly in terms of quality of power and Kenya Power services. However, consumer awareness of hybridization was low.
	Administrative capacity, institutional and implementation arrangements.	No	There is limited capacity to manage renewable energy power generation in hybrid minigrids
	Economic realities	No	The socio-economic environment of the residents does not enable power supply and use to be maximized for

Performance Indicator	Objectives	Accomplishment	Rationale
			sustainable growth and development of the locality.
			Habaswein is a highly remote rural area, whose residents are primarily pastoralists with limited economic activities. Respondents with shops reported that sales and revenues were either the same or decreasing over time despite electricity use, increased hours of operation, and use of appliances. Anecdotal evidence suggests that household

Performance Indicator	Objectives	Accomplishment	Rationale
			incomes are limited and are primarily deployed for necessities, such as food, which are expensive due to distribution to Habaswein from other areas.
	Political feasibility	Yes	Commitment to universal energy access is assumed to be an overarching goal of all political administrations.
Replicability	Potential to be reproduced in other locations	Yes	Technology is mature Technical capacity to implement can be built

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The conclusions have been made in line with the specific objectives set out during the preparation of the research proposal. Further reflections on the findings indicate that the effectiveness of the Habaswein hybrid power generation station could be increased, and significant positive outcomes derived from the project, if a few issues are addressed. Regarding **solar and wind energy resource potential for power generation in Habaswein**; the resource potential was found to be high for both technology options. Solar irradiation in Wajir is high, averaging between 5-6 kWh/m^2/day, and the 30 kWp solar PV system could generate approximately 3,120 – 4,890 kWh per month on average. Further, wind speeds are high at 6.65 m/s, and the 60 kW wind system could generate approximately 9,849 kWh per month on average.

Regarding **performance evaluation of Habaswein power generation station**; renewable energy penetration is low and could be improved. The solar PV and wind systems were found to generate a total of only 149.3 kWh per day on average, and 4,547 kWh per month.

Peak renewable energy penetration was 12%, with solar PV peaking at 7% and wind peaking at 5% of electricity output. However, renewable energy penetration at the time of the study was 0%, as a result of factors including breakdowns of the wind turbines and failure of the solar PV system. Lack of technical training in design, implementation, and operation and maintenance of the renewable energy system are likely to have contributed to the decline of the penetration levels. Operations and maintenance are the most significant barriers to reliability, cost effectiveness and sustainability of the systems. Further because O&M are directly linked to the institutional framework of Kenya Power and Lighting Company, institutional feasibility and replicability are low at present and renewable energy capacity need to be built.

Finally, regarding **optimization of the Habaswein Power Station**, the impact of renewable energy integration is notable but inadequate, due to technical performance of the system. The technical performance of Habaswein power generation system needs to be addressed and improved by adopting the optimal design. Installation of the optimum design of the system consisting of 100 kW diesel generator to meet the base load, 410 kW diesel generator to meet the peak load (switch over option from 100 kW), and 578 kW solar PV would yield further significant impacts. With optimization of the system, 882,471 kWh per year could potentially be produced, displacing 281,358 litres of diesel – five times the current level. Under the optimal design, 739 tons CO_2 would be avoided per year compared to the current 182.5 tons CO_2. Under the optimal design, KSh. 40 million will be saved per year, compared to the current KSh. 8.36 million[16]. The study therefore concluded that hybrid systems indeed have the potential to contribute to meeting the demands of off grid customers and therefore the potential to reduce fuel costs for KPLC. They are effective, efficient, and equitable. Further, in tandem with addressing design, installation and operation and maintenance, interventions to improve the general business environment, create economic activities and increase the purchasing power of residents should be implemented.

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[16] Not considering capital cost of the system

In conclusion, the study recommends cessation of the 360 kW and 280 kW diesel generators operations, replacement with a new 100 kW generator and an additional 548 kW solar PV; complemented by training and capacity building of KPLC’s personnel in operation and maintenance (O&M). Further, the study emphasizes the need for future improvements to match the optimization findings of this robust design approach. Based on the accurate solar and wind resource data at the time of design, detailed study to inform optimal design of the system and O&M training, it is expected that malfunction of the system components will be avoided in the future. The study additionally recommends the use of automated and remote monitoring systems.

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APPENDICES

Appendix I: Existing Mini-grids in Kenya

NO.	STATION	MACHINE NO.	GENERATION SYSTEM TYPE	INSTALLED CAPACITY (KWp)[17]	YEAR OF INSTALLATIONS	TYPE OF FUEL USED	CONNECTION TYPE FOR RENEWABLE ENERGY
1	WAJIR	1	Diesel Engine SWDIESEL F240	673	1988	IDO[18]	RE proposed
		2	Diesel Engine SWDIESEL F240	673	1988	IDO	
		3	Diesel Engine Perkins 2500	400	2010	AGO[19]	

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[17] The renewable energy capacity is not included as it is not firm
[18] IDO - Industrial Diesel Oil
[19] AGO - Automotive Gas Oil

NO.	**STATION**	**MACHINE NO.**	**GENERATION SYSTEM TYPE**	**INSTALLED CAPACITY (KWp)[17]**	**YEAR OF INSTALLATIONS**	**TYPE OF FUEL USED**	**CONNECTION TYPE FOR RENEWABLE ENERGY**
				1746			
2	MANDERA	1	Diesel Engine Perkins 2500	400	2009	AGO	Direct connection to 11kV power line through a step-up transformer with no batteries
		2	Diesel Engine Perkins 2500	400	2009	AGO	
		3	Diesel Engine Perkins 2500	400	2007	AGO	
		4	Diesel Engine Perkins 2500	400	2007	AGO	
		S1	Solar[20]	300	2012		
				1,600			
3	MARSABIT	1	Diesel Engine Perkins 2500	400	2011	AGO	Direct connection to
		2	Diesel Engine Perkins 2500	400	2011	AGO	

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[20] Solar plants only operate during the day, unlike all other stations which operate for 24 hours a day

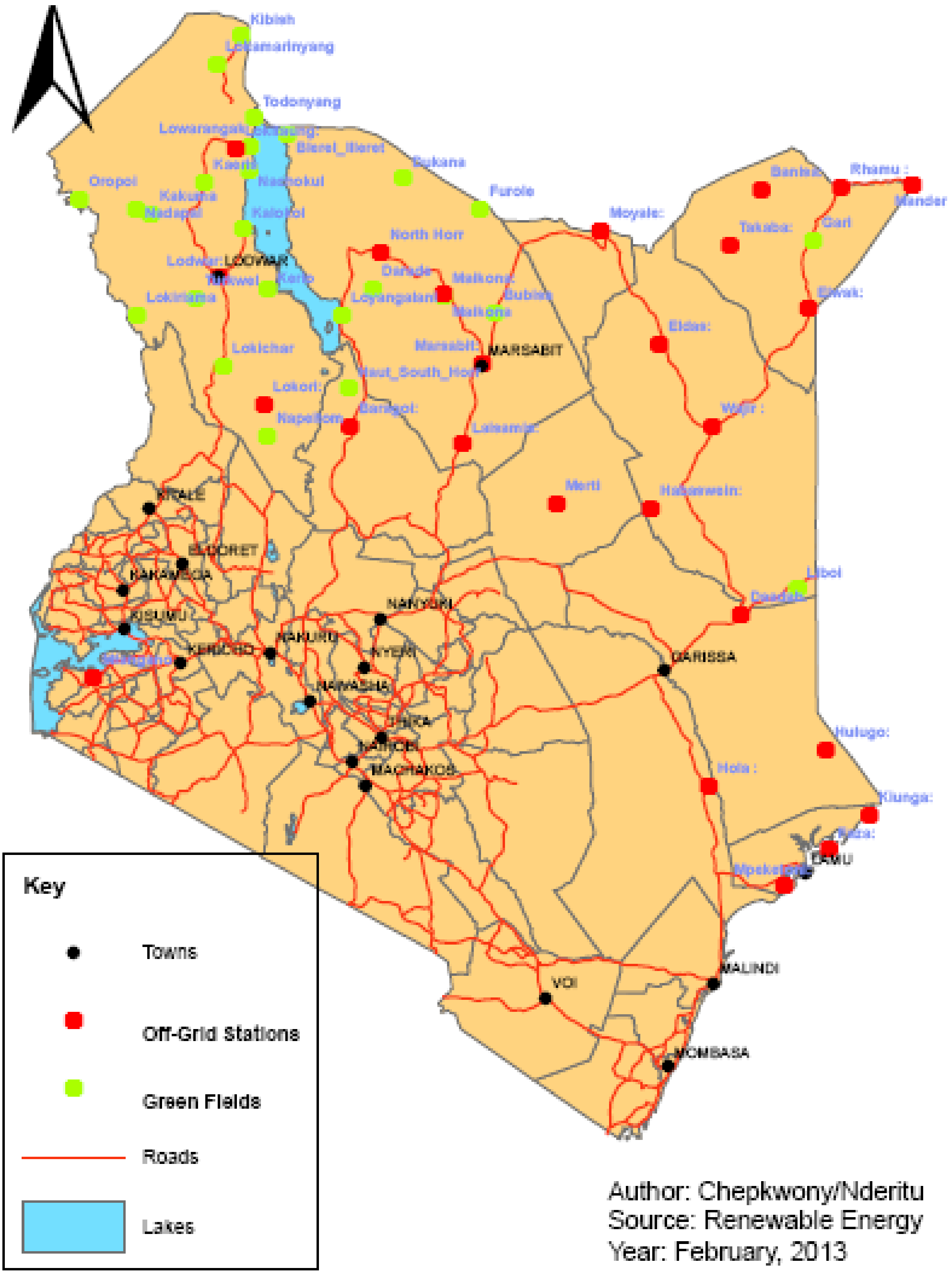
NO.	STATION	MACHINE NO.	GENERATION SYSTEM TYPE	INSTALLED CAPACITY (KWp)[17]	YEAR OF INSTALLATIONS	TYPE OF FUEL USED	CONNECTION TYPE FOR RENEWABLE ENERGY
		W1	Wind Turbine 1	250	2011		11kV power line through a step-up transformer with no batteries
		W2	Wind Turbine 2	250	2011		
				800			
4	LODWAR	2	Diesel Engine Perkins 2500	400	2010	AGO	Direct connection to the busbar with no batteries
		3	Diesel Engine Perkins 2200	240	2010	AGO	
		1	Diesel Engine Perkins 2500	400	2007	AGO	
		4	Diesel Engine Perkins 2500	400	2008	AGO	
		S1	Solar	60	2012		
				1440			

NO.	**STATION**	**MACHINE NO.**	**GENERATION SYSTEM TYPE**	**INSTALLED CAPACITY (KWp)[17]**	**YEAR OF INSTALLATIONS**	**TYPE OF FUEL USED**	**CONNECTION TYPE FOR RENEWABLE ENERGY**
5	HOLA	1	Diesel Engine Perkins 2500	400	2007	AGO	Direct connection to the busbar with no batteries
		2	Diesel Engine Perkins 2500	400	2007	AGO	
		S1	Solar	60	2012		
				800			
6	MERTI	1	Diesel Engine Perkins 1104	64	2007	AGO	Direct connection to the busbar with no batteries
		2	Diesel Engine Perkins 1104	64	2009	AGO	
		S1	Solar	10	2011		
				128			
7	HABASWEIN	1	Diesel Engine Perkins 2300	240	2010	AGO	Direct connection to
		2	Diesel Engine Deutz 500 kVA	410	2012	AGO	

NO.	STATION	MACHINE NO.	GENERATION SYSTEM TYPE	INSTALLED CAPACITY (KWp)[17]	YEAR OF INSTALLATIONS	TYPE OF FUEL USED	CONNECTION TYPE FOR RENEWABLE ENERGY
		S1	Solar	30	2012		the busbar with no batteries
		W1	Wind	50	2012		
				650			
8	ELWAK	1	Diesel Engine Perkins 2300	240	2010	AGO	Direct connection to the busbar with no batteries
		2	Diesel Engine Perkins 1106	120	2009	AGO	
		S1	Solar	50	2012		
				360			
9	BARAGOI	1	Diesel Engine Perkins 1104	64	2009	AGO	RE proposed
		2	Diesel Engine Perkins 1104	64	2009	AGO	
				128			

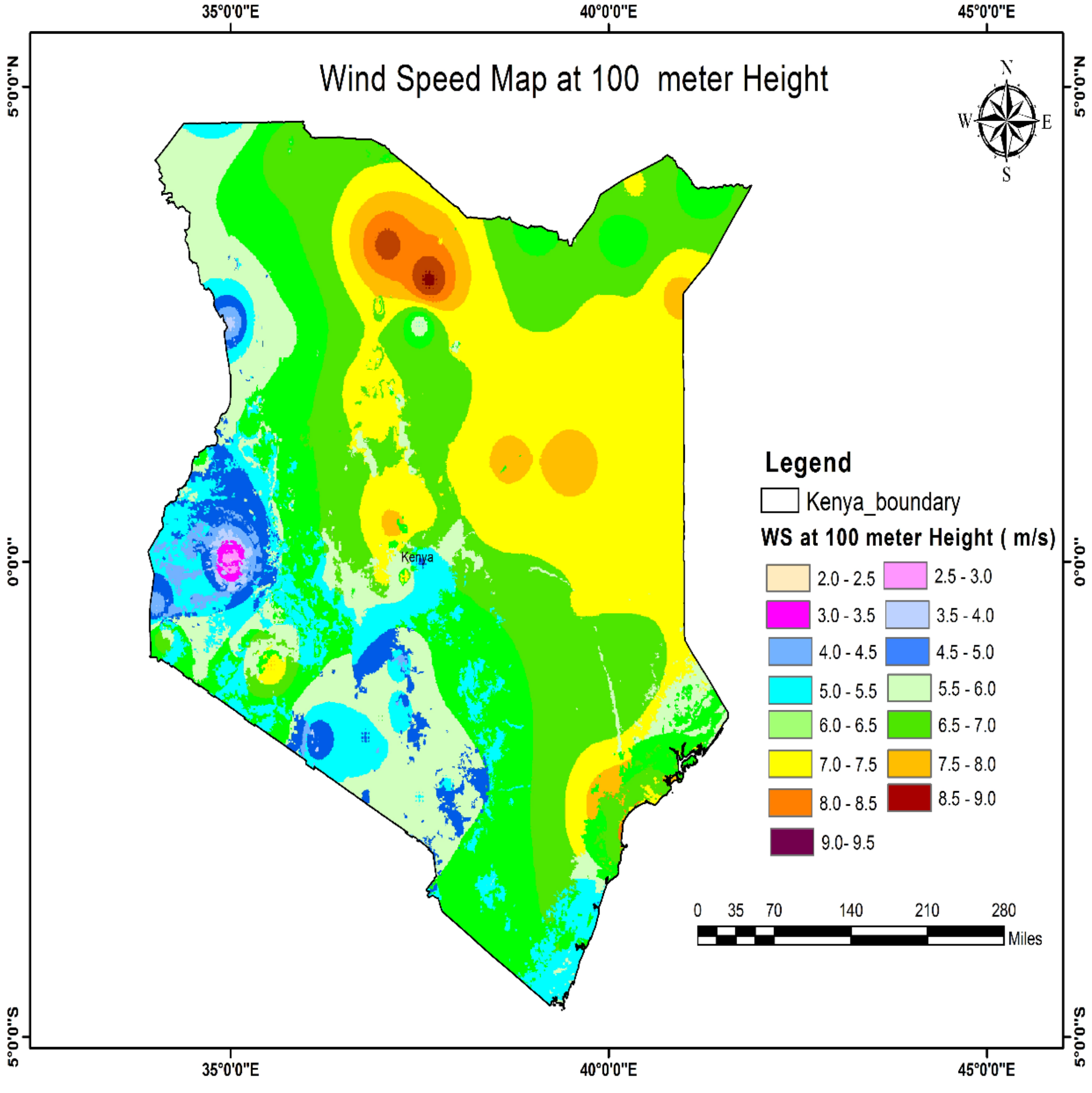
NO.	**STATION**	**MACHINE NO.**	**GENERATION SYSTEM TYPE**	**INSTALLED CAPACITY (KWp)[17]**	**YEAR OF INSTALLATIONS**	**TYPE OF FUEL USED**	**CONNECTION TYPE FOR RENEWABLE ENERGY**
10	MFANGANO	1	Diesel Engine Perkins 2500	64	2010	AGO	RE proposed
		2	Diesel Engine Perkins 1104	120	2010	AGO	
		3	Perkins 2500	400	2010		
				584			

Appendix II: Locations of Off-grid Power Stations

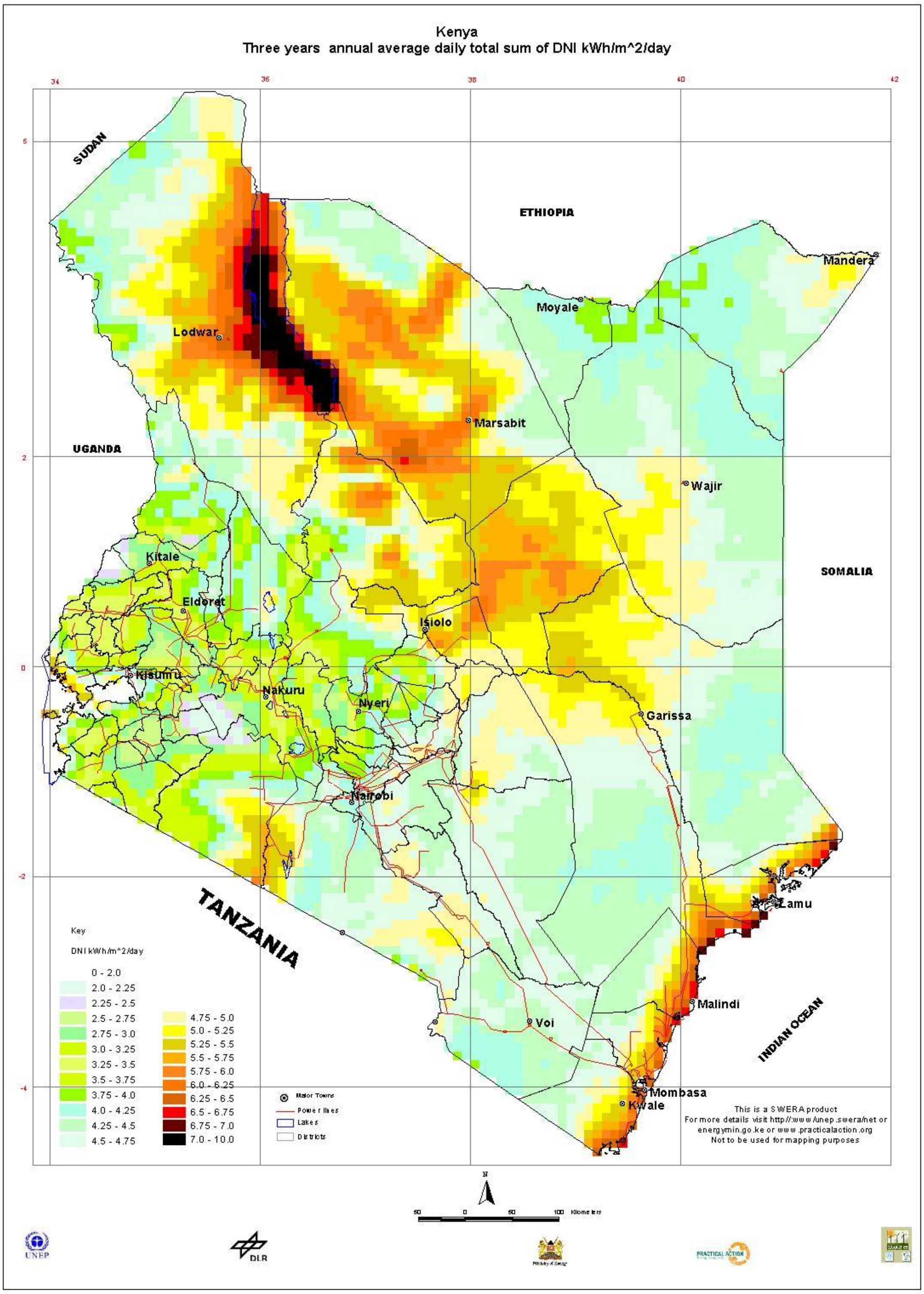


Author: Chepkwony/Nderitu
Source: Renewable Energy
Year: February, 2013

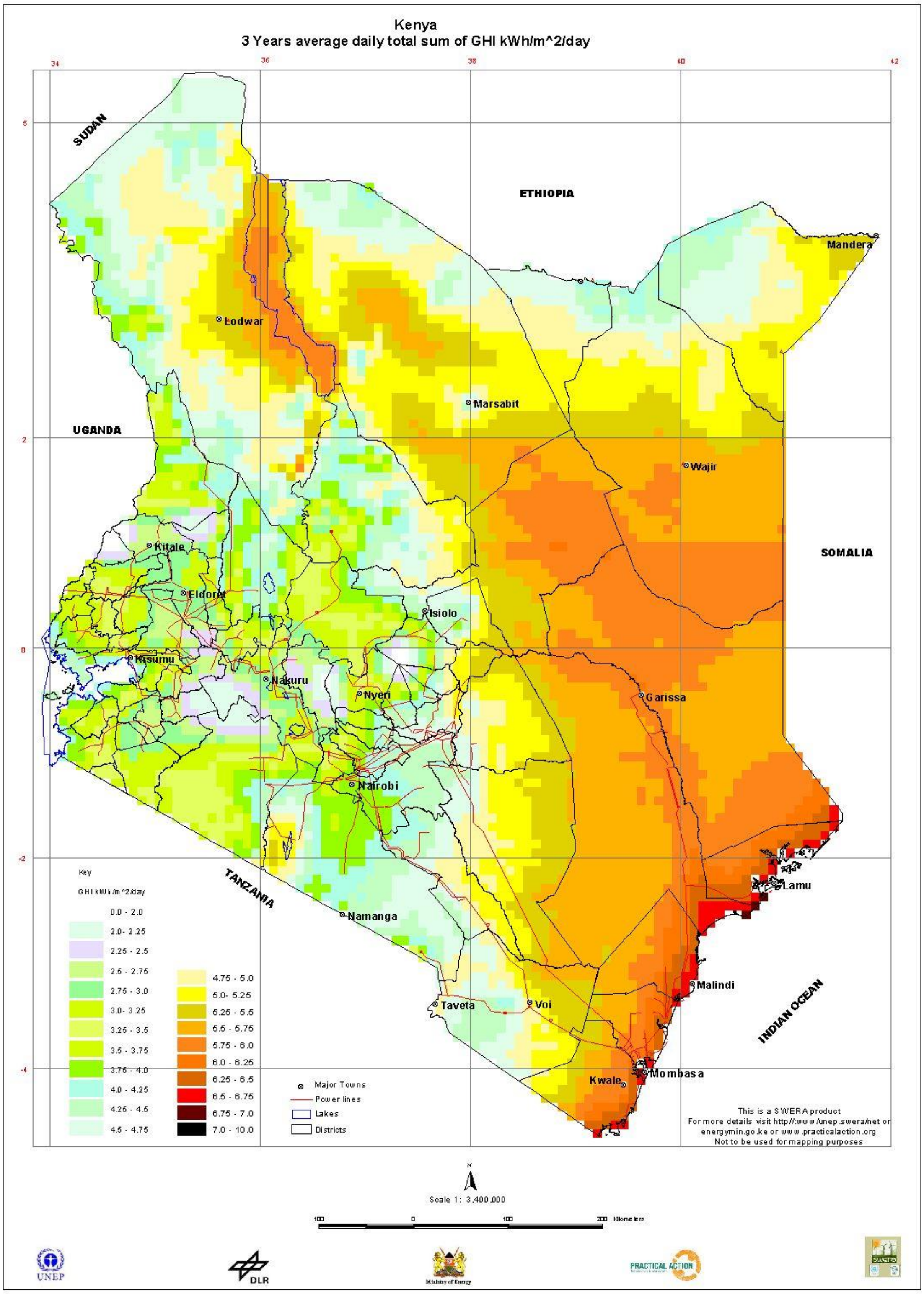
Appendix III: Wind Energy Resource Map



Appendix IV: Solar Energy Resource Potential (DNI)



Appendix V: Solar Energy Resource Potential (GHI)



Appendix VI: Survey A - Questionnaire for Village Representative

A1	Village Coordinates:	Lat:	Long:
A2	Village/Town Name:		
A3	Village/Town Population:		
B1	How many of each type of building is in the village and connected to the power station?		

	Total Number in Village	Number Connected to Power Station
1. Households		
2. Businesses		
3. Places of Worship		
4. Health Centers		
5. Schools		

C1	What are the current energy source(s) and uses for households

Sources	Uses	Approx monthly cost (KSh)
1. Electricity (mini-grid)	(i) (ii) (iii)	(i) (ii) (iii)
2. Electricity (Solar home system)	(i) (ii) (iii)	(i) (ii) (iii)

3. Kerosene	(i) (ii) (iii)	(i) (ii) (iii)
4. Charcoal	(i) (ii) (iii)	(i) (ii) (iii)
5. Firewood	(i) (ii) (iii)	(i) (ii) (iii)
6. LPG	(i) (ii) (iii)	(i) (ii) (iii)
7. Wind	(i) (ii) (iii)	(i) (ii) (iii)
8. Diesel Generator	(i) (ii) (iii)	(i) (ii) (iii)
9 .Other (specify ________________)	(i) (ii) (iii)	(i) (ii) (iii)
D1	What are the existing commercial activities in this Centre?	

	Total No. in Village	No. connected to power station
1. Retail Kiosks/Shops		
2. Restaurants/Cafes/Food Kiosks		
3. Pubs/Local joints		
4. Barber/Salon		
5. Mobile charging		
6. Welding		
7. Posho mill		
8. Agro Vets		
9. Slaughter House		
10. Boutiques/Tailoring Shops		
11. M-Pesa outlets		
12. Chemist		
13. Electronics Shop/Repairs		
14. Mechanics		
15.		
16.		
17.		
18.		

E1	What are the challenges facing commercial activities in this area?

F1	What are the commercial activities if optimization and expansion of the mini-grid is undertaken?

Appendix VII: Survey B – Questionnaire for Individual Business Connections

A1	What is your opinion on level of quality of service from the electricity connection?		
1	Very Good	O	Please explain your answer below.
2	Good	O	
3	Fair	O	
4	Poor	O	
5	Very Poor	O	

B1	Which of the following are you aware off?			
		Yes	No	Not Sure
1	How the electricity is produced?	O	O	O
2	How much a unit costs?	O	O	O
3	How long a kWh unit lasts?	O	O	O
4	Cost of running different appliances?	O	O	O
5	Poor health side effects from Kerosene?	O	O	O

C1	Has the following decreased, increased or stayed the same since grid connection?			
		Decreased	Stayed the same	Increased

1	Income	O	O	O
2	Expenditure	O	O	O
3	Net profit	O	O	O
4	Opening hours	O	O	O
5	Land price/renting cost	O	O	O
6	Number of customers	O	O	O
7	Electrical appliances owned	O	O	O
8	Services offered by your business	O	O	O
9	Hours of electricity use	O	O	O

D1 How often does the power plant turn off?

1. Daily O 2. Weekly O 3. Monthly O 4. Yearly O 5. Never O

E1 Have you noticed any change since you started using power from solar/ wind?

F1 What is your general feeling for the use of solar and wind to the power station?

Appendix VIII: List of Respondents

	Village	**Division**	**Name**	**Role**
1	Adamasajida	Habaswein	Hassan Kusow	Adamasajida Village Central Borehole and Hadodo South Village Borehole Chairman (0729657883)
2	Bulandege	Habaswein	Adan Abdi Madey	Chief
3	Bulajuu	Habaswein	Mahmoud Ahmed	Elder, Ramu Resident 5 years
4	Central	Habaswein	Khalif Sirat Farrah	Chief
5	Central	Habaswein	Yunis Bishar Ismail	Kenya Power Area Business Manager – Habaswein Division
6	Central	Central	Amin Bishar	Kenya Power County Business Manager – Wajir County
7	Central	Central	Hassan	Kenya Power County Relationship Officer – Wajir County
8	Central	Habaswein	Adan	Kenya Power Personnel
9	Central	Habaswein	Peter Ouma	Kenya Power Personnel
10	Central	Habaswein	George Maina	Kenya Power Personnel

	Village	**Division**	**Name**	**Role**
11	Central	Habaswein	Timothy Mutuku	Kenya Power Personnel
12	Central	Habaswein	Timothy Chemai	Kenya Power Personnel

Appendix IX: Sample of Solar PV Electricity Output Data for 2012

	Actual Electricity Output (kW) of 30kWp Solar PV System												
TIME	Jan Tot	Feb Tot	Mar Tot	Apr Tot	May Tot	Jun Tot	Jul Tot	Aug Tot	Sep Tot	Oct Tot	Nov Tot	Dec Tot	Annual Tot
12:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
1:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
1:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
2:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
2:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
3:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
3:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
4:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
4:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
5:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
5:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
6:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
6:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
7:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
7:30:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
8:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
8:30:00 AM	0	18	0	6	0	0	0	0	0	0	0	0	24
9:00:00 AM	0	36	8	12	0	0	0	0	0	0	0	0	56
9:30:00 AM	0	138	42	14	0	0	0	0	0	0	0	0	194
10:00:00 AM	0	156	36	14	0	0	0	0	0	0	0	0	206
10:30:00 AM	0	210	56	16	0	0	0	0	0	0	0	0	282
11:00:00 AM	0	220	42	20	0	0	0	0	0	0	0	0	282
11:30:00 AM	0	240	52	18	0	0	0	0	0	0	0	0	310
12:00:00 PM	0	260	48	18	0	0	0	0	0	0	0	0	326
12:30:00 PM	0	285	52	20	0	0	0	0	0	0	0	0	357
1:00:00 PM	0	272	56	20	0	0	0	0	0	0	0	0	348
1:30:00 PM	0	260	76	20	0	0	0	0	0	0	0	0	356
2:00:00 PM	0	260	70	20	0	0	0	0	0	0	0	0	350
2:30:00 PM	0	286	66	12	0	0	0	0	0	0	0	0	364
3:00:00 PM	0	273	66	10	0	0	0	0	0	0	0	0	349
3:30:00 PM	0	220	54	8	0	0	0	0	0	0	0	0	282
4:00:00 PM	0	230	54	6	0	0	0	0	0	0	0	0	290
4:30:00 PM	0	174	38	8	0	0	0	0	0	0	0	0	220
5:00:00 PM	0	152	26	8	0	0	0	0	0	0	0	0	186
5:30:00 PM	0	106	22	8	0	0	0	0	0	0	0	0	136
6:00:00 PM	0	85	20	4	0	0	0	0	0	0	0	0	109
6:30:00 PM	0	58	14	4	0	0	0	0	0	0	0	0	76
7:00:00 PM	0	38	4	2	0	0	0	0	0	0	0	0	44
7:30:00 PM	0	20	0	0	0	0	0	0	0	0	0	0	20
8:00:00 PM	0	4	0	0	0	0	0	0	0	0	0	0	4
8:30:00 PM	0	4	0	0	0	0	0	0	0	0	0	0	4
9:00:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
9:30:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
8:00:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
10:30:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
11:00:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
11:30:00 PM	0	0	0	0	0	0	0	0	0	0	0	0	0
12:00:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Electricity Output (kWh)	**0**	**2002.5**	**451**	**134**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2587.5**

Appendix X: Performance of a Generic 100 kW Fixed Capacity Genset (Diesel)

Generic 100 kW Fixed Capacity Genset Electrical Summary		
Quantity	**Value**	**Units**
Electrical Production	141,861	kWh/yr
Mean Electrical Output	52.2	kW
Minimum Electrical Output	25.0	kW
Maximum Electrical Output	90.0	kW
Generic 100 kW Fixed Capacity Genset Fuel Summary		
Quantity	**Value**	**Units**
Fuel Consumption	43,507	L
Specific Fuel Consumption	0.307	L/kWh
Fuel Energy Input	428,107	kWh/yr
Mean Electrical Efficiency	33.1	%
Generic 100 kW Fixed Capacity Genset Statistics		
Quantity	**Value**	**Units**
Hours of Operation	2,720	hrs/yr
Number of Starts	975	starts/yr
Operational Life	5.51	yr
Capacity Factor	16.2	%
Fixed Generation Cost	8.25	$/hr
Marginal Generation Cost	0.324	$/kWh

Appendix XI: Performance of Kohler 410 kW Standby (Diesel)

Kohler 410 kW Standby Electrical Summary		
Quantity	**Value**	**Units**
Electrical Production	495,937	kWh/yr
Mean Electrical Output	126	kW
Minimum Electrical Output	102	kW
Maximum Electrical Output	292	kW

Kohler 410 kW Standby Fuel Summary		
Quantity	**Value**	**Units**
Fuel Consumption	163,241	L
Specific Fuel Consumption	0.329	L/kWh
Fuel Energy Input	1,606,287	kWh/yr
Mean Electrical Efficiency	30.9	%

Kohler 410 kW Standby Statistics		
Quantity	**Value**	**Units**
Hours of Operation	3,933	hrs/yr
Number of Starts	602	starts/yr
Operational Life	3.81	yr
Capacity Factor	13.8	%
Fixed Generation Cost	17.8	$/hr
Marginal Generation Cost	0.344	$/kWh

Appendix XII: Performance of a Generic Solar PV

Generic solar PV Electrical Summary		
Quantity	**Value**	**Units**
Minimum Output	0	kW
Maximum Output	449	kW
PV Penetration	80.8	%
Hours of Operation	4,377	hrs/yr
Levelized Cost	0.0791	$/kWh
Generic solar PV Statistics		
Quantity	**Value**	**Units**
Rated Capacity	569	kW
Mean Output	99.1	kW
Mean Output	2,379	kWh/d
Capacity Factor	17.4	%
Total Production	868,391	kWh/yr

Appendix XIII: System Converter Summary

System Converter Electrical Summary		
Quantity	**Value**	**Units**
Hours of Operation	4,332	hrs/yr
Energy Out	440,770	kWh/yr
Energy In	463,968	kWh/yr
Losses	23,198	kWh/yr
System Converter Statistics		
Quantity	**Value**	**Units**
Capacity	193	kW
Mean Output	50.3	kW
Minimum Output	0	kW
Maximum Output	193	kW
Capacity Factor	26.1	%