DESIGN AND OPTIMIZATION OF A RENEWABLE ENERGY BASED SMART MICROGRID FOR RURAL ELECTRIFICATION

A THESIS SUBMITTED TO THE UNIVERSITY OF MANCHESTER
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN THE FACULTY OF SCIENCE & ENGINEERING

2020

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Abstract

The University of Manchester
Jane Namaganda-Kiyimba
Doctor of Philosophy
Design and Optimization of a Renewable Energy Based Smart Microgrid for Rural Electrification
October, 2020

Over 1.5 billion people in the world today are still without access to electricity with many of them living in rural and remote areas that are far away from the national main grid. A large number of these people are in developing countries located in Africa and Asia. Provision of sustainable forms of clean energy sources including electricity to these people is a continuing global developmental challenge that needs to be addressed. While a number of rural electrification projects have been undertaken in these developing countries, it has been noted that many are not sustainable hence they do not survive beyond the initial donor funding phase. Robust metrics to measure sustainability of such projects are still lacking. In this thesis, research is carried out to examine the sustainability of rural microgrids and then develop metrics to enhance how sustainability can be measured for these types of projects. The research further seeks to formulate and design an optimum, robust, sustainable and economical solar PV based microgrid solution for electrification of a remote area focusing on green areas that currently have no access to electricity. The objective is to achieve a system that is cost effective, reliable and sustainable.

First, an examination of the issues surrounding microgrids for rural electrification is carried out with a major focus on the sustainability challenges. Informed by this examination, the important factors to consider when evaluating sustainability are presented and an easy to use sustainability evaluation tool kit is proposed and tested against three microgrid projects.

Since establishment of an off-grid rural electrification system requires accurate prediction of the electrical load so as to have a sustainable system that can meet the electrical needs of the community, an evaluation of the efficacy of the current methods for load estimation was carried out as a critical component of this work. An improved load estimation approach that yields more accurate load estimates has been proposed. Load characteristics that take account of the influence of gender as well as changes in customer habits on estimated load are investigated using the Markov Chain process. MATLAB software is used to generate load profiles. The results show that gender considerations have a significant impact on load profiles and a higher consumption is obtained when gender is considered. Next, an efficient and robust sizing approach for off-grid PV microgrid systems has been developed and named the ComµGrid Sizing Approach. This approach utilizes “Mixed Integer Linear Programming (MILP)” to optimally size the PV microgrid and the “Density Based Spatial Clustering of Applications with Noise (DBSCAN)” algorithm to aggregate load and meteorological data. MATLAB software is used to execute the optimization algorithm. The results show that the proposed method yields a reliable and less expensive system and that it is possible to achieve accuracy and a faster convergence to the solution with this approach.

Lastly, an investigation of affordability of community microgrids is carried out since affordability is essential for their sustainability and effective utilisation of the services they offer. The critical elements that have to be considered when designing microgrids for rural communities are addressed with the aim of reducing the overall cost of electricity.
Declaration

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Dedication

To my wonderful husband Hubert and our lovely children Leon, Leyna, Lanelle and Leandra.
Acknowledgements

First and foremost, I am very grateful to the Almighty God for the precious gifts of life, good health, wisdom, knowledge and understanding which have enabled me to successfully carry out and complete this research. James 1:17, "Every good and perfect gift is from above, coming down from the Father of the heavenly lights, who does not change like shifting shadows." God’s abundant grace and unconditional love for me has sustained me daily and made all this possible. I express my sincere gratitude to my main supervisor Prof. Joseph Mutale for his dedication, continuous support, mentorship, guidance and assistance throughout my PhD studies. His vast knowledge, expertise and valuable advice helped me to make continuous progress in my research. I am grateful for his willingness and openness to share this wealth of knowledge during our meetings and discussions. He has inspired me greatly, guided my steps and set me on the path for lifelong scientific research. I also thank my co-supervisor Prof. Prof. Vladimir Terzija and advisor Prof. Ian Cotton for their advice and support.

I would like to thank the UK government’s Department for International Development (DFID) that has funded my PhD studies at The University of Manchester through the Commonwealth Scholarship Commission in the UK. Without this financial support I would not have been able to pursue postgraduate studies in the UK. Thank you for the faith you had in me and willingness to invest in my further education.

I am extremely grateful to my friends and colleagues; Anita, Anna, Carlos, Etete, James, Jelena, Kelly, Mahmoud, Melake, Melike, Mingyu, Mohamad, Naim, Nzube, Siwei, Steve, Trevor, Yucong, Yushi and Zhong; in the Department of Electrical and Electronic Engineering at The University of Manchester who made my research experience an enjoyable and memorable one. In a special way I thank all the members with whom I have served on the committee of the IEEE PES Student Branch Chapter at the university. You have made a positive impact on my life and I will forever cherish the special times we had together.
My sincere and heartfelt thanks go to my dear loving husband Hubert and our treasured children Leon, Leyna, Lanelle and Leandra who have consistently supported, offered encouragement, prayed and cheered me on throughout this PhD journey. I am grateful for the many sacrifices they have made daily to see that I complete my PhD. Your love, understanding and support have enabled me to stay the course. I am also very grateful to my devoted parents and dear siblings who have always supported, encouraged, advised and motivated me to pursue my dreams and keep aiming higher. I also thank my in-laws for their love, encouragement and support that have been very instrumental on this PhD journey. I would also like to thank my very special close friends back in Uganda who have always been there for me and encouraged me during my PhD studies. I am also grateful to my old and new friends in the UK that have constantly checked on me and my family and offered words of encouragement and advice on life in the UK throughout the time I have spent studying for my PhD. Thank you all so much and I love you all.

I am grateful to my employer Makerere University for granting me study leave and allowing me the opportunity to pursue my PhD studies at the University of Manchester. I am also grateful to my colleagues in the Department of Electrical and Computer Engineering at Makerere University for the encouragement throughout my PhD studies. I will forever be grateful to Prof. Francis F. Tusubira, Prof. James P. Ntozi, Prof. Sandy S. Tickodri-Togboa, Assoc. Prof. Richard Okou and Prof. Udaykumar R. Yarragati who continuously encouraged me to enrol for PhD studies, remained interested in my progress on the programme after I had started and for their overall mentorship.

Last but not least, I would like to thank members of The University of Manchester Alumni Association in Ugandan for the advice, moral support and encouragement offered to me and fellow Ugandan students during our stay in Manchester. This support helped me to create a balanced, enjoyable and meaningful life at the university.

May the Almighty God bless every one of you abundantly throughout your life.
"Let your old age be childlike, and your childhood like old age; that is, so that neither may your wisdom be with pride, nor your humility without wisdom."

— St. Augustine
Publications


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<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>LLP</td>
<td>Loss of Load Probability</td>
</tr>
<tr>
<td>LCE</td>
<td>Levelised Cost of Energy</td>
</tr>
<tr>
<td>SDG</td>
<td>Sustainable Development Goals</td>
</tr>
<tr>
<td>GoU</td>
<td>Government of Uganda</td>
</tr>
<tr>
<td>ATLCC</td>
<td>Annualized Total Life Cycle Cost</td>
</tr>
<tr>
<td>JICA</td>
<td>Japan International Cooperation Agency</td>
</tr>
<tr>
<td>HOMER</td>
<td>Hybrid Optimization of Multiple Energy Resources</td>
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<tr>
<td>DBSCAN</td>
<td>Density Based Spatial Clustering of Applications with Noise</td>
</tr>
<tr>
<td>MILP</td>
<td>Mixed Integer Linear Programming</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of Discharge for the Battery</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Alpha</td>
<td>PV panel temperature coefficient</td>
</tr>
<tr>
<td>Bat</td>
<td>Total number of Batteries</td>
</tr>
<tr>
<td>Bat_{ceff}</td>
<td>Battery Charging Efficiency</td>
</tr>
<tr>
<td>Bat_{deff}</td>
<td>Battery Discharging Efficiency</td>
</tr>
<tr>
<td>Bat_{AH}</td>
<td>AH rating of one Battery</td>
</tr>
<tr>
<td>Bat_{cap}</td>
<td>Battery Storage Capacity (AH)</td>
</tr>
<tr>
<td>Bat_{max}</td>
<td>Maximum Number of Batteries</td>
</tr>
<tr>
<td>Bat_{max_par}</td>
<td>Maximum number of Batteries in Parallel</td>
</tr>
<tr>
<td>Bat_{min}</td>
<td>Minimum Number of Batteries</td>
</tr>
<tr>
<td>Bat_{par}</td>
<td>Number of Batteries in Parallel</td>
</tr>
<tr>
<td>Bat_{ser}</td>
<td>Number of Batteries in Series</td>
</tr>
<tr>
<td>C_{Bat}</td>
<td>Cost of Battery</td>
</tr>
<tr>
<td>C_{Bata}</td>
<td>Annualized capital maintenance cost and replacement cost of the batteries</td>
</tr>
<tr>
<td>C_{CC}</td>
<td>Capital Cost of Batteries</td>
</tr>
<tr>
<td>C_{CW}</td>
<td>Total capital costs for other components</td>
</tr>
<tr>
<td>C_{D}</td>
<td>Capital cost of the disposable components</td>
</tr>
<tr>
<td>C_{OC}</td>
<td>Total capital costs for other components aside PV and Batteries</td>
</tr>
</tbody>
</table>
\( CC_{OCa} \quad Annualized \ Capital \ costs \ of \ other \ components \)

\( CC_{PV} \quad Capital \ Cost \ of \ PV \ modules \)

\( CC_{TR} \quad Capital \ Cost \ of \ transformers \)

\( C_{PV} \quad Cost \ of \ one \ PV \ module \)

\( C_{PVA} \quad Annualized \ capital \ and \ maintenance \ cost \ of \ the \ PV \ modules \)

\( CS_a \quad Annualized \ salvage \ value \ of \ the \ system \)

\( C_{TRA} \quad Annualized \ capital \ and \ maintenance \ cost \ of \ the \ transformers \)

\( C_{Tr} \quad Cost \ of \ one \ transformer \)

\( Ctrler_{ldAmps} \quad Maximum \ DC \ Load \ Amps \ that \ controller \ must \ handle \)

\( Ctrler_{SCC} \quad Controller \ short \ circuit \ current \)

\( Ctrler_{Sel} \quad Controller \ current \ rating \)

\( Ctrler_{Total} \quad Number \ of \ Charge \ Controllers \ in \ operation \ during \ the \ system \ lifetime \)

\( Ctrler_{V} \quad Voltage \ rating \ of \ the \ controller \)

\( Desired_{LLP} \quad Desired \ Loss \ of \ Load \ Probability \)

\( DOD \quad Depth \ of \ Discharge \ for \ the \ Battery \)

\( D_{aut} \quad Days \ of \ Autonomy \)

\( E_{TOT} \quad Total \ energy \ consumed \ by \ the \ load \ from \ the \ system \ per \ year \)

\( fr \quad Inflation \ Rate \)

\( I_{ch}(t) \quad Battery \ Charge \ Current \ at \ time \ (t) \)

\( I_{def}(t) \quad Deficit \ Current \ at \ time \ (t) \)

\( I_{dis}(t) \quad Battery \ Discharge \ Current \ at \ time \ (t) \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$I_{\text{inv}}$</td>
<td>Inverter current rating</td>
</tr>
<tr>
<td>$I_{\text{mp}}$</td>
<td>Peak Amps per module at STC</td>
</tr>
<tr>
<td>$I_{L(t)}$</td>
<td>Load demand current at time (t)</td>
</tr>
<tr>
<td>$I_{\text{PV}(t)}$</td>
<td>Output current of a single PV module at time (t)</td>
</tr>
<tr>
<td>$I_{\text{PV}(t)}$</td>
<td>Total output current of the PV array at time (t)</td>
</tr>
<tr>
<td>$I_{\text{sc}}$</td>
<td>PV Module Short Circuit Current</td>
</tr>
<tr>
<td>$I_{\text{sur}(t)}$</td>
<td>Surplus Current at time (t)</td>
</tr>
<tr>
<td>$i_r$</td>
<td>Real Interest Rate</td>
</tr>
<tr>
<td>$L_{\text{Bat}}$</td>
<td>Lifetime of the Battery</td>
</tr>
<tr>
<td>$L_{\text{PV}}$</td>
<td>PV system Lifetime</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Microgrid System Lifetime</td>
</tr>
<tr>
<td>$L_{\text{TR}}$</td>
<td>Lifetime of the transformer</td>
</tr>
<tr>
<td>$L_{\text{C}}$</td>
<td>Sum of annualized capital, annualized maintenance and annualized replacement costs</td>
</tr>
<tr>
<td>$L_{\text{CE}}$</td>
<td>Levelized cost of energy</td>
</tr>
<tr>
<td>$LLP$</td>
<td>Loss of Load Probability</td>
</tr>
<tr>
<td>M</td>
<td>A large number</td>
</tr>
<tr>
<td>ndr</td>
<td>Net of discount inflation rate</td>
</tr>
<tr>
<td>$\text{Max}_{\text{DCAC}}$</td>
<td>Maximum Continuous Direct Current of the controller</td>
</tr>
<tr>
<td>$\text{MCC}_{\text{Bat}}$</td>
<td>Maintenance cost of batteries</td>
</tr>
<tr>
<td>$\text{MCC}_{\text{PV}}$</td>
<td>Maintenance cost of PV modules</td>
</tr>
</tbody>
</table>
\( \text{MCC}_{\text{TR}} \) \hspace{1cm} \text{Maintenance cost of transformers}

\( \text{N}_{\text{TR}} \) \hspace{1cm} \text{Number of transformers}

\( P_c \) \hspace{1cm} \text{Total Connected AC Power}

\( \text{PSH} \) \hspace{1cm} \text{Peak sun hours per day}

\( \text{PV} \) \hspace{1cm} \text{Number of PV Modules}

\( \text{PV}_{\max} \) \hspace{1cm} \text{Maximum Number of PV Modules}

\( \text{PV}_{\max, \text{par}} \) \hspace{1cm} \text{Maximum Number of PV Modules in Parallel}

\( \text{PV}_{\min} \) \hspace{1cm} \text{Minimum Number of PV Modules}

\( \text{PV}_{\text{par}} \) \hspace{1cm} \text{Number of PV Modules in Parallel}

\( \text{PV}_{\text{ser}} \) \hspace{1cm} \text{Number of PV Modules in Series}

\( S(t) \) \hspace{1cm} \text{Solar Radiation}(W/m^2) \text{ at time (t)}

\( \text{SF} \) \hspace{1cm} \text{safety factor}

\( \text{SOC}(t) \) \hspace{1cm} \text{Battery State of Charge}

\( \text{STC} \) \hspace{1cm} \text{Standard Test Conditions}

\( T(t) \) \hspace{1cm} \text{Ambient Temp (°C) at time (t)}

\( \text{V}_{\text{dc}} \) \hspace{1cm} \text{DC System voltage}

\( \text{V}_{\text{mp}} \) \hspace{1cm} \text{Nominal Module Voltage (Voltage at MPP under STC)}

\( \text{Y}_{\text{Bat}} \) \hspace{1cm} \text{Number of times of Battery Replacement}

\( \text{Z} \) \hspace{1cm} \text{Average Daily Load (Amp-Hour per Day)}

\( \varphi_{\text{ch}}(t) \) \hspace{1cm} \text{Binary variable for charging mode}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi_{\text{ch.sur}} )</td>
<td>Binary variable for the charge/surplus mode</td>
</tr>
<tr>
<td>( \phi_{\text{dis}(t)} )</td>
<td>Binary variable for discharging mode</td>
</tr>
<tr>
<td>( \phi_{\text{dis.def}} )</td>
<td>Binary variable for the discharge/deficit mode</td>
</tr>
<tr>
<td>( \eta_{\text{bat}} )</td>
<td>Battery Efficiency</td>
</tr>
</tbody>
</table>
Chapter One

Introduction

This chapter presents an overview of the current issues in the global development challenge of lack of access to electricity with a major focus on developing countries. An overview of the role microgrids can be expected to play in tackling this challenge is presented with a major focus on the critical issues involved in sustainable microgrids for rural electrification. The main objectives and contributions of this work are summarised. Lastly, an outline of the structure of this PhD thesis is provided.

1.1 Background and Motivation

In excess of 1.5 billion people in the world today are still without access to electricity. Access to electricity is one of the major factors that contribute to economic growth of an area or country at large. With increased level of electrification, people’s standards of living are improved and numerous opportunities open up due to the availability of electric power. Provision of sustainable forms of clean energy including electricity is a continuing global developmental challenge. Rural electrification is a major concern in most developing countries especially those in Africa and Asia [1] as a large proportion of their population live in remote areas that are far away from the main grid. An example is Uganda which is the country of origin of the author of this thesis, in which 83% of the population lives in rural areas with the remaining portion living in urban areas [2].

These people living in rural areas depend on other sources of energy such as biomass, candles, kerosene, and diesel generators which are known to be dangerous to the environment. The pollution from these fossil based sources of energy is a major contributor to the global warming problem faced in the world today. These kerosene lamps that people in these rural areas use also affect their health due to the fumes emitted. Accidents from fire due
to use of kerosene lamps have been reported in various rural communities in Africa and India. In addition, a large percentage of the people living in these rural communities depend on agriculture as a source of living but are not able to commercialise their agricultural produce because of the lack of value addition (local advanced processing of the cash crops and animal products to make them more marketable instead of just the basic processing or bare minimum required for sale to the next part of the value chain in addition to preservation of these products). The value addition is not fully possible due to lack of access to electricity.

Rural electrification refers to the means and process of electrifying rural and remote areas [3]. In most cases, in addition to pausing technical challenges, it is costly and inefficient to extend the main grid to remote areas hence the need for developing countries to find alternative means for rural electrification. This has led to focus being put on microgrids especially those that utilise renewable energy resources. Microgrids are viewed as a possible solution due to their ability to function independently from the main grid and because they can also be designed to interconnect with the main grid should there be an opportunity for extension of the grid to the remote community in the future. Various projects have been undertaken in various developing countries to address the issue of lack of access to electricity. In Africa where most of the countries have extremely low electrification rates, microgrids have been set up to try and bring electricity to people living in villages. These microgrids utilise both conventional fuels and renewable resources. The majority are based on Solar PV deployed in areas that are isolated from the main grid [4]. Examples of these microgrids include a 27.3 kW microgrid in Cape Verde serving 60 homes in the Santo Antao Island. In Uganda, a microgrid was installed in Kasese District and it serves 88 households, a hotel and a video hall [5]. PowerGen, a private company based in Kenya has implemented a number of microgrid projects within the African region. Examples of these include microgrids in Ololailumtia Village that supplies power for lighting, TV, refrigeration to households and medical clinics. There is also a microgrid in Sinda Village, Zambia that brings power to 35 households [6]. Table 1.1 below gives additional details of some of these microgrids that have been established.
Table 1.1: Some Examples of Microgrids Established in Africa

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Country</th>
<th>Capacity</th>
<th>Fuel Source(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Santo Antao Island [7]</td>
<td>Cape Verde</td>
<td>27.3 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>2</td>
<td>Kasese District [8]</td>
<td>Uganda</td>
<td></td>
<td>Solar</td>
</tr>
<tr>
<td>3</td>
<td>Mpeketoni Village, Lamu District [9][10]</td>
<td>Kenya</td>
<td></td>
<td>Diesel</td>
</tr>
<tr>
<td>4</td>
<td>UNEP, Mombasa Solar PV</td>
<td>Kenya</td>
<td>515 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>5</td>
<td>Tawawiri</td>
<td>Kenya</td>
<td>3.57 kW</td>
<td>Solar, Wind</td>
</tr>
<tr>
<td>7</td>
<td>Remba Island</td>
<td>Kenya</td>
<td>1 kW</td>
<td>Wind</td>
</tr>
<tr>
<td>8</td>
<td>Olalialumitia</td>
<td>Kenya</td>
<td>1.4 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>9</td>
<td>Oloshi Oibor PV (4kW), Wind (3kW) Hybrid Electrification</td>
<td>Kenya</td>
<td>7 kW</td>
<td>Solar, Wind</td>
</tr>
<tr>
<td>10</td>
<td>Mokomoni</td>
<td>Kenya</td>
<td>1.5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>11</td>
<td>Nyamondo</td>
<td>Kenya</td>
<td>10 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>12</td>
<td>Matangamano</td>
<td>Kenya</td>
<td>20 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>13</td>
<td>Bara Nne</td>
<td>Kenya</td>
<td>50 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>14</td>
<td>Itumbuzo, Abia State</td>
<td>Nigeria</td>
<td>2.85 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>15</td>
<td>Laje, Ondo State</td>
<td>Nigeria</td>
<td>5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>16</td>
<td>Kwalkwalawa, Sokoto</td>
<td>Nigeria</td>
<td>7.2 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>17</td>
<td>Sayya Gidan Gada, Sokoto</td>
<td>Nigeria</td>
<td>5 kW</td>
<td>Wind</td>
</tr>
<tr>
<td>18</td>
<td>UDUS City Campus, Sokoto</td>
<td>Nigeria</td>
<td>1.5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>19</td>
<td>UDUS NUNET, Sokoto</td>
<td>Nigeria</td>
<td>2 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>20</td>
<td>Kaduna</td>
<td>Nigeria</td>
<td>5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>21</td>
<td>Durumi, Abuja</td>
<td>Nigeria</td>
<td>3 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>22</td>
<td>3 Mechanized Brig. Kano</td>
<td>Nigeria</td>
<td>1 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>23</td>
<td>Kaduna</td>
<td>Nigeria</td>
<td>1.5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>24</td>
<td>Solar Hybrid plant at Lodwar</td>
<td>Kenya</td>
<td>60 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>25</td>
<td>Off-grid solar power project in Kitonyoni, Kenya</td>
<td>Kenya</td>
<td>13.5 kW</td>
<td>Solar</td>
</tr>
<tr>
<td>26</td>
<td>Powerhive East Africa Ltd microgrid Project</td>
<td>Kenya</td>
<td></td>
<td>Solar</td>
</tr>
<tr>
<td>27</td>
<td>SteamaCo's solar microgrid project</td>
<td>Kenya</td>
<td></td>
<td>Solar</td>
</tr>
<tr>
<td>29</td>
<td>Solar Project at Changoi Tea Farm</td>
<td>Kenya</td>
<td>1MW</td>
<td>Solar</td>
</tr>
</tbody>
</table>
It can be noted that for a number of these microgrids, there is little or no information available regarding their current operation status. Some of them like Santo Antao in Cape Verde, Kasese in Uganda, Kenya’s Mpeketoni Village, Kitonyoni solar power plant and Solar Project at Changoi Tea in Kenya are known to still be operational. Solar hybrids also exist in Kenya at Lodwar (60kW), Hola (60kW), Merti (10kW), Elwak (50kW), Mandera (300KW), Takaba (50kW), Eldas (80kW), Rhamu (80kW) and Laisamis (80kW) [14].

1.1.1 Critical Issues in Rural Electrification

As discussed in the previous section, various projects have been undertaken in developing countries to address the issue of lack of access to electricity. However, there are a number of critical challenges faced in rural electrification as discussed below. These issues can be grouped under the categories of general issues, technical issues, economic and financial issues, legal and regulatory issues, institutional issues, social / society issues and sustainability issues. Some of the issues highlighted in literature [15][16] and the corresponding categories are as follows:

1.1.1.1 General Issues

There are various general challenges faced in rural electrification some of which include the following:

- **Nature of the setup of rural communities**
  The setup of rural communities in African countries poses a challenge to rural electrification. Some of the communities are dispersed with houses far apart from each other while others are concentrated in one area making it necessary to find suitable and efficient models for electrification of these varying community configurations.

- **The low ability and willingness to pay as a result of the prevailing poverty in the rural communities** is another major issue faced with rural electrification projects. Most people have no sources of income thus are not able to take on the electricity service. This results into rejection of the projects. The high initial costs associated with these projects also make it hard to set the tariffs at a low value.
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- Another major challenge faced in rural electrification is a lack of or poor understanding of the role of gender in establishment of rural electrification programs. This is partly due to the culture of the communities. This exclusion of gender aspects does affect the electrical load estimation process which in turn affects the sizing and performance of the system.

- Poor or non-existent community involvement in the projects

Rural electrification programmes are faced with the issue of lack of participation or poor involvement of the community. This Poor or non-existent community involvement in the projects also creates additional problems such as:

  a. Ineffective handover process from the project implementation team to the community and government.
  b. Lack of personnel accountable for the operation and maintenance of the system. The community do not know what to do to maintain the service and have no idea about the capacity limitations.
  c. Lack of maintenance and overloading of the system leading to failure.
  d. Failure by the community to accept the system in the hope that the main grid will be extended in the future no matter how long it will take.
  e. Lack of technically empowered people to carry out first level support.
  f. For projects that utilise solar PV, the lack of awareness among the people on the quality of solar products to use results in a poor experience from using low grade products which in turn leads to abandonment of the service.

- There is also the challenge of lack of accurate geospatial data which is crucial for accurate design of rural electrification systems. This makes it hard to scale up the process of electrifying these rural areas and increase the electrification rate. There are also unbearable delays, bureaucracy and red tape when seeking data from government agencies to support research in rural electrification.

- When carrying out studies to understand issues related to existing off-grid solutions, some of the information obtained are independent views of people within the energy sector. It is difficult to ascertain how representative these views are without an official survey information result.
1.1.1.2 Economic Issues
The critical economic issues facing rural electrification include:

- **High Capital cost**
  High capital cost involved in setting up rural electrification systems means that very few private investors are attracted to invest in microgrids deployment [17]. This makes it extremely necessary to design cost effective models and systems.

- **Lack of financing**
  Access to financing from banks and other financial institutions enable private investors to establish rural electrification. However in some cases there is absence of these financing models and in other places, the available models are still not sufficient to attract private investors.

- **Lack of access of credit for the consumer**
  Lack of access to credit makes it difficult for people in rural areas to acquire electricity connectivity.

- **No link with income generation**
  In some cases, small sized electrification systems have been installed in which case they can only provide basic services such as lighting and phone charging but they are not really suitable for productive income generating activities e.g. milling, irrigation and other types of Small and Medium-sized Enterprises (SMEs). This makes it difficult to improve the livelihood of the people in these rural areas as well as making them unable to pay for the electricity in the long term. Eventually such systems cannot be sustained.

1.1.1.3 Policy Issues
The critical issues related to policy that are currently faced in rural electrification include:

- **Lack of policy and legal framework**
  A well-established policy and regulatory framework is essential for establishment of rural electrification systems so as to address investment risks, scale-up deployment of these systems and ensure their long term and reliable operation. There is inadequate and in some places lack of technical standards as regards equipment types that should
be deployed in developing countries. Due to the ongoing growth of the solar technology, many devices are put on the market in these developing countries but have not been regulated or checked against any standards. This has an effect on the reliable operation of the electrification systems.

- Improper use of subsidies
  There are issues when government subsidies are not being appropriately allocated. Appropriately targeted subsidies encourage investment in and continued operation of the rural electrification projects [18].

- Donor dependency
  Most rural electrification projects are donor funded and heavily rely on donor support for their continued operation. With a high dependency on donors for the establishment and running of the rural electrification projects, most of these systems eventually cannot be sustained once the funding ceases or reduces substantially.

- Unrealistic political commitment
  Some governments set extremely ambitious targets for rural electrification that are not well planned hence making it very difficult to meet these set goals. In developing countries, some of these targets are set so as to gain political grassroots support and gains especially around the time of elections without any or much consideration on how these promises can be realised.

- It has also been noted regarding rural electrification in Africa that energy policies and strategies do not clearly address the issues related to basic demands and quality of the installations. In addition there is no clear protection of the customers served by these installations as the monitoring schemes are poor or non-existent. There is need for clear policies and enforcement of any set policies so that the customers can have quality services.

1.1.1.4 Institutional Issues
The institutional challenges include:

- Lack of institutional capacity
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There is a limitation in trained personnel capable of fully establishing and rolling out sustainable rural electrification programs. Some countries also lack government agencies specifically focused on rural electrification. In some countries that already have these types of agencies present, there are cases where implementation of rural electrification programs is not happening as defined in the set policies.

- Lack of trained local personnel to provide basic first line support in case of technical failures. This means that technical failures that could have been rectified in a short time are left unattended to until a trained technician is dispatched to the area leading to long hours of interruption in service delivery. In the long term, this can lead to abandonment of the system by the community.

1.1.1.5 Technical Issues
The critical technical challenges in rural electrification include:

- Lack of technical knowledge
  For most of the rural electrification systems that have been established there is a lack of people with technical knowledge in the communities about the system. This causes problems such as increased tendency to misuse the systems by overloading them. Also this means that there is absence of trained local personnel to provide basic first line support in case of technical failures.

1.1.1.6 Sustainability Issues
Regarding sustainability, some of the challenges faced include the following:

- There is a general lack of metrics to measure sustainability of rural electrification projects. Absence of these metrics makes it difficult for investors to decide whether or not they should take on rural electrification projects since they cannot easily know if the project will be sustainable in the long term. When investors are not convinced to invest in rural electrification, it results into a much slower electrification rate for these rural areas.
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- It has also been noted that a number of rural electrification projects are not self-sustaining in the long run. This is discussed further in Chapter 3 of this thesis.

1.1.1.7 Social/Society

- There is a major challenge of the consumer mind-set and behaviour regarding the possibility of a solar PV system to function as well as the main grid. There is a lot of scepticism about this possibility. Some people are not convinced that solar PV can meet all their needs and would rather wait for main grid connectivity no matter how long it takes. This in turn slows down the rural electrification process.

- There is also a lack of technical knowledge on the type of customer-end equipment to use in terms of energy saving and efficiency. This is partly due to limited community sensitisation and lack of proper regulation on devices sold in the developing countries.

1.2 Research Aims and Objectives

Currently a lot of research and studies have been carried out on the technical aspects of microgrids [19]. These studies can be grouped into the categories of system planning/design, operation and control. To a large extent microgrid studies and development efforts carried out so far have focused on campus, military and remote microgrids. This is because there are funds available to facilitate this research and also there is need to supply energy to critical missions at military bases. Another reason is that microgrids offer a far better option for providing electricity than putting large sums of money in transmission and distribution facilities. However research on design and development of community microgrids, economic aspects of microgrid planning and operation as well as value propositions of this technology is still modest. In addition renewable energy based microgrids especially those designed for rural electrification purposes in developing countries face a lot of issues as regards their implementation. These fall into the categories of general, technical, economic and financial, legal and regulatory, institutional, social / society and sustainability issues. Various researchers have highlighted these issues [20][19][21][22][16][23].

A number of researchers have tried to address some of the above mentioned issues in their studies but additional research is needed in the areas of microgrid economics, appropriate
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technical designs and socio-economic analysis of microgrid deployments [19]. Furthermore research is needed to clarify the expectations from microgrids for isolated/remote areas as regards reliability as they may not be as reliable as the main grid. Research is needed to show that a well-designed, optimised and economically feasible microgrid model can function and deliver services for remote areas. When this is achieved it will attract private investors to participate in rural electrification projects and thus scale up the electrification rates of communities in developing countries. This will enable governments to deliver on their targets in line with the United Nations Sustainable Development Goal 7 (SDG 7). Taking an example of Uganda as one of the developing countries with an aggressive action agenda for its Sustainable Energy For All Initiative [24], it is important to come up with ways in which projects aimed at achieving these targets can be scaled up.

Against this background, this PhD research project was proposed with the main objective of developing a smart sustainable microgrid model that is specifically based on solar PV technology and to address the factor of investment cost in the proposed microgrid model.

The specific objectives are:

- **Identify the challenges in rural electrification.**
  
  This research will start with a critical literature review of the current research in remote electrification. The problems faced in rural electrification and the gaps in knowledge regarding the use of microgrids for rural electrification will be identified.

- **Identify the issues involved in sustainability of rural electrification systems and develop sustainability metrics for these types of projects.**
  
  This involves three important tasks. The first task is to assess the causes of failure of past rural electrification projects and their inability to last beyond the funding phase in many developing countries. The second task is to identify and review any existing forms of measuring sustainability in the context of rural electrification systems. The third and final task is to propose ways of enhancing how sustainability is measured. This involves developing the most appropriate sustainability metrics that can easily be used to determine whether a proposed microgrid deployment for rural electrification will be sustainable or not.
• **Formulate, design and simulate a smart solar PV community microgrid model.**
  The model that is required in this research must be robust, more efficient, reliable and economically feasible in terms of its operation and management. This involves two important tasks. First, the process of electrical load estimation has to be clearly defined after evaluation of existing load modelling approaches because this is a critical step in the design of rural electrification systems. An accurate way of estimating the electrical demand is required such that the likelihood of over/under estimation of the load which in turn affects the cost and performance of the microgrid system is greatly minimised. With some customers expected to require hot water, the microgrid should also be able to incorporate solar water heating. Second, the existing sizing techniques for the PV microgrid components have to be evaluated and a better approach to sizing proposed.

• **Investigate the affordability of the proposed microgrid solution.**
  Some aspects of the microgrid design and set parameters of the microgrid components affect the cost of the system which in turn affects the cost of electricity generated. It is desired that the microgrid solution delivers power at the lowest possible cost without compromising on reliability. The proposed community microgrid solution should be technically acceptable, implementable, economically sustainable and able to attract investment in this mechanism for rural electrification from both government and private investors. For this investigation, case studies will be carried out on a rural community in Uganda, East Africa. Uganda has been chosen as the basis for the case studies because this research has been funded by the United Kingdom’s Department for International Development (DFID) through the Commonwealth Scholarship Commission in the UK that enables selected scholars to carry out research relevant to their home countries with the aim of meeting the United Nations’ Sustainable Development Goals (SDGs). This research focuses on Sustainable Development Goal 7.

The expected end result of this research is a working and implementable model for the rural community microgrid which has been referred to as ‘ComµGrid’. Solar PV resource has been chosen for the ComµGrid model because it is readily available in most of the developing or least developed countries for which the desired design is to be developed. This
is evidenced by the number of the projects that have been undertaken to provide solar lamps for people in these rural areas. It is also known to be a clean and renewable energy resource. Biofuels have not been considered in this particular research as the focus was on investigating the ability of solar PV to meet all the electricity needs of the community. The ComµGrid model that has been proposed in this research is based on the nature of the rural communities in Uganda that have no access to electricity. However, it is important to note that this model has been designed in such a way that it is applicable in other rural communities outside Uganda that have a similar setting.

1.3 Main Research Contributions

In this research, substantial contributions have been made in the design and use of Solar PV microgrids for rural electrification particularly in the areas of load estimation and sizing of the PV microgrid components. This research also shows how existing knowledge on solar thermal for water heating can be incorporated in the microgrid by showing the saving in costs for electricity for customers that require hot water use such as health centres. Furthermore this thesis has addressed the sustainability issues faced with rural electrification projects and developed better ways so as to enhance how the sustainability is measured. This research has also addressed the main problem of consumer mind-set and behaviour regarding possibility of solar PV microgrid to function as well as the main grid. There is a lot of scepticism about this possibility with some people not convinced that solar can meet all their needs and would rather wait for main grid connectivity. This problem has been addressed in this research by proposing a microgrid model that meets all electrical needs of the rural community such that it works just like the main grid would. A detailed description of the main contributions to knowledge of the research carried out in this PhD is as follows:

- **Sustainability metrics and sustainability assessment of rural electrification projects:** The literature survey showed that while a number of rural electrification projects have been undertaken in developing countries, many are not sustainable and do not survive beyond the initial donor funding phase. In addition, the metrics to measure sustainability of these rural electrification projects are still lacking. A thorough analysis of the sustainability issues surrounding rural electrification outlined several areas that are critical for long term continued existence of these types of projects. Basing on this analysis, the important factors to consider when evaluating
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sustainability of rural electrification projects have been proposed in this work and an easy to use sustainability evaluation tool kit has been proposed. This tool kit is based on a risk assessment methodology that evaluates the impact of various risk factors on the sustainability of a rural electrification PV system and likelihood of occurrence of those risk factors to yield the overall sustainability risk of the project. The risk based approach proposed is straight forward, easy to understand, simple to use and can be adopted by all stakeholders involved in rural electrification projects to evaluate sustainability of these types of projects. The tool can be used as a checklist to verify that all important aspects of a project have been taken care of before commencement of the implementation. It is a portable tool that can be saved and accessed on laptops, computers, tablets and related mobile devices.


- **Improved approach to load estimation through incorporation of gender aspects:** As establishment of off-grid rural electrification systems requires accurate prediction of the electrical load, an evaluation of the efficacy of the current methods for load estimation showed areas of improvement that could be exploited; particularly inclusion of gender considerations; so as to have a more accurate estimate of the load. An improved load estimation approach has been proposed that yields more accurate estimates of the electrical demand for off-grid systems in rural areas. It enhances current existing methods for load estimation. It uses stochastic methods to more accurately model uncertainty in the load. In the proposed approach load characteristics that take account of the influence of gender are investigated with the results showing that the effect of gender on estimated demand is critical in microgrid design. The proposed method addresses the gap that exists between engineering modelling and social science theory.

The work highlighting this contribution has been published in: J. Namaganda-Kiyimba and J. Mutale, “Gender Considerations in Load Estimation for Rural
Application of Markov Chain approach in estimating future load demand and load for an unelectrified community: In the proposed load estimation approach, an improvement in the stochastic method to simulate load characteristics that change with change in customer habits and environment is proposed. The changes in customer habits on estimated load are investigated using the Markov Chain process. This facilitates the determination of year to year load profiles for off-grid unelectrified rural communities. The results also show that average electricity consumption in a similar village that is already electrified can be used as a sound basis to estimate the consumption in another village that does not have access to electricity.

Optimal sizing and design of PV microgrid systems: The sizing of system components is a very important step in the design of PV microgrid systems. An evaluation of the current commonly used basic approach to sizing of PV systems shows that the resultant systems are not optimally sized. This basic sizing approach does not evaluate the actual reliability of the system and whether the combination of the equipment used is the most cost effective for a given level of reliability hence it does not optimally size the system. Basing on the need for improvement in the area of PV system sizing, an efficient optimisation algorithm for sizing of off-grid PV microgrid systems using a Mixed Integer Linear Programming (MILP) approach has been proposed. The proposed optimisation approach is robust; making use of hourly load variation, hourly solar irradiance values and hourly ambient temperature to optimally size the system. This is an improvement from the basic sizing approach presented in the solar PV design and installation manuals. The results show that a system sized using the basic method is unreliable and more expensive than one sized using the proposed MILP method.
Chapter 1. Introduction


- **Application of DBSCAN method to analyse weather and load data for faster optimisation:** This proposed MILP approach uses the Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm to aggregate load and meteorological data. This approach enables reduction of the hourly load and irradiance data into fewer time steps to aid in faster execution of the optimisation algorithm and convergence to the optimal solution. The results show that it is possible to achieve accuracy and a faster convergence to the solution using this approach.

  The work highlighting this contribution has also been published in the September 2020 issue of the SAIEE Africa Research Journal: J. Namaganda-Kiyimba and J. Mutale, “An Optimal Rural Community PV Microgrid Design Using Mixed Integer Linear Programming and DBSCAN Approach”

- **Further understanding of the techno-economic design of rural microgrids to enhance their affordability:** Given the high levels of poverty in rural areas and the literature review that has been carried out focusing on affordability of electricity in these areas and sustainable operation of community microgrids, it is very necessary to investigate ways in which the overall cost can be lowered so as to make the electricity affordable. An investigation of the technical parameters that can reduce the cost of the microgrid making the services affordable for the community has been carried out in this work. The research has found that some critical battery parameters can be set at values that optimise the battery size and use thus lowering the overall cost of electricity. In addition, provision of anchor customers as well as consideration of gender and community characteristics in the electrical load estimation process can make a microgrid affordable.
Chapter 1. Introduction


1.4 Thesis Structure

There are seven chapters included in this thesis. The contents of the following chapters are summarised below.

Chapter Two provides a detailed critical literature review of microgrids and their application in remote area electrification. The chapter discusses the current research trends, needs and existing gaps in approaches in this particular area.

Chapter Three provides a detailed discussion of the sustainability metrics developed in this research project. This chapter presents the important factors to consider when evaluating sustainability as identified in this research project and proposes an easy to use sustainability evaluation tool kit based on risk assessment approach. It also provides a detailing of the clear guidelines on how sustainability can be measured for a given rural electrification project. It also presents the results obtained from testing the kit against three microgrid projects.

Chapter Four presents the methodology proposed in this research for designing an optimal community PV microgrid. In this chapter, an efficient optimisation algorithm for sizing of off-grid PV microgrid systems using a Mixed Integer Linear Programming (MILP) approach is presented. The chapter discusses the robustness of the proposed optimisation approach and its use of hourly load variation, hourly solar irradiance values and hourly ambient temperature to optimally size the system. It also presents how the proposed approach in this research uses the Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm to aggregate load and meteorological data. It presents the use of MATLAB software to execute the proposed optimisation algorithm. The chapter further presents the application of the proposed PV microgrid design approach using case studies on a rural community in Uganda. The performance of the proposed sizing approach is compared with that of the basic PV sizing method. The results of the proposed approach are also compared with those obtained using the commercially available HOMER software.

Chapter Five provides a detailed discussion of the process of load estimation used in this PhD research for the PV microgrid design. It provides an evaluation of the efficacy of the
current methods for load estimation and proposes an improved approach that yields more accurate estimates of the electrical demand for off-grid systems in rural areas. An investigation into the load characteristics that take account of the influence of gender as well as changes in customer habits on estimated load is carried out using the Markov Chain process. It also presents the use of MATLAB software to generate the load profiles using the proposed improved approach.

Chapter Six provides an evaluation of affordability of rural community PV microgrids as this is essential for their sustainability and effective utilisation of the services they offer. It presents some of the critical elements that need to be considered when designing these types of microgrids for rural communities. The results obtained from the case studies carried out with various choices of batteries and their specifications and availability of anchor customers on the overall cost of electricity are discussed.

Chapter Seven provides a summary of the conclusions drawn from the work carried out in this research project. The main contributions of this thesis are presented and a detailed discussion of the proposed areas of future research is provided. It also includes recommendations for improvement of the proposed methodology.
Chapter Two

Literature Review

This chapter presents a general overview of the microgrids concept and characteristics. It presents a critical review of the general microgrids literature and their application in remote area electrification. Focus is placed on the current research trends, needs and existing gaps in approaches in this area.

2.1 Introduction

Microgrids can generally be defined according to two basic requirements given below [25]:

i. It should consist of both sources and sinks managed under local control.
ii. It should have the capability to function in both grid connected mode and islanded mode.

A more detailed definition is provided by [26] which refers to a microgrid as a localized grouping of electricity generation, energy storage, energy control and conversion, energy monitoring and management, and load management tools, capable of operating while connected to the traditional main grid or function independently. A simple layout of a microgrid is shown in Figure 2.1[27]. The electricity generation sources are distributed resources that include both renewables and conventional sources. Some of these are listed below:

- Wind
- Solar PV
- Microhydropower
- Diesel
- Fuel Cells
- Single-phase and three-phase induction generators
- Synchronous generators driven by IC engines

Figure 2.1: A Simple Microgrid Architecture [27]
Chapter 2. Literature Review

There are a number of factors that are contributing to the continued desire for microgrids. These include but are not limited to cost, power quality and reliability (meeting the requirements of sensitive loads by local provision of high quality power and maximising services provided by the generation and storage assets through embedded intelligence thus minimising power disturbances), energy efficiency (an increased awareness of the electricity uses, knowledge on energy efficient appliances and switching off appliances, and increased control over loads provides more information which leads to more efficient use of the electricity), availability of harvestable local clean and renewable energy. Furthermore, the benefits associated with microgrids have led to an increase in the introduction of policy and regulatory incentives for the development and actual implementation of microgrids [25]. These include provision of subsidies, tax incentives, financial support and concessions. These are shown in Figure 2.2 that has been adopted from [28].

![Figure 2.2: Policy Incentives for Microgrid Projects][28]

Subsidies are provided to reduce the initial investment costs and operational costs of the microgrid implementation [29][30][31]. Tax incentives are provided through exemption or reduction in taxes on renewable energy equipment [32][33]. Financial support policies aim at
securing finances for rural electrifications through provision of reduced rates [34][35]. Concession policies aim at reducing competition among the investors by assigning them geographical areas to which they are the sole providers of electricity services [28]. The benefit of concessions is that they encourage the investors to invest in microgrid projects because they protect these investments from competition in medium to long-term.

2.2 A Review of Current State of Research on Microgrids

Microgrids have been and continue to be a major focus for many researchers in the areas of distributed generation, energy systems, sustainable power and remote area electrification. Countries such as USA, Japan, China, Canada and the UK are involved in research on microgrids for isolated communities and several papers have been published on this area [36]. The focus of this particular PhD thesis is on the planning aspects of remote microgrids.

In [21], the state of microgrids in China basing on the past, present and future is discussed. The author notes that microgrids are a critical part of the future smart grid that is to offer control flexibility, improved reliability and better power quality. This is further stressed by [37] in which experimental and test microgrids were reviewed. The results from the study show that microgrids have a critical role to play in the evolution of smart grids. However, it was identified that there is need for more research in the islanding detection method to make it more reliable and fast responding in addition to development of a generic simulation tool that would facilitate additional research on transient stability performance, protection and control strategies and development of design guidelines standards for microgrids [37].

2.2.1 Microgrid Design

Microgrid design consists of several aspects of the microgrid such as generation modelling, load modelling, storage option, sizing of the components and determination of the control strategy. System reliability and cost are major considerations to make when designing the microgrid. In [19], a review of different issues in microgrids and what research studies have been carried out in microgrids is presented. The areas of study in microgrids have included distributed generation, microgrids benefits, applications of power electronics, economic issues, microgrid operation and control, microgrid clusters as well as protection and communications. A study on microgrid village design and its economic feasibility is
presented in [38]. Five steps for the village microgrid design are provided which include; 1. Estimation of the annual demand and location climate conditions, 2. The selection of the combined heat and power (CHP) facility, subsidiary facility and renewable energy resources, 3. Optimization of the selected facility, 4. System operational stability analysis and 5. Economic evaluation taking into consideration both the fixed and variable costs.

Another study on design and operation of a remote microgrid was carried out in [39] and the results obtained showed that for such remote microgrids, the use of optimal rating of energy storage units and renewable generators together with an optimal unit dispatch mechanism leads to significant reduction in the lifetime cost and emissions. Similar results as these were obtained in a study given in [40] which looked at the optimal design and operation of a grid-connected microgrid.

In microgrid design, it is important to note that microgrids can be AC or DC. In deciding whether to go for AC or DC microgrids, [41] recommends to consider the ratio of dc loads. A change in this ratio leads to a change in the total cost. This makes it a worthwhile way of determining the point where it would be more economical to go for a DC microgrid than the AC microgrid. The AC microgrid would be considered economical when the ratio is smaller than the threshold ratio and for larger ratios, then the DC microgrid is more economical. The costs considered in the total cost include the investment cost, operation cost and the reliability cost.

### 2.2.2 Demand Side Management Overview

The concept of demand side management (DSM) considers active participation of the consumers in the utilisation of the electricity. According to the US Department of Energy, DSM can be defined as “changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [42].

In DSM all demand-reducing measures, which include Demand Response (DR) and programs that encourage the end user to be more energy efficient, are considered. The aim is to
achieve, at the least possible cost and sustainably, a balance between the electricity supply and consumption (demand).

Demand response indicates the result of an electricity consumer’s response to a stimulus and involves usage pattern changes. Its wholesome value to the community is derived from resulting cumulative effect on the whole electric system. These two perspectives need to be considered when characterizing and valuing demand response and specifying the limitations around it [43]. Figure 2.3 below shows the role of demand response in electric system planning and operations. As seen in the figure, demand response can be applied at any point in the electricity system management.

Figure 2.3: Role of Demand Response in Electric System Planning and Operations [43]

With the introduction of DSM programs, customers can change their usage patterns such that the need for increasing generation is reduced [44]. The advantages associated with DSM can be grouped into economic, environmental and reliability categories. These include:

- Reduction in costs [45]
- Reduction in the number of blackouts
- Increase in system reliability
- Helps to delay investments in capacity expansion of the generation, transmission and distribution network [44].
It is important to note that the success of DSM highly depends on the percentage of controllable loads in the grid. DSM considerations that allow for efficient load management include:

i. Encouraging customers to use more energy efficient products and equipment.
ii. Encouraging customers to move non-critical loads from peak hours to less busy times such as the evening and early morning time periods as was done in the study carried out in [46].
iii. Encouraging construction of buildings that are energy efficient.
iv. Carrying out energy awareness and education.

2.2.3 Energy Storage in Microgrids

Energy storage is an important feature of microgrids as some of the generation resources used in microgrids are intermittent in nature e.g. solar and wind. This allows such microgrids to maintain power supply even when there is no generation from the resource. Furthermore, microgrids can operate in islanded mode independent of the main grid hence there is need for incorporation of storage [19][47][48]. Different types of storage technologies are available for electrical energy and these have been a focus of research for many authors. Some of these technologies include the following:

- Electrochemical battery
- Supercapacitor
- Compressed air energy storage
- Superconducting magnetic energy storage
- Flywheel energy storage

When designing microgrids, it is important to consider the storage option and the sizing for that particular storage. Battery storage is one of the major options for energy storage in systems utilising solar PV and/or wind energy [49].

In [49], a study was carried out on the optimal sizing of energy storage for microgrids. Lithium ion (Li-ion) batteries were the focus of the study in which the cost-benefit analytical
Chapter 2. Literature Review

technique was used to estimate the economic feasibility of the battery storage for both the grid-connected and islanded modes.

In [50], an investigation was carried out to determine the impact of electrical storage and grid upgrades on the optimal design and operation of a microgrid under different carbon emissions constraints. The trade-off between storage and grid upgrade was examined and results compared to those of a reference case.

In general, cost of the energy storage option is a crucial factor in deciding the type of storage to be used. A comprehensive study on costs of various storage technologies has been carried out and published by Lazard [51] [52]. The findings can be summarised as follows:

i. Even though some energy storage technologies have become attractive for numerous special grid uses, they are all still expensive and not competitive enough as hoped by some advocates for renewable energy.

ii. Costs are expected to go lower by a large margin within the next five years due to increase in use of renewables, enforcement of government policies that support energy storage and the call for reduction in use of fossil fuels and the numerous changes expected on the power grid as it evolves.

2.3 Renewable Energy: Concept and Types

The term renewable energy refers to those energy resources that are naturally occurring and self-renewing. These resources are naturally distributed thus providing us with the ability to generate energy in remote areas eliminating the need for investment in large transport systems [53]. Examples of renewable resources include [54]:

- Biomass—including:
  - Wood and wood waste
  - Municipal solid waste
  - Landfill gas and biogas
  - Ethanol
  - Biodiesel
- Hydropower
Chapter 2. Literature Review

- Geothermal
- Wind
- Solar
- Tidal Energy

Figure 2.4 shows the major energy paths of the earth from which renewable energy can be obtained. For selected geographical regions such as the location considered in this thesis, PV is the most appropriate making it clear that the sun is the main source for easily accessible renewable energy in these regions [53].

Figure 2.4: Renewable Energy Flow Paths [53]
Apart from the ability to generate energy in remote areas, renewables possess several other advantages namely:

i. They are clean (non-polluting) due to their low or nearly zero carbon and greenhouse emission.

ii. They are sustainable / inexhaustible.

iii. Maintenance for renewable energy facilities could be less expensive as compared to traditional generators.

iv. With proper planning and infrastructure in place, renewables offer a reliable source of energy.

Renewables offer the much needed flexibility needed in power generation leading to a reduction in the dependence on fossil fuels [55].

2.3.1 Photovoltaics: An Overview and Principles

2.3.1.1 The Photo cell

A Photovoltaic (PV) system defines a mechanism of converting sunlight into electricity. A solar cell is the device that converts sunlight into electricity [56]. It consists of two semiconductor layers usually monocrystalline or polycrystalline that are sandwiched and doped such that one layer has too few electrons (referred to as a p-type) and the other has many electrons (the n-type) [57]. The resultant is a p-n junction. This concept is illustrated in the Figure 2.5 below.

![Figure 2.5: PV Cell Concept](image)

During the presence of radiation from the sun, more electrons will be generated from the n-type layer. These electrons are however repelled by the electric field at the p-n junction.
Availability of an external circuit will allow the electrons to move from the n layer to the p-layer. Therefore a current flows from the positive terminal to the negative terminal. The equivalent electrical circuit of the solar cell may be represented by the Figure 2.6 below as shown in [58]. It consists of a current source in parallel with a diode. The series resistor $R_s$ and shunt resistor $R_{sh}$ are added to cater for any losses that may occur in the solar cell.

![Figure 2.6: Equivalent Electrical Circuit of a Cell][58]

The current delivered to the load connected to the solar cell is given by the equation [59].

\[
I = I_L - I_D - \frac{V + IR_s}{R_{sh}} \quad (2.1)
\]

The current $I_D$ diverted through the diode may be represented with Shockley’s equation [60] and it is dependent on the temperature (T) of the p-n junction. In the equation, $k$ is Boltzmann constant and $q$ is the electron charge.

\[
I_D = I_o \left( e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) \quad (2.2)
\]

$q=1.60217646 \times 10^{-19} \text{ C}$, $(k=1.3806503 \times 10^{-23} \text{ J/K})$, T (in Kelvin) is the temperature of the p–n junction, and $n$ is the diode ideality constant. Figure 2.7 shows the resultant I–V curve.

Therefore;

\[
I = I_L - I_o \left( e^{\frac{q(V+IR_s)}{nkT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (2.3)
\]
In an ideal solar cell, $R_{sh}$ is infinite and $R_s = 0$ therefore the current delivered to the load is represented as in equation (2.4).

$$I = I_L - I_o \left( e^{\frac{q(V+IR)}{nkeT}} - 1 \right)$$  \hspace{1cm} (2.4)

The I-V curve of the solar cell is represented by the Figure 2.7 below [58].

![I-V Curve of a Solar Cell](image)

**Figure 2.7: I-V Curve of a Solar Cell [58]**

The significant characteristics of the solar cell that are explained by this graph include the short circuit current ($I_{sc}$), the open circuit voltage $V_{oc}$ and the maximum power point $P_{max}$ which is a product of $I_{sc}$ and $V_{oc}$. As shown in the graph, the cell attains a maximum current when the voltage is zero. The cell attains maximum voltage when the current is zero. In this case, the photon current is cancelled out by the diode current.
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2.3.1.2 The PV module

The PV module consists of a number of parallel and series combinations of PV cells [59]. The current output from the module is dependent on the number of cells in parallel while the voltage output depends on the number of cells in series. For instance, if the number of cells in series is \( N_s \) and those in parallel is \( N_p \) and the current and voltage output of one cell is \( I_c \) and \( V_c \) respectively then the current and voltage from the module are given by equations (2.5) and (2.6) respectively.

\[
I_M = N_p \times I_c \\
V_M = N_s \times V_c
\]  

(2.5) \hspace{1cm} (2.6)

[59] further explains that the current output from the PV module is directly proportional to the solar irradiation. However the voltage output and therefore power output reduces with increase in temperature. The cell temperature of the module depends on the irradiation and the relationship between the voltage and the temperature is expressed by the equation (2.7) below.

\[
T_c(t) = T_{amb}(t) + G(t) \times \frac{NOCT - 20}{800}
\]  

(2.7)

Where \( T_{amb}(t) \) is ambient temperature, \( G(t) \) is the irradiance and \( NOCT \) is the operating cell temperature for a ambient temperature of 20°C, an irradiance of 800 W/m², and wind speed of 1 m/s.

The power output of the solar panel may thus be given as in equation (2.8).

\[
P = P_{rated} + \alpha_p(T_{stc} - T_{amb}(t)) \times P_{rated}
\]  

(2.8)
Where $\alpha_p$ is the power output temperature coefficient and $T_{stc}$ is temperature at standard testing conditions. (25°C). For instance if cell temperature is 45°C and coefficient of power is $-0.5%/^\circ C$ then a PV module rated at 200W will deliver a power of 180W.

### 2.4 A Review of Existing Research and Design Approaches in the Application of Microgrids in Remote Area Electrification

As discussed already, technical challenges and high costs make it difficult to extend the main grid to remote areas. This has made it necessary to undertake off-grid rural electrification projects. Figure 2.8 shows the costs of electricity for on-grid, mini-grid and off-grid technologies in sub-Saharan Africa in 2012 as well as the anticipated total costs in the year 2040 [53].

![Figure 2.8: Indicative Levelised Costs of Electricity for On-Grid, Mini-Grid and Off-Grid Technologies in Sub-Saharan Africa in 2012 [61]](image)

*Costs of grid extension are calculated as the average cost of extending the medium-voltage grid a certain distance (e.g. 1 km) to each community on a levelised cost basis.*

Microgrids have been regarded as one of the main ways for rural electrification and electrifying areas that cannot be easily served by the main grid. This has led to what are called community microgrids. This is the origin of the term ComµGrid used in this particular thesis. Community microgrids can address the ever increasing demand for reliable and quality power while also ensuring minimal costs and a clean environment.
Chapter 2. Literature Review

These rural electrification projects utilise both renewable and non-renewable sources e.g. diesel generators. There are many factors that determine which generation resource to use for mini-grid or off-grid systems. Renewables become the much sought after option if the costs involved are considered on a life-cycle basis. However there is still need for financing to facilitate the establishment of rural electrification systems. It is also noted that the initial costs involved for renewables are still much higher than those for fossil based generation systems such as diesel generators [61]. In order to reduce carbon emissions, renewables are the preferred option when it comes to electrification of remote areas. However in some cases due to the high initial costs involved and the need to offer flexibility and reliability of supply, hybrid combinations of renewables and non-renewables are installed e.g. a combination of solar and diesel.

In the long term renewable technologies cost lower partly due to improvements in technology and mass production. It is expected that in the future, solar PV will be more competitive with diesel and other renewables. Sub-Saharan African countries can be expected to have more solar PV installations in the future due to the abundance of the resource in the continent. Figure 2.9 shows the projected mini-grid and off-grid power generation in 2040.

![Figure 2.9: Technology mix for mini-grid and off-grid power generation in sub-Saharan Africa in 2040 [61]](image)

2.4.1 Approach to Evaluation of Sustainability

In numerous developing countries such as those in Africa, microgrids have been set up in remote communities but many of them are unsustainable as they do not last beyond the initial
Chapter 2. Literature Review

funding phase. Robust clear metrics to measure sustainability of such projects are still lacking. Some previous studies have focused on indicators for sustainability of electrification projects as evidenced in [62]–[64]. In [65] a discussion on sustainability metrics of PV systems is given but focusing mainly on PV modules. A review of off-grid rural electrification projects that was carried out in [64] mentions only four categories of sustainability namely; institutional, economic, environmental and socio-cultural. However these alone cannot provide a wholesome evaluation of a project’s sustainability. Additional research is thus needed on overall sustainability metrics for rural electrification projects such that governments, developers, owners and all participants in these projects can have a benchmark for any projects to be undertaken.

2.4.2 The Current Typical Approach to PV Microgrid Systems Sizing

Studies show that solar PV microgrids are widely being researched and utilised for rural electrification. The sizing of the system components such as PV modules, batteries, controller, etc.; is a very important step in the design of these PV microgrid systems. The current approach to sizing of PV systems provided by PV manuals such as [66] involves the use of sizing sheets to determine the number and specifications of the components required. This approach is very basic consisting of six major steps listed below and is based on the user’s projected needs, goals and budget.

Step1: Estimating the electric load

This involves making a note of all the equipment that will use the electricity generated by the system. The loads are then categorised into AC loads and DC Loads. The daily energy load in Watt-hours is then estimated for each load.

Step2: Sizing and specifying batteries

In this step the number of batteries needed is calculated and specified. According to [66] the batteries in series (Bat_{series}), batteries in parallel (Bat_{paral}) and the total number of batteries (Bat_{Total}) are determined by equations (2.9) to (2.12).

\[
\text{Bat}_{\text{cap}} = \frac{Z \times D_{\text{aut}}}{\text{DOD}}
\]  

(2.9)
\[ \text{Bat}_{\text{paral}} = \frac{\text{Bat}_{\text{cap}}}{\text{Bat}_{\text{AH}}} \quad (2.10) \]
\[ \text{Bat}_{\text{series}} = \frac{V_{\text{dc}}}{V_{\text{Bat}}} \quad (2.11) \]
\[ \text{Bat}_{\text{Total}} = \text{Bat}_{\text{paral}} \times \text{Bat}_{\text{series}} \quad (2.12) \]

Where; \( Z \) is the total daily load, \( V_{\text{dc}} \) is the DC system voltage, \( V_{\text{Bat}} \) is the nominal battery voltage, \( D_{\text{aut}} \) is the days of autonomy, \( \text{Bat}_{\text{cap}} \) is the total storage capacity required, \( \text{Bat}_{\text{AH}} \) is the rating of the chosen battery supplied by the manufacturer and DOD is the Depth of Discharge which is the maximum discharge allowed by the battery.

**Step 3: Sizing and specifying the PV array**

During this step the number of PV modules in series (\( \text{PV}_{\text{series}} \)), modules in parallel (\( \text{PV}_{\text{paral}} \)) and the total number of PV modules to make up the PV array is calculated using equations (2.13) to (2.16).

\[ \text{PV}_{\text{peak}} = \frac{Z}{\eta_{\text{bat}} \text{ PSH}} \quad (2.13) \]
\[ \text{PV}_{\text{paral}} = \frac{\text{PV}_{\text{peak}}}{I_{\text{mp}}} \quad (2.14) \]
\[ \text{PV}_{\text{series}} = \frac{V_{\text{dc}}}{V_{\text{mp}}} \quad (2.15) \]
\[ \text{PV}_{\text{Total}} = \text{PV}_{\text{paral}} \times \text{PV}_{\text{series}} \quad (2.16) \]

Where; \( I_{\text{mp}} \) is the peak amps per module at STC, \( \text{PSH} \) is the peak sun hours per day, \( \eta_{\text{bat}} \) is the battery efficiency, \( \text{PV}_{\text{peak}} \) is the current of the PV array and \( V_{\text{mp}} \) is nominal module voltage / voltage at MPP under STC.

When sizing the PV module array using this basic sizing approach, the average solar radiation for the month with the least solar irradiance is considered. The assumption is that if the PV system is designed to meet the load demand at this radiation, then it will be sufficient for meeting the load demand throughout the year.
Step 4: Specifying a Controller

The role of the charge controller is to protect the battery from damage through over charging by the PV array and under charging below DOD by the load demand [67][68]. It is sized in such a way that it can match the battery system voltage and also withstand the current from the PV array.

Step 5: Sizing and specifying an inverter

The first step in sizing the inverter is to estimate the continuous amount of current required by the connected loads. This is obtained by dividing the power drawn by the equipment that run at the same time by the DC system voltage [66][69].

Step 6: Sizing system wiring

The system wiring is chosen such that it can withstand the maximum current produced by the PV modules, inverter, charge controller and battery. Improper sizing of the system wiring will affect the safety and reliability of the system [69]. Besides the current through the wire, another consideration is the voltage drop along the wire. This is dependent on the current and length of the wire. In [66], the voltage drop was assumed to be 2%. [66] provides wire sizing charts that aid in choosing a wire gauge for a given system voltage, current and length of wire. In order to cater for future growth, a higher cable current rating should be chosen.

2.4.2.1 Merits of the Current Typical PV System Sizing Approach

The above procedure in [66] presents simple equations that can be used to size solar PV systems. [70] mentioned that, using this procedure, the results obtained were comparable to those obtained using commercial software such as PVSyst. The equations can be scripted in available tools such as Microsoft Excel to further ease computation and replication of the procedure to various locations [71][70].

In regards to reliability, [72] and [70] mention that the systems designed were reliable. Reliability of the system is achieved by designing to satisfy the load demand using the minimum average monthly irradiance. A number of days of autonomy is also chosen to
ensure that the battery bank can satisfy the load for a predetermined number of consecutive days in the event that the energy supplied by the PV modules is insufficient. To further enhance reliability and life time of the system, the battery minimum depth of discharge and maximum state of charge are monitored by a charge controller. [73] recommends this method for designers to cost effectively achieve high performance and long lasting stand-alone PV systems.

2.4.2.2 Shortcomings of the Current Approach to Sizing PV Systems

The current basic approach to sizing PV systems that involves use of sizing sheets for each component of the PV system poses the following issues:

1. **Inaccurate load estimation:**
   The load estimation, as described in section 2.4.3, is done by approximating the daily load using the power rating of each equipment and the number of hours that the equipment is used per day. The step of sizing the PV system has a number of shortcomings. It is highly dependent on the initial information for sizing the load and there are some cases where the load estimation has been inaccurate leading to oversizing or under sizing of the solar PV system [74]. The load time of use (duration of use) is considered based on what the customer says which may not be so accurate. There are also loads that consume power even when they are in standby mode. These need to be considered.

   Secondly, it does not take into consideration the daily variations of the load or increase in demand. There is no consideration for what happens if the demand increases. Common practice is that if the loads vary significantly on a seasonal / monthly basis or are of critical nature, then the highest value is used in designing the system [73]. The potential problem with this approach is that it can lead to system oversizing thus higher cost.

2. **Lack of optimal sizing**
   One of the objectives when designing a solar PV system is achieving reliability of the system at a minimum cost [67] [59]. The reliability of the system is its ability to continuously serve the expected load demand [75]. The designer of the PV system therefore should have an option to choose the most reliable system depending on how much they are able to spend.

   The designer should also be able to estimate how many days in a year that this system is actually able to meet the load. The limitation with the sizing approach discussed is that it
does not evaluate the actual reliability of the system and whether the combination of the equipment used is the most cost effective for a given reliability. Therefore it does not optimally size the system.

During PV array sizing, the discussed approach uses only peak sun hours and does not take into consideration the variation of the radiation in each hour or cloud movements that cause shading. The variation in solar radiation during the rainy season needs to be considered as it reduces to values lower than the average in other seasons in a year. The approach does not consider the module performance under the climate of the given area. Other factors like dust or sand storms are not considered as well yet these do have an effect on the module performance.

Due to the above discussed factors, a number of researchers consider the approach above as one that leads to an oversized/undersized non optimal system [75] [67] [76]. The investigation has shown that the current typical PV system sizing procedure does not consider the variation in the load demand and irradiance with time throughout the year. If the load demand consists of consecutive days where the daily load is higher than the average daily load, the battery capacity designed using this simple procedure may be insufficient to meet the desired days of autonomy and therefore the system is undersized. However, if the days of high load demand are relatively spread over time, the simple sizing procedure may oversize the system since the same system reliability could be achieved by designing with a lower daily load [74] [75] [67] [76].

2.4.3 A Review of Current Approaches to Load modelling

Load modelling enables us to create load profiles that show the trend of electricity consumption as a function of time usually over a full day. The energy consumption represents quantity of energy in Watthours (Wh) that the particular users require in a given day [77].

The determination of the load profile for rural areas in developing countries is quite challenging. Among the reasons for this is that information about the user’s electric profile is not present since a majority of rural areas do not have electricity. The available electricity usage is usually limited to minimal uses such as lighting, phone charging and use of small radios [78]. Nevertheless, a number of studies have been done in regards to rural
electrification in developing countries. This section shall evaluate the efficacy of these methods.

In order to effectively evaluate the methods previously used to develop load profiles in developing countries, a criteria of what constitutes a good load profile for rural areas has been defined. This criteria has been adopted from [78], [79] and [80]. A good load profile in rural areas in developing countries should have the following characteristics:

1. It is parametric thus able to simulate various scenarios of energy consumption [80].
2. The specificities of the load categories (such as households, Small and Large business enterprises) and equipment must have contribution towards the load profile results [80].
3. The socioeconomic conditions and the daily behaviours of the rural community must have a contribution to the load profile [78] [81].
4. It has to be stochastic in nature to embrace the uncertainty of energy consumption in the rural areas [78].
5. It must be aggregative allowing profiles to be generated by summing up multiple profiles for different categories of the community (households, schools etc.) [80].

A review of the current methods that have been used to analyse load profiles in rural areas may be summarised as follows;

i. The researchers do not provide any explanation on how the load profile was developed. There is therefore no chance to evaluate whether the researcher undersized or oversized a profile. In addition, it does not take into consideration the socioeconomic behaviours of the rural communities and produces a static load profile thus does not embrace the uncertainty of energy consumption in the rural areas [77][82][83].

ii. For some methods, the appliances, power ratings, and time windows within which an appliance may be switched on are determined. The hourly power consumption of each appliance is determined by assuming that all appliances are on at the same time in a specific defined window. It is given by (\textit{Power rating} \ast \textit{window width}). This method overestimates the peak usage and will most likely result into oversizing of the system. It also does not take into consideration the socioeconomic behaviours of the
rural communities and produces a static load profile thus does not embrace the uncertainty of energy consumption in the rural areas [77][82].

iii. The appliances, power ratings, and time windows within which an appliance may be switched on are determined. In addition, the actual time in hours (h) for which the appliance is switched on is determined. The power consumption of the appliance is determined \((\text{power rating} \times h)\). The result power is distributed equally over the time windows for which the appliance may be active. This method will produce a peak power that is most likely less than the actual peak power therefore may lead to under sizing of the system. Just like in (i) and (ii), It also does not take into consideration the socioeconomic behaviours of the rural communities and produces a static load profile thus does not embrace the uncertainty of energy consumption in the rural areas [77][82].

iv. The load profiles are assumed to be similar to those in rural communities of similar contexts [82][84]. The research however does not provide an explanation as to how the characteristics of the two communities are compared. Just like in (i), (ii) and (iii), it produces a static load profile thus does not embrace the uncertainty of energy consumption in the rural areas.

v. In another method, the users’ electric needs are categorised into user classes, electric appliances and usage habits. This categorisation includes appliances, power ratings, and time windows within which an appliance may be switched on and actual hours in a day that an appliance is on. The appliance hourly usages are aggregated into a load profile. Random variables are introduced to simulate the likelihood of appliance usage throughout the day and reasonable estimations of the load profiles are obtained [78][84][85][81].

These methods provide more accuracy than those described in (i) to (iii) and can simulate various stochastic scenarios of energy consumption [81][86][87][82][88]. They are suitable for use to estimate load profiles in rural areas that have never had electricity [82] [88]. However, they have the following limitations:

1. Their accuracy may be affected by inaccurate predictions of the current and anticipated appliance inventory, power ratings, and times of use. In [81] the majority
of the high energy appliances that the initial energy survey had predicted to be owned by customers were not present after two years of operation.

2. They do not also consider changes in load depending on anticipated changes in the welfare and habits of the communities [89][81]. A forecast of how many customers will have connected after a given period of time and the growth of appliances purchased during that time is critical to the design of a reliable and financially viable rural electrification system.

The research trend shows there is still need for a load estimation approach that incorporates socioeconomic and gender aspects into the design of year to year load profiles for off grid unelectrified rural communities. Load approaches that show how gender affects current and future loads in households and community income generating projects are needed for proper design and planning of rural electrification systems.

2.4.4 A Review of Affordability of Rural Community Microgrids

With the focus on utilisation of solar PV microgrids to scale up the rural electrification process for countries on the African continent and developing countries in other continents such as Asia, affordability of such community microgrids is essential given the low income levels of the people in rural areas and the still high cost of PV systems [90]. Even though the costs of PV are expected to decrease further, it has been observed that investors still find it hard to take on projects aimed at rural electrification. The approach that is being employed to overcome this challenge is provision of subsidies to these investors by governments. These subsidies are meant to lower the capital and operation costs of these systems. These costs greatly influence the electricity tariffs. If tariff levels are too high for the people in the given community, it will be impossible for the microgrid project to last [1]. This is because the people will naturally be forced to go back to using their cheaper unclean sources of energy. While the cost of solar panels has reduced in recent years as mentioned earlier, the cost of battery storage needed for these microgrids is still high. It is therefore necessary to investigate ways in relation to the microgrid technical design in which the overall cost can be lowered so as to make the electricity affordable.
2.5 Summary

This chapter has discussed the critical literature review on microgrids with a focus on their application and use in remote area electrification. It has also presented a detailed discussion on the current research trends in this area, needs and the existing gaps in the approaches. The next chapter will present a detailed discussion on sustainability of rural electrification systems and address the aim to fill the existing gap in the area of measurement and evaluation of sustainability of rural electrification projects by presenting the sustainability metrics that have been developed in this PhD research.
Chapter Three

Sustainability of Rural Electrification Projects

This chapter presents the sustainability metrics for evaluation of sustainability of rural electrification projects. It discusses and details the important factors to consider when measuring sustainability of these types of projects and proposes an easy to use sustainability evaluation tool kit including guidelines on how the measurement can be done for a given project.

3.1 Introduction

According to the Brundtland Commission, “Sustainability” simply refers to “the ability to meet the needs of the present without compromising the ability of the future generation to meet their needs”. In general sustainability encompasses the social, economic, cultural and environment. When looking at rural electrification projects, a much better definition for sustainability in their context is given in [62] where the authors define sustainability as “The systematic preparedness for a project to maintain an electricity service provision over its life span”. This is the definition that has been adopted in formulation of the sustainability metrics for PV based rural electrification projects in this research. It is essential that rural electrification projects and systems are designed, planned, implemented and managed appropriately for them to be fully sustainable. According to [64] in which a review of off-grid rural electrification projects was carried out, the four categories of sustainability mentioned are institutional, economic, environmental and socio-cultural. Much as these categories are important for project sustainability, other aspects like health and safety, legal
framework, security, technological aspects, supplier and procurement aspects, documentation, ethical and gender aspects are equally important.

3.2 Sustainability Metrics

In this research work a risk analysis based approach to develop a scoring kit for sustainability has been considered. This process involves generation of a list of parameters that highlight the risks involved in setting up rural electrification projects. Previous studies on sustainability of standalone PV systems in developing countries [9], [16], [18], [22], [74], [91]–[99], [62], [100], [64] and reports on energy sustainability [1], [90], [101]–[103], have categorised the factors that affect project sustainability into six main groups. These include technological, economic, social, regulatory, legal and environmental factors. In this research work, we seek to provide a better assessment of sustainability and thus propose inclusion of four additional factors namely health and safety, ethical, gender and security (both physical and political) considerations. The proposed major factors necessary for long term sustainability of rural electrification projects are thus:

1. Technological factors
2. Economic / Financial factors
3. Social/Society
4. Regulatory framework
5. Legal framework
6. Environmental factors
7. Health and Safety considerations
8. Ethical considerations
9. Gender
10. Physical and Political security

In this research, these major factors have been broken down further into sub-factors referred to as the risk descriptions.

3.2.1 Sustainability Risk Description

The risk descriptions (RDs) formulated from the major sustainability factors form the basis for the sustainability metrics proposed. The developed metrics are critical in the planning of microgrids for rural electrification as they enable the project planners to determine whether a
Chapter 3. Sustainability of Rural Electrification Projects

A particular system will be sustainable in the long term. The sustainability factors are interrelated as shown in Figure 3.1 in which case failure on one can lead to poor performance on another and eventually failure of the entire electrification project.

![Diagram of Sustainability Factors](image)

Figure 3.1: Electricity Access Challenge Issues [1]

3.2.1.1 Technological factors

For a rural electrification project to be sustainable, it is important to evaluate and address all the technological challenges anticipated. Issues such as proper demand/load estimation [74], technical-know-how of the people in the community and general knowledge about the PV technology should be put into consideration. If a system is not well dimensioned/sized, it will not meet the requirements of the community and thus risks being abandoned by the community. It is also crucial to consider the potential increase in demand when the electricity service is availed. If this is not done, there is danger of the system being overwhelmed in a short time after commissioning. A system that is designed accurately according to the needs of community will not easily be rejected or abandoned due to less disappointments [64].
Furthermore, if the system is designed in such a way that it improves the performance of activities in the area, enables development of income generating projects in the area, allows people to add value to their agricultural produce and is generally tied to overall development of the areas, then that system stands a much higher chance of becoming self-sustaining in the long run. Reliability should also be considered as this gives a bonus to long term sustainability [62]. It is also necessary to put in place a clear maintenance and operation plan [90]. Spares should be available such that components that fail are easily replaced to ensure continuous operation of the system. Another technological factor that needs to be considered is the standard of appliances and components used. These should be approved according to country and international standards. Due to the continued growth of the PV market, many products that do not meet required international and national standards are released into the market. In some low developed countries, these standards do not exist or in cases where they exist, they are not enforced. Another consideration that contributes to technological sustainability of a project is capacity building of people to carry out operations and maintenance work. If training processes and procedures are put in place and adhered to, then there is bound to be sustainable system operation. Documentation of the system’s technical aspects is important to ensure smooth operation and continuity in case of maintenance staff turnover. It is important that procedures and processes such as fault management and system performance are well documented.

It is also important to ensure the energy resources utilised are fully renewable as these are sustainable. Use of fossil based fuels like diesel leads to high operation costs, environmental pollution and the system operators have to deal with numerous challenges associated with delivery of the fuel thus making the system unsustainable. Lastly, the system should be designed in such a way that it is futureproof with the capability of integration with the main grid once it is extended to the area. This will ensure continuous operation instead of abandonment of the equipment.

- Technological Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

RD1 Poor sizing of system due to inadequate energy demand assessment

This risk description entails both oversizing and undersizing of the system. An oversized system leads to increased costs of installation, operation and maintenance making it
financially unsustainable. When a system is undersized, there is a decrease in its reliability forcing customers to abandon it completely [104] [105].

**RCM:** Consider the anticipated increase in demand and correctly estimate the current load. Make use of internationally approved standards when sizing the system.

**RD2  Lack of technical knowledge about the technology / system among the people in the community**

The impact on sustainability of a project if people do not have any technical knowledge about the system can be quite huge. This is because there will be increased tendency to misuse the system by overloading it and other poor user behaviours that can cause the batteries to be drained in a short time. Also absence of trained local personnel to provide basic first line support does not favour long term sustainability.

**RCM:** Make provision for technical training of personnel, capacity building and knowledge sharing [106]. The training should be adequate, well conducted and appropriate. The appropriateness is a critical factor because rural people are majorly semi-illiterate or completely illiterate. Basic technical principles should be well articulated.

**RD3  Technical solution is not tied to the economic activities in the area**

This RD looks at the solution presented to the community and evaluates its ability to enhance the commercial activities of the area. It is important for an electrification project to help the community to increase earnings from their commercial ventures and add value to their products.

**RCM:** Thorough community engagement during the needs assessment process. This will help to ensure that the technology enhances the activities of the community and allows for the development of businesses. Things like value add to agricultural produce, improvement of existing commercial activities will boost the sustainability of the rural electrification project.

**RD4  Project does not promote creation of income generating projects**

Rural communities are faced with low or no incomes. In other words they are poor. It is important that electrification projects promote economic activities in the area that can allow the people to earn money and in turn be able to pay for the electricity. This will help ensure long term sustainability for the project.
RCM: Availability of electricity service should allow for the start up of income generating projects that were not previously possible. Needs assessment should be thoroughly done together with anticipated future activities that can arise from provision of electricity.

RD5  Low reliability of the system
In electrical systems, system reliability simply refers to quality and consistent electricity supply. It is necessary that the community is provided with reliable power to be able to meet their needs. Poor or low reliability has a negative effect on project sustainability as people grow tired of using a system that does not meet their needs. They eventually revert to previous unclean sources of energy or find alternatives.

RCM: Proper needs assessment and system planning. It is also important to make arrangements for consistent performance evaluation of the system.

RD6  Lack of a clear maintenance and operation plan
As with any technical system, rural electrification systems require some level of maintenance and operations work so that the system consistently delivers the required power and performs as expected. It is important to have in place clear guidelines on how these activities should be conducted. This will help to ensure long term project sustainability.

RCM: Operation and maintenance plans should be well formulated and documented. Documentation helps to ensure continuity even after change of staff.

RD7  Lack of spares for system components
There is a possibility of system components breaking down or failing to work. This affects the sustainability greatly making it necessary to replace these components. Spares should be acquired and readily available.

RCM: Provision should be made for acquisition of spares. The "how", "what", "where" and "when" of the process should be clearly defined.

RD8  No standards against which system components and appliances are checked
Due to the growing interest in solar PV systems, a number of companies are manufacturing and dealing in system components and appliances that use solar energy. Most of these companies ship their products to developing countries that are seeing a boom in solar technology use. However many of these low developed countries do not have standards
against which these components and appliances can be checked. This creates a risk of using sub-standard equipment which may not be sustainable in the long term.

**RCM:** In the absence of national standards, international standards can and should be followed.

**RD9  Absence of system documentation**

System documentation is very important in a rural electrification project as it is in any other engineering or network system. Things like network layout, operation and maintenance guides should be well documented. This allows for the continuity of operations work in case of staff turnover and also makes roll back to earlier configurations easy in case of failed upgrades or changes.

**RCM:** Documentation should be done and updated in case of any system changes.

**RD10  Poor installation and inability of the system to be integrated with the main grid**

It is not unusual to find poorly installed equipment in rural electrification systems. Poor installation can lead to equipment malfunction and eventual complete failure. This negatively impacts on the sustainability. It is therefore important to ensure that proper standards and guidelines are followed when installing this type of equipment. Furthermore it is important to ensure that installed systems have provision for connection to the main grid when it is eventually extended to the area [106].

**RCM:** Internationally approved installation standards should be followed. Project should be future proof so as to avoid having stranded assets.

**RD11  Electricity access is not linked to other services and infrastructure in the community**

It is important to note that access to electricity is critical for overall sustainable development of an area. Reliable and affordable electricity enables economic development in communities allowing them to become industrialised and service-oriented. The more electricity access enables modernisation of areas, the higher the chances of survival of the rural electrification project [107].

**RCM:** Ensure the technology enhances development of additional infrastructure and services in the community. Electricity access should facilitate other developmental programs.
RD12 Electricity access is not able to improve the agricultural productivity of the community

Most rural areas rely on agriculture as their source of livelihood. When electricity access enables these farmers to improve on their produce through mechanisation and value addition, then the chances of long term survival of the rural electrification system are higher.

**RCM:** Consideration should be given to opportunities for value add to agricultural produce and betterment of the way agricultural activities are done by ensuring secure and efficient electricity service.

RD13 No interaction with all stakeholders (customers, government, private investors, donors, civil society organisations) during planning stage of the project

Provision for active participation of communities which will be served by the electrification project is crucial for ensuring long term sustainability [108]. Other stakeholders such as the donors, civil society and the government also help to ensure that the new technology is presented in a manner that fully meets the requirements of the community and also encourages community acceptance of the project [109] [110]. This has a positive effect on overall project sustainability [111].

**RCM:** Views of all stakeholders should be put into consideration when designing the systems.

RD14 Solution utilises non-renewable energy sources

It is increasingly becoming important for countries to move towards a fossil-free electricity generation so as to ensure long term sustainable societies [109]. This is because fossil fuels are reducing greatly and they are not good for the environment [112], [113]. There is growing and urgent need to look at alternative sources of generation, i.e. renewables in order to secure a sustainable future.

**RCM:** Renewables should be explored as the best options for sustainable electricity supply when designing rural electrification projects.

RD15 Short lifespan of system components

The lifespan of the system components can have a negative effect on sustainability of a project when it is too short. This is because there will always be need to replace these components hence increasing the cost of operation [105]. This could even occur before the
break-even point for the investment. Less frequent replacements help to enhance the sustainability of an electrification project.

**RCM:** Proper and thorough consideration should be given to the life span of the equipment as this dictates the replacement times. A financing model for battery replacement should also be in existence.

### 3.2.1.2 Economic / Financial factors

Economic sustainability of a project is critical for overall project sustainability given the low income levels of the people in rural areas and the still high cost of PV systems [90]. Even though the costs of PV are expected to decrease, investors still find it hard to take on projects aimed at rural electrification. If governments provide appropriate subsidies to these investors, then it will lower the capital and operation costs of these systems hence boosting the prospects of sustainability. Closely inter-linked with the technological factors are the prices and choice of system components as this has an impact on the cost (investment cost and operational cost). Furthermore evaluation of the community’s ability and willingness to pay for the service is necessary so that the investor can adequately plan for the financial aspects of the project such as cost of the electricity, maintenance budget, expected breakeven point etc. If tariff levels are too high for the people in the given community, it will be impossible for the project to last [1]. This is because the people will naturally be forced to go back to using their cheaper unclean sources of energy. As mentioned in the technical category, it is important to ensure that the electricity use is linked to productive income generating activities. This will enable people to pay for the electricity used and thus make cost recovery achievable [9]. Clear business models are very crucial for project self-sustainability as investors move away from relying on government financial support when appropriate subsidies are given [99]. It is important to note that the subsidies should be appropriately targeted so as to encourage investment in and continued operation of rural electrification projects [18].

- **Financial Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)**

**RD16  High cost of system components**

The cost of system components is an important factor in deciding how much can be invested in the rural electrification projects. High costs negatively affect the sustainability of the
project because they increase the capital costs [114] and operational costs when they need to be replaced. This eventually makes it financially difficult to sustain.

Risk control measures include: Economies of scale can be explored in addition to the available financing mechanisms.

**RD17 Absence of government subsidies for investment in rural electrification projects**

Rural electrification projects are capital intensive often requiring huge amounts of money from the investor to be able to execute the project [95] [105]. This, coupled with the low ability to pay for the service makes them very unattractive investment options. The costs for maintenance also get higher when components fail or have a short life span and also need for payment of taxes. This makes it financially unsustainable.

**RCM:** Governments should consider provision of subsidies as these encourage investors to install and operate rural electrification projects.

**RD18 High tariff levels**

Due to the high costs involved in setting up these rural electrification costs, investors are forced to charge a high fee for the electricity. Generally people in rural areas are poor and thus their ability to pay is very low. This results in them abandoning the new technology in favour of cheaper unclean sources.

**RCM:** Take advantage of any available subsidies so as to minimise capital and operational costs thus creating an opportunity for charging a lower fee for the electricity.

**RD19 Community is not able to pay for the electricity**

When users are not able to pay for the services, it is impossible for the investor to continue operating the system. There is need to have mechanisms in place to enable the people in these rural communities to earn some money which they can use to pay for the electricity.

**RCM:** Availability of electricity service should allow for the startup of income generating projects that were not previously possible which in turn economically empowers the community to pay for the electricity. Also ensure that the tariffs are not too high.

**RD20 Community is not willing to pay for the electricity**

In cases where the electricity tariffs are higher than the amount paid for unclean sources of energy, the community will not be willing to pay for the service [9]. This makes it difficult to operate the electrification project and can lead to complete shutdown of the system.
Chapter 3. Sustainability of Rural Electrification Projects

**RCM:** Ensure affordable tariffs (almost to the value or less than what was previously paid for the unclean energy sources)

**RD21 Absence of business models to guide operations**
Business models help to speed up deployment of rural electrification projects and also ensure that they stay operational [106] [99] [111]. These also further help customers to find ways of paying for the electricity [17] which means the system can be profitable for the investor.

**RCM:** Business models should be well formulated so that the financial gains to the investor are clear. Financial management processes should also be put in place.

**RD22 Existing subsidies poorly targeted**
As mentioned before, government subsidies play a big role in helping to lower the capital and operational costs of rural electrification projects. However if these subsidies are not appropriately allocated, they cannot be of benefit to the investor. This in turn leads the investors to shy away from participation in such projects.

**RCM:** Government should revise subsidies to ensure that they are appropriate and beneficial.

**3.2.1.3 Social/Society**
The behaviour and lifestyle of the community, community leadership and impact access of electricity will have on the community have to be put into consideration when planning rural electrification projects. This is necessary so that the people within the community view the availability of new services [101] that they could not access before in a positive way. If proper consideration is not given to this factor, there is a high risk of people not embracing the new technology. Creation of awareness among the people through education about the new technology should be done. In this way the community gains a better understanding of the project to be undertaken in their area. It is important to note that many people in rural areas in developing countries do not want technology to suppress their cultural norms and beliefs. Furthermore if social networks within the community are utilised to promote the adoption of PV technology, it boosts the sustainability prospects of the project [16]. These social networks can also be incorporated into ownership of the project. Once the community feels they have a stake in the project through ownership, they will do all it takes to ensure that it does not collapse. An example of social consideration is seen in Ghana [95] where
successful implementation of rural electrification projects increased due to the involvement of the community leadership.

- Social Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

**RD23 Community's lifestyle and way of life ignored during project design**

For any development project in rural areas to be sustainable, it should take into consideration the community lifestyle. This makes it easy for the people to accept the technology and ensure its survival.

**RCM:** A proper assessment and understanding of the community social setup should be done in the early stages of project formulation.

**RD24 Electricity service/access is interfering with the cultural norms and beliefs of the community**

Many communities in less developed countries especially in Sub-Saharan Africa have strong cultural beliefs and ties that they would want to protect. In these communities, it is necessary that the new technologies introduced do not cause the people to abandon their cultural norms. If this happens, people tend to have a negative attitude to the development and there would be less acceptance of the new service [115].

**RCM:** A proper assessment and understanding of the community social setup should be done in the early stages of project formulation.

**RD25 Lack of awareness in the community about the new service**

Creation of awareness in the community goes hand in hand with training of people about the new technology. When people understand the new developments, they are more receptive of the enhancements and changes. This has a positive effect on the sustainability of the project as the community is more willing to ensure that it stays operational.

**RCM:** Community should be trained and awareness created about the project.

**RD26 Project ignores potential role of existing associations / groups within the community**

In order to have a sustainable business model for implementation of rural electrification projects, it is critical that existing groups such as cooperatives are integrated in the project structure. These associations act as pipelines for getting the technology to the people.
Furthermore, they offer the opportunity for facilitation of financing needed by the rural people to acquire electrification kits [116]. This offers a boost to long term sustainability of the project.

**RCM:** Involve existing groups and associations in the running of the project.

**RD27  Community leadership lacks proper understanding of project activities**
Community leadership can encourage fast roll out of rural electrification projects if the project goals and activities are well understood [95]. In a similar manner the leaders also ensure that the project is maintained and continues to be operational thus contributing to its sustainability. This is possible if the leaders are fully aware of what the project is meant to deliver and achieve.

**RCM:** Community leaders should be made aware of the project and involved in the planning stage.

### 3.2.1.4 Regulatory framework

The regulatory framework and presence of institutional policy is very crucial for ensuring that the projects undertaken to electrify remote areas last in the long term. This can be achieved by governments putting in place an authority or agency that coordinates and oversees all projects aimed at rural electrification. A number of developing countries have formed these types of authorities as indicated in [63]. Furthermore there should be standards in place to be followed when setting up these electrification projects and the regulatory authority should ensure that they are correctly followed. Absence of regulations and policies has been known to lead to failure of electrification projects [64].

- **Regulatory Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)**

**RD28  Absence of a rural electrification authority**
A rural electrification authority or agency helps countries to organise, regulate and oversee rural electrification programs. This allows for faster deployment of projects and continued support during operation. Projects can be easily tracked by the authority [1], [63], [102].

**RCM:** Governments should create rural electrification agencies to regulate the activities of the various players.
RD29 No clear policy on rural electrification processes
Absence of a clear policy to govern rural electrification programs and processes makes it difficult to regulate the activities of investors and ensure long term sustainability. Without policies, it is hard to ensure that customer needs are fully met and that the projects are carried out in an acceptable manner.
RCM: Governments should formulate and enforce policy on rural electrification.

RD30 Absence of mechanism for monitoring of the impacts of the defined government policies and strategies
It is important to ensure and verify that set government policies on rural electrification are met. Proper monitoring helps the government to know if the policies are furthering growth of the rural electrification sector.
RCM: Monitoring and evaluation of the defined government policies and strategies should be done to determine if they are supporting / furthering sustainability.

RD31 Absence of standards for ascertaining service quality
Poor quality of service can greatly reduce overall sustainability of a rural electrification project. This is because people increasingly become dissatisfied with the solution being offered and end up abandoning it. It is thus necessary for governments to put in place standards defining acceptable quality of service levels. This helps to ensure long term sustainability.
RCM: Country standards on service quality need to be formulated based on internationally approved standards.

3.2.1.5 Legal framework
The legal framework encompasses the laws governing rural electrification projects. These laws are necessary to protect all parties involved in the project. This includes the government, investors in the sector and electricity consumers (customers). It also puts into consideration laws to protect the environment [63]. Lack of a proper legal framework for regulation of operation of off-grid electrification projects is a major hindrance in obtaining long term sustainability of these projects. An example of this is given in [117] where it is noted that absence of a good legal framework needed for regulation of the renewable energy industry is a hindrance to its growth and eventual sustainability.
Legal Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

RD32  Absence of laws governing rural electrification projects
Due to the growing demand for renewables, many players are attracted to the market but without clear laws to govern the processes and activities in rural electrification, a number of projects eventually die out after the a short time in operation [4].
RCM: Legal framework should be clearly stipulated when policy on rural electrification is formulated.

RD33  Absence of laws to protect the environment from effects of electricity generation activities in rural areas
It is important to note that for rural electrification projects to be sustainable, they should favour a clean and sustainable environment. Laws on protection of the environment and general environmental awareness are needed to ensure that the projects are sustainable [118].
RCM: Legal framework should clearly define and provide a law on waste management and environmental protection.

3.2.1.6 Environmental factors
Protection of the environment is a major concern globally. Even though most renewable resources are environmentally friendly, it is important to have clear regulations and standards for disposal of system components at the end of their life or when they become defective. Items such as solar panels, batteries, worn out cables etc. should be well disposed off. With clear environmental regulations and policies, off-grid electrification projects can be sustainable [93]. Governments can put in place regulations that require the investors to have a plan for recycling of the components. Management of the waste is very important.

Environmental Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

RD34  Absence of regulations and standards for disposal of system components
This is related to RD33 on environmental protection. There are should be clear rules to govern disposal of components such as batteries, PV panels etc. This helps to ensure that the electrification project is run in an environmentally sustainable manner.
RCM: Legal framework should be defined and clearly provide a law on waste management.
RD35 No provision for recycling of system components
System components that can be recycled should be collected and proper procedures for recycling followed when handling them. A clear recycling plan boosts the overall sustainability of a rural electrification project [64].

RCM: Laws should be put in place and enforced. Certificates can be issued for compliance e.g. if batteries are recycled.

RD36 Absence of a clear waste management plan
A clear and implementable waste management plan (e.g. disposal of components such as batteries) needs to be defined when planning a rural electrification project. This is necessary for ensuring a clean environment and general acceptance of the project in the community. Once this is achieved, the sustainability of the project will be boosted.

RCM: Waste management process should be part of the project design process.

3.2.1.7 Health and Safety considerations
It is important to consider health and safety of the consumers and maintenance personnel when designing off-grid electricity projects [63]. This should be enforced by the regulators. Certificates should be issued for projects that pass the stipulated health and safety standards. Failure to promote safety standards in these installations can be fatal and eventually lead to closure of the project. There should be clear processes and procedures for management of electrical faults like overcurrents on the system. Consumers are also hesitant to trust a system that has no health and safety clearance given that many of these people already know that electricity is dangerous. In addition, consideration should be given to what needs to be done in case of a fire outbreak so as to prevent extreme damage to the system components and fatal injuries.

- Health and Safety Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

RD37 Absence of health and safety processes and procedures for electrical fault management
Rural electrification involves currents and voltages. These can cause fatal injuries if any faults are not carefully handled. Projects that lack health and safety procedures cannot be sustainable in the long term.
RCM: Only project designs that have proper health and safety considerations/measures should be approved for implementation.

RD38 Absence of regulator-defined health and safety measures
As stated before, health and safety measures are necessary for ensuring sustainability of a rural electrification project. Presence of standards in this regard can help investors and project owners check if their health and safety measures are in line with the regulator-defined measures.

RCM: Health and Safety standards should be formulated and enforced. A certificate of compliance can be issued for projects that measure up to recommended standards.

RD39 No provision for fire management at the facilities housing equipment and other system components
Fires can occur due to electrical faults and also as a result of external factors. It is therefore important to ensure that systems and people are protected in the event of a fire. This can help to prevent complete loss of system and eventual closure of the project.

RCM: Fire protection should be ensured and procedures for what needs to be done in case of a fire should be made known. Trainings should be carried out to create awareness among the people that work at the premises.

RD40 Consumers/Community has a general "bad feeling" about the safety of the project
This risk factor should be mitigated as it can lead to refusal to accept and utilise the system hence rendering it unsustainable.

RCM: Create awareness among the people on measures that have been undertaken to ensure safety in service delivery.

3.2.1.8 Ethical considerations
Development of rural electrification projects should be done in an ethical manner following proper code of conduct. Corruption exists in a number of developing countries [96], [119] and this creates lack of trust in the government. If ethical standards are adhered to, this will create trust from the consumers in their governments and the electricity supplier/investor. Once trust is not established, some of the consumers will not be interested in utilising the system and will sit back and wait for eventual connection to the main grid no matter how
long it takes. The end result would be for the investor to pull out of operation of the project leading to eventual closure. Without adhering to proper code of conduct in management of projects, there will be little progress on sustainable technological advances [119].

- **Ethical Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)**

  **RD41 Engineering ethical standards not followed in project design**
  Failure to follow engineering ethical standards leads to sub-standard projects that cannot last for a long time. This is because the projects are poorly designed and implemented which in most cases results into unsuitable and sometimes dangerous to use systems.
  **RCM:** Stipulated standards should be adhered to and enforced by the regulatory authority and engineering associations. Penalties for failure to comply should be clearly outlined so that all players in the process know the cost of bypassing or ignoring the standards.

  **RD42 High level of corruption during execution of project activities**
  Corruption has a negative effect on sustainability of projects because it lowers the efficiency of implementation and operation [115].
  **RCM:** Government laws on corruption should be clear and enforced.

  **RD43 Lack of proper code of conduct in management of project activities**
  This risk description also affects the implementation efficiency leading to sub-standard projects that cannot be sustainable in the long term.
  **RCM:** Processes should be clear and adhered to. There should be penalties for misconduct.

**3.2.1.9 Gender**
This factor is not given enough consideration when it comes to planning and designing of rural electrification projects. In most of the surveys done prior to implementation of these types of projects, men are the most interviewed as compared to women thus most solutions are designed basing on what men want to use energy for [64]. It is important to put women as well at the forefront when planning these systems because women are the most users of this electricity in a home since they do most of the activities like cooking, washing, ironing, mending clothes etc. They are also the ones that go out in search of alternative sources of energy like wood to use for cooking together with their female children. Furthermore in a number of African countries like Uganda, women in rural areas play a major role in ensuring
that their school-going children do their homework in the evening after completion of house chores. Overall women benefit highly from electrification projects as has been stated in [1]. Once the system is designed to meet their requirements, it would be a bonus in ensuring long term sustainability.

- **Gender Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)**

**RD44  Women are not involved in initial surveys done during project planning phase**

In most rural communities, women are the major consumers of energy and thus should be at the forefront of rural electrification programs [115]. They are able to provide a near accurate description of activities that can be electrified and thus help the engineers to correctly estimate the load.

**RCM:** The role of women in design, operation and management of projects should be considered.

**RD45  Poor understanding of the daily routine of a typical woman in the community where the project is to be implemented**

A clear understanding of the work and activities done by women in a society on a daily basis enables projects designers to create solutions that can improve their lifestyle thus leading to greater acceptance of the solutions. This boosts the chances for survival of the project.

**RCM:** Women's role in the homes and community at large should be put at the forefront during project planning. Research shows that women are now driving growth of renewable energy technologies.

**RD46  Lack of knowledge about the corresponding percentage share of commercial activities undertaken by men and women**

It is important to have a clear understanding of the commercial activities undertaken by men and women in the community. This helps to properly size the system to suit the needs of the community. If only men are thoroughly interviewed during the initial surveys then there is a great risk of under-sizing the system.

**Risk control measures include:** Proper and accurate surveys should be done during the planning phase.
RD47 Lack of knowledge about the cultural expectations of women and men in the community
This risk leads to poorly designed electrification systems that do not improve the lifestyle of the community. In the long term, it becomes unsustainable as people remain comfortable in the traditional setting.

RCM: Proper and accurate surveys should be done during the planning phase so that a suitable electrification project is implemented.

3.2.1.10 Physical and Political Security
This category seems obvious to many people but it is necessary to put considerable effort in evaluating its effect on the sustainability of a rural electrification project. This is because a number of developing countries especially in Africa are still growing democracies. A poor political environment characterised by political instability cannot favour sustainable development which includes electrification of rural areas.

In addition to the political environment, physical security of the systems has to be ensured to reduce theft of system components. Theft of components leads to decline in service reliability and increase in maintenance costs as new components have to be bought to replace the ones stolen. This creates financial strain on the investor who may be forced to pull out of operation. Also access to premises where system components are located needs to be streamlined to have clear accountability of what takes place at the site and easy follow-up on persons responsible when something goes wrong at the premises.

- Security Risk Descriptions (RD) and Corresponding Risk Control Measures (RCM)

RD48 Theft of solar equipment and other system components
Theft of equipment as a result of poor security systems leads to increased cost of operation and service disruptions. This affects project sustainability since it becomes expensive to keep replacing the components.

RCM: Provide for security of the premises and equipment during project planning.
RD49  Danger of constantly changing governments
When governments are constantly changing as a result of power struggles, it becomes hard to implement and enforce policies on rural electrification. This negatively affects sustainability of rural electrification projects.
RCM: Clearly review and analyse the political situation.

RD50  Political unrest in the community
Political unrest makes it difficult to implement, maintain and operate rural electrification projects. When political tensions arise in a country, there is a risk of violence which is negatively affects these projects.
RCM: Clear review and analysis of the political situation.

3.2.2 Sustainability Risk Assessment
Each individual risk description described in section 3.1.1 is ranked basing on its impact on the system and likelihood of occurrence. The ranking takes on three levels with an appropriate score for each level. The levels and corresponding scores are as shown in Table 3.1.

Table 3.1: Ranking Levels for Sustainability Risk Assessment

<table>
<thead>
<tr>
<th>Impact On the System (Impact)</th>
<th>Likelihood of Occurrence (Likelihood)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

In this approach, a risk is a measure of what can go wrong regarding project sustainability. It is the product of the impact of the parameter on the project and likelihood of occurrence as shown in equation (3.1).

\[
\text{Risk} = \text{Impact} \times \text{Likelihood} \tag{3.1}
\]
Basing on the score for each level, there are nine possible values for this product as seen in Figure 3.2 below. These result from the following combinations of Impact and Likelihood.

A product higher than 16 is considered highly risky. This is because at that value, given the clear cut boundaries defined in the risk assessment matrix used in this particular research, the parameter under consideration has both medium impact on the system and medium likelihood of occurrence at which point a higher rank in either one of the two negatively affects the system.

**3.2.2.1 Guideline for Evaluation**

Considering that the allocation of the rank values for the risk descriptions is subjective, the guide below has been formulated to assist the evaluator in this critical task of assessing a project’s sustainability. It is important to ascertain which risk control measures exist as these lower the likelihood of occurrence for the particular risk description to be evaluated.

- **Impact on the System**
  - **A. Impact on the system: High Ranking (9)**
    
    A ranking of 9 is given when the risk factor can have the following effect on the rural electrification project:
    
    - Causes complete shutdown of the system hence rendering it unusable.
    - Only allows the system to function for the first few weeks and thereafter the system becomes unusable.
    - Causes equipment failure.
    - Leads to incompatibility between the components.
    - Causes people to become dissatisfied with the level of electrical service and eventually abandon it all together.
Chapter 3. Sustainability of Rural Electrification Projects

- Causes the investor to pull out of operation of the rural electrification system.

**B. Impact on the system: Medium Ranking (4)**
A ranking of 4 is given when the risk factor can have the following effect on the rural electrification project:
- It can cause premature failure of easily available components.
- It can lead to minor disruption in the service.

**C. Impact on the system: Low Ranking (1)**
A ranking of 1 is given when the risk factor can have the following effect on the rural electrification project:
- Does not cause disruption of service.
- Does not discourage users from utilising the electrical service provided.

- **Likelihood of Occurrence**
The ranking of likelihood of occurrence is governed by the existence of risk mitigation factors. These are also known as the risk control measures.

**A. Likelihood of occurrence: High Ranking (9)**
A ranking of 9 is given in the following circumstances:
- When no control measures or risk mitigation factors are in place.
- When critical control measures have been adopted but to only a small extent.

**B. Likelihood of occurrence: Medium Ranking (4)**
A ranking of 4 is given in the following circumstances:
- When some of the control measures have been adopted to a large extent.
- Only critical control measures have been put in place and adopted but others not in place.

**C. Likelihood of occurrence: Low Ranking (1)**
A ranking of 1 is given in the following circumstances:
- When all the risk control measures or mitigation factors have been put in place.

A risk assessment table has been prepared in MS Excel containing all the risk parameters and allows the user to input the individual values for impact and likelihood. It then calculates the
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sum of the individual risks. The sum is then divided by the worst possible total risk to obtain the percentage total risk as shown in equation (3.2).

\[
\% \text{ Total Risk} = \left( \frac{\text{Total Risk}}{\text{Worst Total Risk}} \right) \times 100
\]

\[(3.2)\]

Where; Worst Total Risk = 81 x Total Number of Risk Descriptions

In this research work, the total number of risk descriptions (RDs) is 50. The proposed risk assessment method was tested against three successful rural electrification projects in Chile, Cape Verde and Kenya. The following results were obtained.

I. Santo Antao in Cape Verde
The microgrid solution set up in Santa Antao has been considered a successful project and similar types of projects are being replicated in West Africa [120]. This project scored 20.78% for overall risk assessment.

II. Huatacondo in Chile
This project was established in 2010 and is currently still operational [111]. The proposed risk assessment method was used to evaluate it and the resulting score was 19.14%.

III. Mpeketoni in Kenya [9][10]
This community microgrid scored 25.73% when evaluated using the proposed risk assessment method.

From the results obtained, it is can be seen that the overall risk assessment for successful projects is approximately 20%. In order to cater for assumptions made during the evaluation, a margin of +5% has been assigned which results into 25% as the overall risk for projects that are sustainable. Hence in this research a range of 0 to 25% has been set as the acceptable risk range for sustainable projects. In order to obtain the range for medium risk, the maximum value for sustainable projects is multiplied by two and a margin of +5% added to the result to take into consideration assumptions that may be made. This results into a range of 25% to 55%. Finally, it can then be considered that beyond 55% is unsustainable. These ranges are indicated in Figure 3.3 shown below. Figure 3.3 can be used to determine whether a planned rural electrification project will be sustainable or not by checking the value obtained from risk assessment process against the ranges indicated.
For projects whose percentage total risk falls within the green zone (≤25%) as indicated in Figure 3.3, it means that they can be implemented because they are deemed highly sustainable. For those that lie within the amber zone (25%-55%), it means that a few aspects have to be taken care of before the project can be implemented. Lastly for projects whose percentage total risk falls within the red zone, it means that they are highly risky and should not be implemented because they will not be sustainable. It thus requires full re-evaluation of the project before any implementation can take place.

In using this sustainability score toolkit, it is important to note that a clearer description of the risks and controls for any electrification projects gives a better evaluation of the project’s sustainability. It is important to have a clear understanding of the controls needed to lower the risk value before a project is undertaken.

### 3.3 Comparison of Proposed Approach with Other Approaches in Literature

In [18], the authors discuss the energy indicators for sustainable development (EISD) grouped into three major themes namely; social, economic and environmental. These are further broken down into sub-themes and the inter-linkage between the categories noted. However some parameters such as gender, technological and ethical aspects were not adequately addressed. In the risk based approach proposed in this research, a base of indicators for sustainability has been increased hence giving a better way of ascertaining if a rural electrification project will be sustainable.
There are four main categories of sustainability presented in [93] basing on a study carried to determine if rural electrification projects in Ecuador are sustainable. These are; institutional, economic, environmental, and socio-cultural. These categories have been discussed adequately but metrics to measure the sustainability parameters have not been provided. The risk based approach taken in this research work provides an easy way of determining sustainability of the project.

In [62], an analysis of sustainability of off-grid PV systems in Malawi was done by carrying out a field survey of 43 projects. This survey involved verification of the working state of the systems, expected electricity service delivery and what electricity was actually delivered. The categories of sustainability indicators evaluated were; technical, economic, social and organisational. However even though environmental sustainability was identified as necessary for project sustainability, it was not studied in detail. The 43 projects were scored and ranked against each other basing on the indicators for sustainability. A number of parameters for poor sustainability were identified and stated just like has been given in this risk based approach but the sustainability measurement method does not cater for additional sustainability indicators and does not give a straightforward method for prior assessment of sustainability of a project in the planning phase. It is thus not possible to predict the sustainability of the project as is the case with the risk based approach presented in this research.

The world bank staff together with teams from external organisations [63] have put together a comprehensive and substantial document consisting of regulatory indicators for sustainable energy that can be used by policy makers as a scorecard to ensure that their countries have a proper regulatory framework that can attract investments in energy projects. The scorecard is applicable to any country. The main concentration of the indicators provided is on policies, standards and regulations as regards energy technology adoption, use, energy efficiency and electricity service delivery. These are similar to the regulatory, legal and some of the technological parameters considered in the risk based approach taken in this research. The proposed risk based approach can be used as a quicker and easier way of verifying overall sustainability of a project before it is implemented.
3.4 Summary

This chapter has given a detailed analysis of the sustainability issues in rural electrification and presented the metrics that have been developed in the research for measuring sustainability of rural electrification projects. The next chapter provides a detailed methodology for designing an optimal and sustainable microgrid for rural communities.
Chapter Four

An Optimal Rural Community PV Microgrid Design

This chapter discusses the methodology and approach proposed in this research for designing an optimal community PV microgrid for rural electrification. An efficient and robust sizing approach for off-grid PV microgrid systems that has been named as the ComµGrid Sizing Approach is developed and presented. The approach utilizes “Mixed Integer Linear Programming (MILP)” to optimally size the PV microgrid and the “Density Based Spatial Clustering of Applications with Noise (DBSCAN)” algorithm to aggregate load and meteorological data.

4.1 Introduction

As discussed in the previous chapters, extending the main grid to rural remote communities where most people, especially in Africa, live cannot be easily achieved because of the technical and financing difficulties associated with such projects. Microgrids offer a cost effective option for electrifying these remote areas as they can both function independently from the main grid and also be designed to interconnect with the main grid should there be an opportunity for extension of the grid to the remote community. Microgrid design consists of several aspects of the microgrid such as generation modelling, load modelling, storage, local network, sizing of the components and determination of the control strategy. Sizing of the system components is a very important step in the design of PV microgrid systems. As discussed in Chapter Two, the current existing PV system sizing approaches have a number of limitations making it necessary to develop an efficient and improved approach for sizing PV systems. It should be noted that when sizing PV systems, the main aim should be to find
an optimum size of the components. The optimum solution is one that meets the given load demand at a set reliability level while minimising capital and operational costs [59].

Numerical methods are among the methods proposed in literature to improve the accuracy of PV system sizing. These methods evaluate the load, the PV output energy and battery state of charge for each hour throughout the year. The battery charges when the PV output energy is greater than the load demand current and discharges when the PV output is less than the load demand. If the output from the PV and battery cannot meet the load demand, there is a deficit [74]. A Loss of Load probability (LLP) is used as the measure of the system’s reliability. The LLP is defined as the ratio of the total deficit energy to the total load demand over the period of consideration, typically one year. With a predefined LLP based on the user’s satisfaction, an optimal configuration of the PV and battery is determined. Numerical methods yield more reliable and optimum systems. The shortcoming with the numerical method discussed above is that the process of iterating through hourly data leads to long execution times and may sometimes lead to inability to converge to an optimal solution [76]. One way of overcoming this challenge is to reduce the time steps of the iteration without affecting the outliers in the hourly load demand and PV output energy.

This PhD research presents the ComµGrid Sizing approach as a new method for PV system sizing based on the Density Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm and Mixed Integer Linear Programming (MILP) algorithm to determine the sizing of the solar PV system components that will give a minimum Annualized Total Life Cycle Cost (ATLCC) for a predefined desired LLP. MATLAB has an optimization toolbox which has been used in the thesis. The toolbox includes solvers for linear programming (LP), mixed-integer linear programming (MILP), quadratic programming (QP), nonlinear programming (NLP), constrained linear least squares, nonlinear least squares, and nonlinear equations. While various other clustering algorithms exist such as K-Means, CLARA, CURE, CLARANS etc., the DBSCAN algorithm has been used in this thesis as it was sufficient for analysing and clustering of the particular data handled. The ComµGrid Sizing approach provides a more reliable sizing procedure than the basic sizing method since it considers the variation in the load demand and irradiance throughout the year instead of average values of load and irradiance. It also provides improvement to the numerical method discussed above by reducing the time steps of the iteration. The next sections of this chapter will describe the
DBSCAN clustering algorithm, the MILP algorithm and the optimization process of the proposed sizing approach. Sections 4.1 and 4.2 define the DBSCAN algorithm and the MILP techniques respectively that have been applied in the ComµGrid Sizing approach. Section 4.3 presents the ComµGrid sizing approach. A case study is then used to compare the ComµGrid sizing approach with the basic sizing approach, the numerical approach defined in [74] and the sizing based on Homer software.

4.1 DBSCAN Clustering Algorithm

Clustering is defined as the process of subdividing a set of data objects into smaller subsets, called clusters, according to a certain measure of similarity [121]. One measure of similarity is the density whereby objects that are close together are grouped together into one cluster. The main concept of the DBSCAN algorithm is that all the points within a cluster, with minimum points ($\text{Minpts}$), are such that the distance between them is less than a predefined radius referred to as the $\text{eps}$ [121].

![Figure 4.1: An Illustration of the DBSCAN Core, Border and Outlier Points](image)

The DBSCAN defines three types of points namely, the core, border and outlier points. These are illustrated in Figure 4.1. The core and border points are part of the cluster but the outlier points are not. A core point is one with at least minimum points within its $\text{eps}$ neighbourhood including itself. A border point is one with less than minimum points within its $\text{eps}$ neighbourhood but it’s within $\text{eps}$ neighbourhood of a core point. An outlier point has less than minimum points within its $\text{eps}$ neighbourhood and in addition, it’s not within $\text{eps}$ neighbourhood of a core point.
4.2 Mixed Integer Linear Programming Approach

The goal of the mathematical optimisation is to determine a set of values $x_i$ that provides the maximum or minimum of an objective function $f$, while at the same time satisfying a set of constraints. In regards to mixed integer linear programming (MILP), the constraints consist of a set of linear equalities and inequalities and there is a restriction on some values $x_i$ to be integers. The MILP problem may be represented as shown in equation (4.1):

$$\begin{align*}
\text{minimise } f(x) & \quad \text{subject to } \sum_i a_{ji}x_i \leq b_j \quad (j = 1, 2, \ldots, n) \quad (4.1) \\
& \quad x_i \geq 0 \quad (i = 1, 2, \ldots, m)
\end{align*}$$

It is a requirement of the MILP that all constraint equations are satisfied simultaneously. However, there are cases where the constraints are not simultaneous. Examples of these include constraints with the following logical operations:

- one of two equations must be satisfied,
- One of two sets of equations must be satisfied.

In each of these cases, the non-simultaneous equations should be converted into simultaneous equations. In the case of the Either/Or constraints, only one of two equations must be satisfied. Assume these constraints are represented in equations (4.2) and (4.3) where either should hold but not both.

**Either** :

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \leq b_1 \quad (4.2)$$

**OR**

$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \leq b_2 \quad (4.3)$$

These equations are converted into simultaneous equations by introducing a binary variable $y$ and a large number $M$ and re-writing the constraints as two simultaneous equations (4.4) and (4.5) [122].

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 - b_1 \leq My \quad (4.4)$$
\[ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 - b_2 \leq (1 - y)M \]  \hspace{1cm} (4.5)

In this case, if \( y = 0 \), the constraint equation (4.5) will always be satisfied, hence redundant. The constraint in equation (4.4) is also satisfied as specified in equation (4.2). If \( y = 1 \), equation (4.4) is redundant and equation (4.5) is satisfied as specified in equation (4.3). Similarly, the cases where one of two subsets must be satisfied are illustrated in equations (4.6) to (4.9).

*Either Set 1:*

\[ a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 \leq b_1 \]  \hspace{1cm} (4.6)

\[ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 \leq b_2 \]  \hspace{1cm} (4.7)

*OR Set 2:*

\[ d_{11}x_1 + d_{12}x_2 + d_{13}x_3 + d_{14}x_4 \leq b_1 \]  \hspace{1cm} (4.8)

\[ d_{21}x_1 + d_{22}x_2 + d_{23}x_3 + d_{24}x_4 \leq b_2 \]  \hspace{1cm} (4.9)

These equations are converted into simultaneous equations by introducing two binary variables \( y_1 \), \( y_2 \) and a large number \( M \) and re-writing the constraints as simultaneous equations (4.10) to (4.14) [122].

\[ a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 - b_1 \leq My_1 \]  \hspace{1cm} (4.10)

\[ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 - b_2 \leq My_1 \]  \hspace{1cm} (4.11)

\[ d_{11}x_1 + d_{12}x_2 + d_{13}x_3 + d_{14}x_4 - b_1 \leq My_2 \]  \hspace{1cm} (4.12)

\[ d_{21}x_1 + d_{22}x_2 + d_{23}x_3 + d_{24}x_4 - b_2 \leq My_2 \]  \hspace{1cm} (4.13)

\[ y_1 + y_2 = 1 \]  \hspace{1cm} (4.14)

In this case, if \( y_1 = 0 \), the constraints in set 2 represented by equations (4.12) and (4.13) will always be satisfied, hence redundant. The set 1 constraints are also satisfied as specified in
equations (4.6) and (4.7). If \( y_2 = 0 \), set 1 constraints are redundant and Set 2 constraints are satisfied as specified in equations (4.8) and (4.9).

### 4.3 The Proposed Com\(\mu\)Grid Sizing Approach

In this section, a solar PV community microgrid (Com\(\mu\)Grid) whose components are indicated in the block diagram shown in Figure 4.2 is presented and optimally sized.

![Block Diagram for the Proposed Community Microgrid (Com\(\mu\)Grid)](image)

The transformer in the block diagram of the proposed community microgrid is important to cater for the different possible village configurations i.e. some villages can be sparsely populated or densely populated, clustered or non-clustered/dispersed or a combination of the two. In cases where the customers are dispersed, there is need to invest in the transformer and corresponding transmission lines.
The procedure for sizing the microgrid is presented in Figure 4.3 and is discussed in detail below.

**Step 1:** Obtain meteorological data and component specifications.

The hourly irradiance, $S(t)$, and temperature, $T(t)$, of the community’s location are defined. In addition, the following specifications for the PV, Battery and Inverter are defined.
a) DC system voltage ($V_{dc}$)
b) Efficiency of the inverter ($\eta_{inv}$)
c) Days of Autonomy of the system ($D_{aut}$)
d) Nominal Battery Voltage ($V_{dc}$)
e) Depth of Discharge (DOD)
f) Battery DOD vs cycle life
g) Battery Efficiency
h) Peak Amps per module at STC ($I_{mp}$)
i) Nominal Module Voltage / Voltage at MPP under STC ($V_{mp}$)
j) Module Short Circuit Current supplied by the chosen manufacturer ($I_{sc}$)

**Step 2:** Estimate the load demand for each hour of the year

The procedure for estimating the hourly load demand is described in detail in Chapter Five of this thesis. One of the assumptions in this procedure is that there exists an electrified rural community whose average consumption can be used to predict the consumption of the unelectrified rural community. The customers in the unelectrified community are classified according to their electric needs and each customer is assigned a daily load based on consumption of a similar customer in the electrified village. The hourly load $I_L(t)$ over the year for the unelectrified village is then generated. This profile is adjusted depending on the differences in the socioeconomic and gender characteristics of the two villages.

**Step 3:** Determine the hourly PV output current

The hourly PV output current $I_{pv}(t)$ is calculated using equation (4.15).

$$I_{pv}(t) = \frac{S(t)}{1000} + \text{Alpha}(T(t) - 25)$$

(4.15)

**Step 4:** Consolidate the Load and Irradiance for consecutive time steps

This step involves consolidation of the load and PV outputs into fewer time steps using the DBSCAN algorithm as follows:

A three dimensional point $(t, I_L(t), I_{pv(t)})$, is defined for each hour $t$ where $I_L(t)$ is the load demand and $I_{pv(t)}$ is the Output current of a single PV module at each hour. First, all consecutive points where the PV output is zero are clustered. These correspond to the night
hours of each day. The points are consolidated into one time step \( t \) where the PV output for the time step is zero and the load is the sum of the respective loads. Thereafter, all consecutive points for which the PV output \( I_{PV(t)} \) are in a range of \( m\% \) of each other and the loads \( I_L(t) \) are also in a range of \( m\% \) of each other are clustered and consolidated into one time step. The PV output for the time step is the sum of the respective PV outputs and the load is the sum of the respective loads. For instance, if \( m = 10\% \) then all the consecutive points \( t \) for which \( 0.9I_{PV(t)} \leq I_{PV(t)} \leq 1.1I_{PV(t)} \) and \( 0.9I_L(t) \leq I_L(t) \leq 1.1I_L(t) \) are consolidated into a single time step. The implementation of the DBSCAN algorithm is shown in Listing 4.1. Arrays \( I_{pv1}(t) \) and load \( I_{L1}(t) \) hold the PV output and Load after combining all consecutive time steps \( (t) \) where \( I_{pv1}(t) = 0 \). Arrays \( I_{pv2}(t) \) and load \( I_{L2}(t) \) hold the PV output and Load after combining all consecutive time steps \( (t) \) where the values in \( I_{pv1}(t) \) are close to each other by a distance measurement of \( m\% \) and where values in \( I_{L1}(t) \) are close to each other by a distance measurement of \( m\% \).

The consolidation is illustrated in Figure 4.4 using a value of \( m =10\% \). All the shaded values in the first table on the left are consolidated into one time step resulting into the second table on the right with fewer time steps. Listing 4.1 presents a function that implements the consolidation.
Listing 4.1: Function that Consolidates Hourly PV Output and Load Data

Function $[I_{PV2}, I_{L2}, Asize2] = \text{analysePVLoad}[I_{PV}, I_{L}, m]$

1. Initialise variables $t = 1, p = 1, Asize_1, Asize_2, Sum_L, Sum_p$
2. Initialise Arrays $I_{L1}(8760), I_{PV1}(8760)$
3. If the current hour $t$ is not the last hour of the year
4.   If $I_{PV}(t)$ and $I_{PV}(t + 1)$ are equal to zero
5.     Assign the sum of $I_{L}(t)$ and $I_{L}(t + 1)$ to $Sum_L$
6.     Increment $t$ by one
7.   Else
8.     Assign $Sum_L$ to $I_{L1}(p)$
9.     Set $I_{Pv1}(p)$ to 0
10.    Increment $p$ by one
11.   If the current hour $t$ is not the last hour of the year
12.      Increment $t$ by one
13.   End IF
14.   End IF
15.   Assign $p$ to $Asize_1$
16.   End IF
17.   Initialise arrays $I_{PV2}, I_{L2}$ of size $Asize_1$
18.   Set $t = 1, p = 1$
19.   For each time step $t$ in $I_{PV2}$ and $I_{L2}$
20.      If the current time step $t$ is not the last time step
21.         If ratio of $\min(I_{PV}(t), I_{PV}(t + 1))$ to $\max(I_{PV}(t), I_{PV}(t + 1)) \leq m\%$ and
22.            the ratio of $\min(I_{L}(t), I_{L}(t + 1))$ to $\max(I_{L}(t), I_{L}(t + 1)) \leq m\%$
23.            Assign the sum of $I_{L1}(t)$ and $I_{L1}(t + 1)$ to $Sum_L$
24.            Assign the sum of $I_{Pv1}(t)$ and $I_{Pv1}(t + 1)$ to $Sum_p$
25.            Increment $t$ by one
**Step 4:** Determine the range of number of PV modules ($\text{PV}_{\text{min}}, \text{PV}_{\text{max}}$) and batteries ($\text{Bat}_{\text{min}}, \text{Bat}_{\text{max}}$) for the optimization process.

Ideally, the minimum and maximum number of PVs and Batteries would be from one to infinity. However, this search space is quite big and the optimisation may not converge to an optimal solution. The method based on sizing sheets is used to determine the initial number of PV modules and Batteries.

In order to determine the minimum values ($\text{PV}_{\text{min}}, \text{Bat}_{\text{min}}$), consider the month with the least average load and assume that the LLP is larger than the desired LLP for the community. Using the range derived from the basic method above and the optimization procedure described in subsection 4.3.1, determine the values ($\text{PV}_{\text{min}}, \text{Bat}_{\text{min}}$).

In order to determine the maximum values ($\text{PV}_{\text{max}}, \text{Bat}_{\text{max}}$), consider the month with the highest average load and assume that the LLP is smaller than the desired LLP for the community. Using the range derived from the basic method above and the optimization procedure described in subsection 4.3.1, determine the values ($\text{PV}_{\text{max}}, \text{Bat}_{\text{max}}$).

**Step 5:** Use the MILP procedure as described in subsection 4.3.1 to determine the size of system components that give minimum ATLCC for the desired LLP.
4.3.1 Utilising the Mixed Integer Linear Programming Approach

This section presents the Mixed Integer Linear Programming Approach. The objective of this optimization method is to obtain the optimal design of a system that minimizes the ATLCC while meeting the load demand with a desired LLP that is dependent on the customer’s satisfaction. The symbols and acronyms used in this section are presented below.

Symbols and Acronyms:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLCC</td>
<td>Annualized Total Life Cycle Cost</td>
</tr>
<tr>
<td>Alpha</td>
<td>PV panel temperature coefficient</td>
</tr>
<tr>
<td>Bat</td>
<td>Total number of Batteries</td>
</tr>
<tr>
<td>Bat_eff</td>
<td>Battery Charging Efficiency</td>
</tr>
<tr>
<td>Bat_d_eff</td>
<td>Battery Discharging Efficiency</td>
</tr>
<tr>
<td>Bat_AH</td>
<td>AH rating of one Battery</td>
</tr>
<tr>
<td>Bat_cap</td>
<td>Battery Storage Capacity (AH)</td>
</tr>
<tr>
<td>Bat_max</td>
<td>Maximum Number of Batteries</td>
</tr>
<tr>
<td>Bat_max_par</td>
<td>Maximum number of Batteries in Parallel</td>
</tr>
<tr>
<td>Bat_min</td>
<td>Minimum Number of Batteries</td>
</tr>
<tr>
<td>Bat_par</td>
<td>Number of Batteries in Parallel</td>
</tr>
<tr>
<td>Bat_ser</td>
<td>Number of Batteries in Series</td>
</tr>
<tr>
<td>Bat_thr</td>
<td>Energy through put for a single battery (kWh)</td>
</tr>
<tr>
<td>C_Bat</td>
<td>Cost of Battery</td>
</tr>
<tr>
<td>C_Bata</td>
<td>Annualized capital maintenance cost and replacement cost of the batteries</td>
</tr>
<tr>
<td>CC_Bat</td>
<td>Capital Cost of Batteries</td>
</tr>
<tr>
<td>CC_CW</td>
<td>Total capital costs for other components</td>
</tr>
<tr>
<td>CC_D</td>
<td>capital cost of the disposable components</td>
</tr>
<tr>
<td>CC_OC</td>
<td>Total capital costs for other components aside PV and Batteries</td>
</tr>
<tr>
<td>CC_OCa</td>
<td>Annualized Capital costs of other components</td>
</tr>
<tr>
<td>CC_PV</td>
<td>Capital Cost of PV modules</td>
</tr>
<tr>
<td>CC_TR</td>
<td>Capital Cost of transformers</td>
</tr>
<tr>
<td>C_PV</td>
<td>Cost of one PV module</td>
</tr>
<tr>
<td>C_PVA</td>
<td>Annualized capital and maintenance cost of the PV modules</td>
</tr>
<tr>
<td>CS_a</td>
<td>Annualized salvage value of the system</td>
</tr>
<tr>
<td>C_TRA</td>
<td>Annualized capital and maintenance cost of the transformers</td>
</tr>
<tr>
<td>C_Tr</td>
<td>Cost of one transformer</td>
</tr>
<tr>
<td>Ctrl_LdAmps</td>
<td>Maximum DC Load Amps that controller must handle</td>
</tr>
<tr>
<td>Ctrl_SCC</td>
<td>Controller short circuit current</td>
</tr>
<tr>
<td>Ctrl_Sel</td>
<td>Controller current rating</td>
</tr>
<tr>
<td>Ctrl_Total</td>
<td>Number of Charge Controllers in operation during the system lifetime</td>
</tr>
<tr>
<td>Ctrl_V</td>
<td>Voltage rating of the controller</td>
</tr>
<tr>
<td>DBSCAN</td>
<td>“Density Based Spatial Clustering of Applications with Noise”</td>
</tr>
<tr>
<td>Desired_LLP</td>
<td>Desired Loss of Load Probability</td>
</tr>
</tbody>
</table>
DOD \quad \text{Depth of Discharge for the Battery}

D_{\text{aut}} \quad \text{Days of Autonomy}

E_{\text{TOT}} \quad \text{Total energy consumed by the load from the system per year}

f_r \quad \text{Inflation Rate}

I_{\text{ch}}(t) \quad \text{Battery Charge Current at time } (t)

I_{\text{def}}(t) \quad \text{Deficit Current at time } (t)

I_{\text{dis}}(t) \quad \text{Battery Discharge Current at time } (t)

I_{\text{inv}} \quad \text{Inverter current rating}

I_{\text{mp}} \quad \text{Peak Amps per module at STC}

I_{\text{L}}(t) \quad \text{Load demand current at time } (t)

I_{\text{PV}}(t) \quad \text{Output current of a single PV module at time } (t)

IPV(t) \quad \text{Total output current of the PV array at time } (t)

I_{\text{sc}} \quad \text{PV Module Short Circuit Current}

I_{\text{sur}}(t) \quad \text{Surplus Current at time } (t)

i_r \quad \text{Real Interest Rate}

L_{\text{Bat}} \quad \text{Lifetime of the Battery}

L_{\text{PV}} \quad \text{PV system Lifetime}

L_s \quad \text{Microgrid System Lifetime}

L_{\text{TR}} \quad \text{Lifetime of the transformer}

\text{LCC} \quad \text{Sum of annualised capital, annualised maintenance and annualised replacement costs}

\text{LCE} \quad \text{Levelised cost of energy}

\text{LLP} \quad \text{Loss of Load Probability}

M \quad \text{A large number}

ndr \quad \text{Net of discount inflation rate}

\text{Max}_{\text{DCAC}} \quad \text{Maximum Continuous Direct Current of the controller}

\text{MCC}_{\text{Bat}} \quad \text{Maintenance cost of batteries}

\text{MCC}_{\text{PV}} \quad \text{Maintenance cost of PV modules}

\text{MCC}_{\text{TR}} \quad \text{Maintenance cost of transformers}

\text{MILP} \quad \text{“Mixed Integer Linear Programming”}

N_{\text{TR}} \quad \text{Number of transformers}

P_c \quad \text{Total Connected AC Power}

PSH \quad \text{Peak sun hours per day}

PV \quad \text{Number of PV Modules}

PV_{\text{max}} \quad \text{Maximum Number of PV Modules}

PV_{\text{max,par}} \quad \text{Maximum Number of PV Modules in Parallel}

PV_{\text{min}} \quad \text{Minimum Number of PV Modules}

PV_{\text{par}} \quad \text{Number of PV Modules in Parallel}

PV_{\text{ser}} \quad \text{Number of PV Modules in Series}

S(t) \quad \text{Solar Radiation(W/m}^2\text{) at time } (t)

\text{SF} \quad \text{safety factor}

SOC(t) \quad \text{Battery State of Charge}

\text{STC} \quad \text{Standard Test Conditions}

T(t) \quad \text{Ambient Temp (°C) at time } (t)

V_{\text{dc}} \quad \text{DC System voltage}

V_{\text{mp}} \quad \text{Nominal Module Voltage (Voltage at MPP under STC)
Y_{Bat} \quad \text{Number of times of Battery Replacement} \\
Z \quad \text{Average Daily Load (Amp-Hour per Day)} \\
\varphi_{ch}(t) \quad \text{Binary variable for charging mode} \\
\varphi_{ch, \text{sur}} \quad \text{Binary variable for the charge/surplus mode} \\
\varphi_{dis}(t) \quad \text{Binary variable for discharging mode} \\
\varphi_{dis, \text{def}} \quad \text{Binary variable for the discharge/deficit mode} \\
\eta_{bat} \quad \text{Battery Efficiency}

Optimization Problem

The objective function for the mixed-integer linear programming (MILP) problem is;

\[
\text{minimise } ATLCC \quad \text{(4.16)}
\]

subject to the constraints defined by equations (4.18) to (4.51). The ATLCC is determined using equation (4.17).

The ATLCC is the sum of the annualized capital costs and annualized component replacement, operation and maintenance costs. [59]

\[
ATLCC = CC_{OCA} + C_{PVA} + C_{Bata} - CS_a \quad \text{(4.17)}
\]

Where; \( C_{PVA} \) is the annualized capital and maintenance costs of the PV modules, \( C_{Bata} \) is the annualized capital, maintenance and replacement costs of the batteries, \( CC_{OCA} \) is the annualized capital costs of other components , \( CS_a \) is the annualized salvage value of the system.

The PV System Model

The number of PV modules is within a maximum and minimum range determined above.

\[
P_{V_{min}} \leq PV \leq P_{V_{max}} \quad \text{(4.18)}
\]

\[
IPV(t) = I_{PV(t)} \cdot P_{V_{par}} \quad \text{(4.19)}
\]

\[
PV = P_{V_{par}} \cdot P_{V_{ser}} \quad \text{(4.20)}
\]

The current balance at each time period is given as

\[
IPV(t) + I_{dis}(t) + I_{def}(t) - I_{ch}(t) - I_{sur}(t) = 0 \quad \text{(4.21)}
\]
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\[ I_{\text{dis}}(t) \geq 0, I_{\text{def}}(t) \geq 0, I_{\text{in}}(t) \geq 0, I_{\text{ch}}(t) \geq 0, I_{\text{sur}}(t) \geq 0 \]  

(4.22)

**Battery Model**

The number of batteries is within a maximum and minimum range.

\[ Bat_{\text{min}} \leq Bat \leq Bat_{\text{max}} \]  

(4.23)

\[ Bat = Bat_{\text{par}} \times Bat_{\text{ser}} \]  

(4.24)

\[ Bat_{\text{cap}} \leq Bat_{\text{AH}} \times Bat_{\text{max.par}} \]  

(4.25)

\[ Bat_{\text{par}} = \frac{Bat_{\text{cap}}}{Bat_{\text{AH}}} \]  

(4.26)

It is assumed that initially, the battery is full. Thereafter, in each time period, the battery cannot charge to more than the battery capacity and cannot discharge to less than the minimum allowable battery capacity.

\[ SOC(0) = Bat_{\text{cap}} \]  

(4.27)

\[ SOC(t) \leq Bat_{\text{cap}} \]  

(4.28)

\[ SOC(t) \geq (1 - DOD)Bat_{\text{cap}} \]  

(4.29)

In each time period, the battery shall be either in charging or discharging mode. This presents two sets of constraints as shown in Figure 4.5. Only one set of constraints holds at a given time.

**Discharging**

\[ I_{\text{ch}}(t) = 0 \]

\[ I_{\text{sur}}(t) = 0 \]

Either: Battery is discharged to minimum

\[ SOC(t) - I_{\text{def}}(t) / (Bat_{\text{eff}} \times Bat_{\text{eff}}) - (1 - DOD)Bat_{\text{cap}} \leq 0 \]

OR: No deficit current

\[ I_{\text{def}}(t) = 0 \]

**Charging**

\[ I_{\text{sur}}(t) = 0 \]

Either: Battery is charged to maximum

\[ Bat_{\text{cap}} - SOC(t) - I_{\text{in}}(t) \times Bat_{\text{eff}} \times Bat_{\text{eff}} \leq 0 \]

OR: No surplus current

\[ I_{\text{sur}}(t) = 0 \]

**Figure 4.5: Equations Representations for the Charging and Discharging States of the Battery**
During charging mode, the load demand current is wholly met by the PV system. The PV system charges the battery. There is no discharge current and deficit current.

\[ I_{\text{def}}(t) = 0 \] 
\[ I_{\text{dis}}(t) = 0 \] \hfill (4.30)
\[ I_{\text{sur}}(t) = 0 \] \hfill (4.31)

When the battery is full, the excess current is the surplus current. There is a surplus only when the battery is full. This condition is represented by “Either/Or equations” constraints in equations (4.32) and (4.33) [123].

*Either : Battery is charged to maximum*

\[ \text{Bat}_{\text{cap}} - \text{Soc}(t - 1) - I_{\text{ch}}(t) * \text{Bat}_{\text{eff}} * \text{Bat}_{\text{d eff}} \leq 0 \] \hfill (4.32)

*OR: No Surplus current*

\[ I_{\text{sur}}(t) = 0 \] \hfill (4.33)

During discharging mode, the PV system current is insufficient to meet the load demand. The battery supplies the extra current to meet load demand. There is no charge current and surplus current.

\[ I_{\text{ch}}(t) = 0 \] \hfill (4.34)
\[ I_{\text{sur}}(t) = 0 \] \hfill (4.35)

When the battery is discharged to the minimum state of charge required for the battery, the demand not met is the deficit current. There is a deficit only when the battery is discharged to minimum. This condition is represented by “Either/Or equations” constraints in equations (4.36) and (4.37).

*Either: Battery is discharged to minimum*

\[ \text{Soc}(t - 1) - I_{\text{def}}(t)/ (\text{Bat}_{\text{eff}} * \text{Bat}_{\text{d eff}}) - (1 - \text{DOD})\text{Bat}_{\text{cap}} \leq 0 \] \hfill (4.36)

*OR : No deficit current*

\[ I_{\text{def}}(t) = 0 \] \hfill (4.37)
As mentioned in section 4.2, it is a requirement of the MILP that all constraint equations are satisfied simultaneously. Binary variables $\varphi_{ch}(t)$ and $\varphi_{dis}(t)$ are introduced to represent charging and discharging mode. Binary variable $\varphi_{ch,sur}(t)$ is introduced to represent the Either/Or constraint for charging mode of the battery. Binary variable $\varphi_{dis,def}(t)$ is introduced to represent the Either/Or constraint for discharging mode of the battery. Using the discussion presented in section 4.2, the charging and discharging modes are represented with the simultaneous equations (4.38) to (4.46) [123].

\[
\varphi_{ch}(t) + \varphi_{dis}(t) = 1 \tag{4.38}
\]

**Charging mode:**

\[
I_{def}(t) \leq M \cdot \varphi_{ch}(t) \tag{4.39}
\]
\[
I_{dis}(t) \leq M \cdot \varphi_{ch}(t) \tag{4.40}
\]
\[
I_{sur}(t) \leq M \cdot \varphi_{ch,sur}(t) + M \cdot \varphi_{ch}(t) \tag{4.41}
\]
\[
Bat_{cap} - Soc(t - 1) - I_{ch}(t) \cdot Bat_{eff} \cdot Bat_{eff} \leq (1 - \varphi_{ch,sur}(t))M + M \cdot \varphi_{ch}(t) \tag{4.42}
\]

**Discharging mode:**

\[
I_{ch}(t) \leq M \cdot \varphi_{dis}(t) \tag{4.43}
\]
\[
I_{sur}(t) \leq M \cdot \varphi_{dis}(t) \tag{4.44}
\]
\[
I_{def}(t) \leq M \cdot \varphi_{dis,def}(t) + M \cdot \varphi_{dis}(t) \tag{4.45}
\]
\[
Soc(t - 1) - I_{def}(t) / (Bat_{eff} \cdot Bat_{eff}) - (1 - DOD)Bat_{cap} \leq M(1 - \varphi_{dis,def}(t)) + M \cdot \varphi_{dis}(t) \tag{4.46}
\]

The charge and surplus currents cannot exceed the maximum PV output for each hour

\[
I_{sur}(t) \leq I_{PV(t)} \cdot PV_{max,par} \tag{4.47}
\]
\[
I_{ch}(t) \leq I_{PV(t)} \cdot PV_{max,par} \tag{4.48}
\]

The Deficit and Discharge currents cannot exceed the Load current

\[
I_{def}(t) \leq I_{L}(t) \tag{4.49}
\]
\[
I_{dis}(t) \leq I_{L}(t) \tag{4.50}
\]
The LLP is less than or equal to a desired LLP [59]

\[
\frac{\sum I_{\text{def}}(t)}{\sum I_L(t)} \leq Desired\_LLP
\]  

(4.51)

**Cost Analysis**

The capital cost for the PV array and the battery storage is given by equations (4.52) and (4.53) respectively [59].

\[
CC_{PV} = PV \times C_{PV}
\]  

(4.52)

\[
CC_{Bat} = Bat \times C_{Bat}
\]  

(4.53)

Maintenance cost of PV modules and Batteries per year is assumed to be 2% of the capital costs [72]. This is presented in equations (4.54) and (4.55) respectively.

\[
MCC_{PV} = CC_{PV} \times 0.02
\]  

(4.54)

\[
MCC_{Bat} = CC_{Bat} \times 0.02
\]  

(4.55)

The annualized capital and maintenance cost of the PV modules is estimated using equation (4.56) [76].

\[
C_{PVa} = \frac{CC_{PV} + (L_s \times MCC_{PV})}{L_{PV}}
\]  

(4.56)

The annualized capital, maintenance cost and replacement cost of the batteries is calculated using equation (4.57) [76].

\[
C_{Bata} = \frac{CC_{Bat} \times (1 + Y_{Bat}) + MCC_{Bat} \times (L_s - Y_{Bat})}{L_{Bat}}
\]  

(4.57)

*Where:*

\[
Y_{Bat} = \frac{L_s}{L_{Bat}} - 1
\]  

(4.58)
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The capital cost for the transformers is calculated using equation (4.59)

\[ CC_{TR} = N_{TR} \times C_{Tr} \]  \hspace{1cm} (4.59)

Maintenance cost of the transformers per year is given by equation (4.60).

\[ MCC_{TR} = CC_{TR} \times 0.02 \]  \hspace{1cm} (4.60)

The annualized capital and maintenance cost of the transformers is estimated using equation (4.61)

\[ C_{TRA} = \frac{CC_{TR} + (L_s \times MCC_{TR})}{L_{TR}} \]  \hspace{1cm} (4.61)

The total capital costs for other components are lumped together as 20% of PV cost as given in equation (4.62).

\[ CC_{CW} = CC_{PV} \times 0.2 \]  \hspace{1cm} (4.62)

The total capital costs for other components aside PV and Batteries are given by equation (4.63).

\[ CC_{OC} = CC_{CW} + CC_{TR} \]  \hspace{1cm} (4.63)

The annualized Capital costs of other components is estimated using equation (4.64) [59]

\[ CC_{OCA} = \frac{CC_{OC} \times \frac{L_s}{(1 + ndr)^{1-s} - 1}}{(ndr \times (1 + ndr)^{1-s} - 1)} \]  \hspace{1cm} (4.64)

Where:

\[ ndr \] is the net of discount inflation rate and is given by equation (4.65). \( ir \) is the real interest rate and \( fr \) is the inflation rate [59].

\[ ndr = \frac{1 + ir}{1 + fr} - 1 \]  \hspace{1cm} (4.65)

The total life cycle cost is the sum of the respective component costs and is given by equation
The annualised salvage value of the system is given by equation (4.67). [59]

\[
CS_a = \frac{0.13 \times CC_D}{\left( (1 + ndr)^{L_s} - 1 \right) / \left( ndr \times (1 + ndr)^{L_s} \right)}
\]  

(4.67)

Where;

\[CC_D\] is the capital cost of the disposable component and is given by equation (4.68). [59]

\[
CC_D = CC_{PV} + CC_{Bat}
\]  

(4.68)

As defined by equation (4.17) and using the result obtained from equation (4.66), the annualised total life cycle cost is thus given by equation (4.69). [59]

\[
ATLCC = LCC - CS_a
\]  

(4.69)

The levelised cost of energy (LCE) is obtained using equation (4.68) [76]. The LCE provides an estimate of the cost of a unit of energy considering the full life cycle of the project. It is the ratio of the annualised total life cycle cost to the total annual energy generated by the system.

\[
LCE = \frac{ATLCC}{E_{TOT}}
\]  

(4.70)

### 4.3.2 Incorporating Solar Water Heating

There are some customers/users that need hot water such as hospitals, schools and healthcare centres. While dimensioning of the solar water heating components is not covered in this thesis, the processes for designing and dimensioning of the system given in both [124] and [125] can be adopted for the community. Care should be taken to ensure that approved international standards are followed while designing the system.

Furthermore in cases where water is required at a higher temperature than possible with solar water heating, then electricity generated from the PV system can be used to boil the pre-heated water. There are savings on overall cost when pre-heated water is boiled as compared to boiling cold water at room temperature as detailed in [124]
4.4 Case Study Using the ComµGrid Sizing Approach

The ComµGrid Sizing approach proposed in this research was implemented using MATLAB software. MATLAB has been chosen as the preferred software for creating the ComµGrid model because of the freedom it offers users to define their own parameters in order to achieve the desired design. The huge amount of data to be handled in this research such as weather data, load data, solar irradiance data, etc., also necessitates using a fast computing platform which MATLAB offers. Using MATLAB will also allow for flexibility in manipulating and fine tuning parameters for control of various microgrid components which may not be possible when using already designed software. Uganda which is the home country of the author of this PhD thesis was chosen as the case study for application of the ComµGrid design. It is located in East Africa. Section 4.4.1 below gives a brief description of the state of electrification in Uganda.

4.4.1 An Overview of the State of Electrification in Uganda

Uganda is a developing African country with 83% of the population living in rural areas [2]. The Human Development Index for Uganda is 0.493 [126]. 93% of the country’s energy demand is met with biomass, 6% by fossil fuel combustion and 1% electricity from hydro and fossil fuelled thermal power plants. Approximately 10% of the population has access to electricity. The percentage of people in rural areas with access to electricity is less than 5% [127].

There are strategies that have been put in place by the Uganda government and private sector regarding sustainable energy for all. These include [24]:

1. Government Driven Strategies
   - National Development Plan (2010)
   - Uganda Vision 2040
   - Biomass Energy Strategy (2013)
2. Private Sector Strategies
   o Uganda National Alliance for Clean Cooking Master Plan
   o Uganda National Renewable Energy and Energy Efficiency trade association

3. Key technical documents supported by Donors
   o Master Plan Study on Hydroelectric Development (2011, JICA)

The Action Agenda Objectives for Uganda in line with the sustainable energy for all initiative include the following:

i. Improve national electricity access to >98%
ii. Increase national access to non-solid fuels to >99%
iii. Increase the renewable energy output to >90%
iv. Improve energy efficiency to the range of 15% - 25%

As far as rural electrification is concerned in Uganda, the Rural Electrification Agency (REA) is responsible for promoting electrification of rural areas [128]. A Rural Electrification Strategy and Plan for 2013 – 2022 (2013) was formulated with a major objective of achieving universal electrification by 2040 while ensuring that the use of kerosene for lighting in rural homes in Uganda is ended by the year 2030. The targeted rural electrification access is 22% by 2022 from the current level where it is expected that the consumers will have the ability to use electricity in their homes, businesses or institutions.

4.4.2 Applying the ComµGrid Approach in a Village in Uganda

The developed ComµGrid kit was used to design a community microgrid for a village in the district of Tororo in eastern Uganda. The location chosen for the microgrid is not connected to the main utility grid. The village considered has 100 households, a maize mill, ladies and men’s salons, a primary school and a clinic. The household categories and appliance usage were estimated based on the energy survey conducted by the Uganda Bureau of Statistics and Ministry of Energy and Mineral Development for 2012 [129] as well as the Uganda National household survey for 2016 [130]. The appliance usage times were estimated based on the energy surveys by [77], [131], [132], [133], [134], [89] and [81] for various rural communities in Uganda, Kenya and Tanzania. The assumed community composition and
load characteristics are shown in Appendix B. The average load demand per day is 485kWh. Details on the load profile estimation for the village are presented in Chapter Four.

The renewables.ninja tool [135] [136] [137] was used to generate the hourly solar data and ambient temperature for the target location. The make and model of the PV module chosen for the system is the TT, Auversun, AV275M96NB-5P while the battery chosen is the Concorde Sun Xtender PVX-2580L. These types of battery and PV module were chosen as they have been successfully used in other studies on PV systems such as those in [72]. The electrical and reliability parameters have been adopted from [59] and [72]. The costs of the components have been estimated from [138]. The electrical, reliability and cost parameters are presented in Table 4.1.

Table 4.1: Electrical, Reliability and Cost Parameters of the System

<table>
<thead>
<tr>
<th>System Electrical Parameters</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC System voltage (V)</td>
<td>24</td>
</tr>
<tr>
<td>Peak Amps per PV module at STC (A)</td>
<td>5.37</td>
</tr>
<tr>
<td>PV Module Short Circuit Current (A)</td>
<td>5.8</td>
</tr>
<tr>
<td>Nominal PV Module Voltage / Voltage at MPP under STC (V)</td>
<td>51.2</td>
</tr>
<tr>
<td>NOCT (°C)</td>
<td>43.6</td>
</tr>
<tr>
<td>PV Module Temperature Coefficient (%/°C)</td>
<td>0.068</td>
</tr>
<tr>
<td>Current at MPP (A)</td>
<td>6.89</td>
</tr>
<tr>
<td>Battery Amp-Hour capacity (AH)</td>
<td>258</td>
</tr>
<tr>
<td>Battery Nominal voltage (V)</td>
<td>12</td>
</tr>
<tr>
<td>Battery Charge efficiency</td>
<td>0.97</td>
</tr>
<tr>
<td>Battery Discharge efficiency</td>
<td>1</td>
</tr>
<tr>
<td>Depth of Discharge for Battery</td>
<td>0.8</td>
</tr>
<tr>
<td>Battery lifetime Throughput(kWh)</td>
<td>1657</td>
</tr>
<tr>
<td>Short circuit current of controller (A)</td>
<td>60</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>1.25</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Reliability Parameters**

| Desired Loss of Load probability (LLP) | 0.01 |
| Battery Days of Autonomy              | 4    |

**Cost Parameters**

| System lifetime (Years) | 20 |
| The total lifetime period for battery(Years) | 10 |
| The total lifetime period for Charge Controller(Years) | 20 |
| The total lifetime period for Inverter(Years) | 20 |
| The total lifetime period for PV array(Years) | 20 |
| Capital Cost for one PV module (£) | 81.14 |
| Capital Cost for a battery (£) | 581 |
| Subsidy (as % of annualised capital, annualised maintenance and annualised replacement costs) | 30% |
The results obtained using the ComµGrid Sizing approach are detailed in Table 4.2.

Table 4.2: Results Obtained Using the ComµGrid Sizing Approach

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proposed ComµGrid Sizing</th>
<th>MILP based Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Batteries</td>
<td>281</td>
<td></td>
</tr>
<tr>
<td>Battery Capacity (AH)</td>
<td>72,240</td>
<td></td>
</tr>
<tr>
<td>Total Number of PVs (Modules)</td>
<td>2032</td>
<td></td>
</tr>
<tr>
<td>PV array Peak Amps (Amps)</td>
<td>10908</td>
<td></td>
</tr>
<tr>
<td>LLP</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>ATLCC (£)</td>
<td>75,136</td>
<td></td>
</tr>
<tr>
<td>LCE (£)</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>LCE (£) when no batteries are used</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

4.4.3 Sensitivity Analysis

The following sensitivity analysis was done to determine changes in cost of energy and reliability of the system.

a) Effect of consolidation factor (m%) to the microgrid sizing

The microgrid was sized using different consolidation values for m = 5%, 10%, 20% and 30%. The results are shown in Table 4.3.

Table 4.3: Comparison Between Results For Different Values Of Consolidation Parameter m%

<table>
<thead>
<tr>
<th>Parameter</th>
<th>m = 5%</th>
<th>m=10%</th>
<th>m=20%</th>
<th>m=30%</th>
<th>m=80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Batteries</td>
<td>281</td>
<td>281</td>
<td>280</td>
<td>281</td>
<td>282</td>
</tr>
<tr>
<td>No. of PV Modules</td>
<td>2034</td>
<td>2032</td>
<td>2033</td>
<td>2031</td>
<td>2032</td>
</tr>
<tr>
<td>LLP</td>
<td>0.009</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>ATLCC (£)</td>
<td>72,240</td>
<td>75,136</td>
<td>75,602</td>
<td>75,055</td>
<td>72,498</td>
</tr>
<tr>
<td>LCE (£)</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>Total Time Steps</td>
<td>3,876</td>
<td>3456</td>
<td>3084</td>
<td>2724</td>
<td>1716</td>
</tr>
</tbody>
</table>

The results show that the total time steps processed reduce with an increase in m. However, the results for the ATLCC, LCE, Number of PV modules and batteries are similar for the
different values of m. This is because the consolidation maintains the outlier periods for the irradiance and load demand.

b) Effect of subsidy on the Cost of energy

A number of microgrid implementations in rural communities require government subsidies to make the cost of electricity affordable. The LCE obtained of (£0.43 as shown in Table 4.2) is equivalent to 2,000/= UGX. This is higher than the cost of a unit from the main grid which is 752.5/= (£0.15) UGX [139]. Table 4.4 shows the cost of electricity at different levels of subsidy.

**Table 4.4: Cost of Electricity at Different Levels of Subsidy**

<table>
<thead>
<tr>
<th>Subsidy (%)</th>
<th>LCE (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.38</td>
</tr>
<tr>
<td>20</td>
<td>0.33</td>
</tr>
<tr>
<td>30</td>
<td>0.29</td>
</tr>
<tr>
<td>40</td>
<td>0.24</td>
</tr>
<tr>
<td>50</td>
<td>0.19</td>
</tr>
<tr>
<td>60</td>
<td>0.15</td>
</tr>
<tr>
<td>70</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**c) Effect of lower Lifetime of the system components**

The quality of maintenance is one of the factors that affect the overall cost of the microgrid. Rural microgrids are sometimes not maintained due to lack of technical expertise and poor management practices. Due to lack of maintenance and other factors such as the environment, the microgrid system components may not serve to the full lifetime considered during the design. Table 4.5 shows the effect on the LCE when the microgrid components operate for a percentage of their designed lifetime.

**Table 4.5: Effect on the LCE When the Microgrid Components Operate for a Percentage of Their Designed Lifetime**

<table>
<thead>
<tr>
<th>Lifetime as Percentage of that Used in the Design (%)</th>
<th>LCE (£/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1.34</td>
</tr>
<tr>
<td>60</td>
<td>0.95</td>
</tr>
<tr>
<td>70</td>
<td>0.69</td>
</tr>
<tr>
<td>80</td>
<td>0.53</td>
</tr>
<tr>
<td>90</td>
<td>0.43</td>
</tr>
</tbody>
</table>
d) Effect of a higher load demand

The effect of Load demand on reliability was considered by computing the LLP for the microgrid assuming up to 5% increase in the Load demand. The results are shown in Table 4.6.

Table 4.6: Effect of Load Demand on Reliability

<table>
<thead>
<tr>
<th>Percentage Increase in Load Demand (%)</th>
<th>LLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td>1</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>0.015</td>
</tr>
<tr>
<td>3</td>
<td>0.018</td>
</tr>
<tr>
<td>4</td>
<td>0.021</td>
</tr>
<tr>
<td>5</td>
<td>0.023</td>
</tr>
</tbody>
</table>

The results show that the microgrid’s reliability, which is at LLP value of 0.01 at Year₀, will have halved by the 3rd year (Year₃) to LLP value of 0.018. The microgrid was sized considering a load increase of 5% and LLP of 0.01. Table 4.7 shows a comparison of the results with the original results. The number of batteries slightly increased. The number of PVs increases from 2032 to 2134 and the LCE increases from £0.43/kWh to £0.46/kWh.

Table 4.7: Comparison of the Results Obtained Before and After Increase in Load Demand

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No increase in Load demand</th>
<th>5% increase in load demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Batteries</td>
<td>281</td>
<td>289</td>
</tr>
<tr>
<td>Battery Capacity (AH)</td>
<td>72,240</td>
<td>74,443</td>
</tr>
<tr>
<td>Total Number of PVs (Modules)</td>
<td>2032</td>
<td>2134</td>
</tr>
<tr>
<td>PV array Peak Amps (Amps)</td>
<td>10,908</td>
<td>11,459.</td>
</tr>
<tr>
<td>LLP</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>ATLCC (£)</td>
<td>75,136</td>
<td>80,560</td>
</tr>
<tr>
<td>LCE (£)</td>
<td>0.43</td>
<td>0.46</td>
</tr>
</tbody>
</table>

e) Elimination of battery storage.

The Levelised Cost of Energy obtained using the ComµGrid approach (£0.43/kWh approximately 2,000/= UGX) is higher than that for the main utility grid, which is 752.5/=.
UGX [139]. This is due to the cost of storage. When storage is not considered, the price for the electricity is £0.07/kWh (approximately 350/= UGX). The LLP in this case is however 0.53.

### 4.4.4 Comparison with the Basic Sizing Method

The community microgrid was also sized using the basic sizing method defined in [66]. The basic sizing method was implemented in Matlab Software. The procedure shown in Listing 4.2 was used to determine the size and cost of the components. The procedure shown in Listing 4.3 was used to determine the LLP. The results comparison with the ComµGrid sizing approach is shown in Table 4.8.

#### Table 4.8: Comparison Between Results from the Proposed Sizing Approach and the Basic Sizing Method

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Basic Method</th>
<th>Proposed ComµGrid MILP based Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Batteries</td>
<td>944</td>
<td>281</td>
</tr>
<tr>
<td>Battery Capacity (AH)</td>
<td>114,500</td>
<td>72,240</td>
</tr>
<tr>
<td>Total Number of PVs (Modules)</td>
<td>1176</td>
<td>2032</td>
</tr>
<tr>
<td>LLP</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>ATLCC (£)</td>
<td>108,226</td>
<td>75,136</td>
</tr>
<tr>
<td>LCE (£)</td>
<td>0.62</td>
<td>0.43</td>
</tr>
</tbody>
</table>

The ComµGrid sizing approach has a higher number of PVs and less number of batteries than the Basic Sizing method. This implies that ComµGrid PVs generate more energy than the Basic method thereby having more excess energy to charge the batteries than the Basic sizing method. The difference in number of PVs and batteries is because the basic sizing method only considers the average irradiance and load for only the worst month of the year. It does not consider the outliers in load and solar radiation throughout the year. The ComµGrid sizing approach considers the variation of irradiance and load demand throughout the year.

The performance of the two methods was compared considering the month with highest load. Figure 4.6 and Figure 4.7 show the sample hourly performance of such a system when sized using the two methods. During this period, The LLP for the system sized using the basic method was 0.44 and the average state of charge was 0.21 as shown in Figure 4.7. The graph for the Basic sizing method shows that most of the energy generated by the PVs was
consumed by the load and there was almost no excess energy to charge the battery. The graph for the ComµGrid sizing approach shows that there were periods when the energy generated by the PVs would serve the load and also charge the battery. The battery would then serve the load when the energy generated by the PV is less than the load demand. The system sized using the basic method was unable to meet the load demand for a period equivalent to 13 days and the battery was operating near minimum DOD for most of the time as shown. The period of deficit is longer than the 4 days of autonomy used during the sizing. The LLP for the system sized using the proposed ComµGrid MILP based method was $0.05$ and the average state of charge was $0.5$. This means that the system sized using the proposed ComµGrid MILP based method was unable to meet the load demand for a period equivalent to just $1.5$ days.

**Listing 4.2: Function to Implement Basic Sizing Method**

```
1 Read the electrical, Reliability and cost parameters from an excel file
2 Read the Ambient Temperature (°C) from an excel file
3 Read the Solar Radiation (W/m²) from an excel file
4 Generate the hourly load profile for the year (8760 hours)
5 Compute the average daily load for the year
6 Compute the peak Sun hours for the month with least irradiance
7 Initialise hourly PV output array
8 Initialise Cell Temperature Array
9 For each hour of the year
10   Compute the cell Temperature $T(k)$
11   Compute the Output Current for a single PV ($I_{PV}$)
12 End For Loop
13
14 Compute the average daily load for the month with least irradiance
15 Compute the number of PV modules
16 Compute the number of batteries
17 Compute the Capital cost of the PV modules
18 Compute the maintenance cost of the PV array
19 Compute the annualised capital and annualised maintenance costs for PV
```
Chapter 4. An Optimal Rural Community PV Microgrid Design

20 Compute the Capital cost of the Batteries
21 Compute the maintenance cost of the Batteries
22 Compute the annualised capital and annualised maintenance costs for Batteries
23 Compute the Array Short Circuit Current that Controller must handle under Short circuit conditions
24 Compute the number of controllers
25 Compute the costs for the civil works
26 Compute the capital costs for other components aside PV and Batteries, including civil works
27 Compute the Annualized Capital costs of other components
28 Compute the LCC
29 Compute the Capital costs of Disposable components
30 Compute the Annualized salvage value of the system
31 Compute the Annualized Total Life Cycle Cost (ATLCC)
32 Compute the ATLCC
33 Compute the LCE
34 Compute the LLP
Figure 4.6: Sample Hourly Performance of the Proposed Com\(\mu\)Grid MILP Based Sizing and Basic Sizing Methods

Figure 4.7: Comparison of Battery State of Charge for the Basic and Proposed Com\(\mu\)Grid MILP based Sizing Methods
Listing 4.3: Function to determine the Loss of Load probability (LLP)

```matlab
function [LLP] = findLLP (SOC(Bats, PVs, DOD, I_L, I_PV, Bat_eff, Bat_AH))

1  Compute the Battery Capacity
2  Initialise arrays SOC(len), I_df (len)
3  Compute the minimum allowed Battery Capacity
4  Set initial capacity of Battery at the start of the first hour to the Maximum Capacity
5  For each time step t
6  Compute the PV output current
7
8  If PV output Current is greater than the Load current
9    Set deficit current I_df(t) to zero
10   Compute the Battery state of charge SOC(t) after charging Battery
11   If the Battery is full
12      Set state of charge SOC(t) to maximum
13      End If
14   Else
15       Compute the Battery state of charge SOC(t) after discharging Battery
16       If state of charge is less than minimum
17          Compute the Deficit Current I_df(t)
18       End If
19   End If
20  Compute the total Load demand
21  Compute the total deficit Current
22  Compute the LLP
```

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The reliability of the basic sizing method was further analysed by increasing the number of days of autonomy. The results are shown in Table 4.9. The LLP for all the days of autonomy considered is higher than that obtained using the ComµGrid.

**Table 4.9: Reliability of the Basic Sizing Method with Increasing Number of Days of Autonomy**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>4 Days</th>
<th>6 Days</th>
<th>8 Days</th>
<th>10 Days</th>
<th>12 Days</th>
<th>14 Days</th>
<th>16 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Batteries</td>
<td>944</td>
<td>1,374</td>
<td>1,828</td>
<td>2,288</td>
<td>2,744</td>
<td>3,204</td>
<td>3,662</td>
</tr>
<tr>
<td>Battery Capacity (AH)</td>
<td>114,500</td>
<td>177,246</td>
<td>235,812</td>
<td>295,152</td>
<td>353,976</td>
<td>413,316</td>
<td>472,398</td>
</tr>
<tr>
<td>Total Number of PVs (Modules)</td>
<td>1,176</td>
<td>1,177</td>
<td>1,175</td>
<td>1,177</td>
<td>1,176</td>
<td>1,177</td>
<td>1,178</td>
</tr>
<tr>
<td>ATLCC (£)</td>
<td>108,226</td>
<td>217,509</td>
<td>290,170</td>
<td>363,783</td>
<td>436,762</td>
<td>510,378</td>
<td>583,673</td>
</tr>
<tr>
<td>LCE (£)</td>
<td>0.62</td>
<td>1.24</td>
<td>1.65</td>
<td>2.07</td>
<td>2.49</td>
<td>2.91</td>
<td>3.33</td>
</tr>
<tr>
<td>LLP</td>
<td>0.20</td>
<td>0.19</td>
<td>0.19</td>
<td>0.18</td>
<td>0.18</td>
<td>0.17</td>
<td>0.16</td>
</tr>
</tbody>
</table>

The results discussed above show that the ComµGrid Sizing approach yields a better system that is both technically reliable and cost effective as compared to the one achieved using the basic sizing method.

### 4.4.5 Comparison with Iterative Method

The community microgrid was sized using the iterative sizing method defined in [75]. Similar to the ComµGrid sizing approach, the iterative method in [75] aimed at minimising the ATLCC while meeting the load demand with a desired LLP. The method iteratively considers each PV and battery capacity within the search space and computes the ATLCC. Thereafter, the number of PVs and batteries that give the minimum ATLCC is obtained. The ComµGrid sizing approach was compared with the iterative method to determine the differences in the optimal PV and Battery obtained and the execution time of both approaches.

The iterative method was implemented in Matlab Software. The procedure shown in Listing 4.4 was used to determine the size and cost of the components. The procedure shown in Listing 4.3 was used to determine the LLP. The results comparison with the ComµGrid sizing
approach showed that the results were the same. The difference was that the ComµGrid approach provided an optimal solution faster than the iterative approach. The difference in time is attributed to the DBSCAN consolidation that reduces the amount of data to be processed.

**Listing 4.4: Function to Implement the Iterative Method**

```plaintext
1. Read the electrical, Reliability and cost parameters from an excel file
2. Read the Ambient Temperature (°C ) from an excel file
3. Read the Solar Radiation (W/m²) from an excel file
4. Generate the hourly load profile for the year (8760 hours)
5. Compute the average daily load for the year
6. Compute the peak Sun hours for the month with least irradiance
7. Initialise hourly PV output array
8. Initialise Cell Temperature Array
9. For each hour of the year
10. Compute the cell Temperature T(k)
11. Compute the Output Current for a single PV (I_PV)
12. End For Loop
13. Compute the average daily load for the month with least irradiance
14. Compute the number of PV modules
15. Compute the number of batteries
16. Determine the initial range of PVs and Batteries
17. Compute the ATLCC considering the PVs and Batteries. This is initial minimum ATLCC
```
19 For each Battery in the range
20 For each PV in the range
21 Compute the LLP considering a period of one year
22 If LLP is within ± 1% of the desired LLP
23 Compute the ATLCC considering PVs and Batteries
24 If the ATLCC is less than the minimum ATLCC
25 Set minimum ATLCC to the new ATLCC
26 Set optimum values to the values of batteries and PVs
27 End IF function
28 End IF function
29 End for Loop (for the PVs)
30 End For Loop (for the batteries)
31 Compute the Capital cost of the PV modules
32 Compute the maintenance cost of the PV array
33 Compute the annualised capital and annualised maintenance costs for PV
34 Compute the Capital cost of the Batteries
35 Compute the maintenance cost of the Batteries
36 Compute the annualised capital and annualised maintenance costs for Batteries
37 Compute the Array Short Circuit Current that Controller must handle under Short circuit conditions
38 Compute the number of controllers
39 Compute the costs for the civil works
40 Compute the capital costs for other components aside PV and Batteries, including civil works
41 Compute the Annualized Capital costs of other components
42 Compute the LCC
43 Compute the Capital costs of Disposable components
44 Compute the Annualized salvage value of the system
45 Compute the Annualized Total Life Cycle Cost (ATLCC)
46 Compute the ATLCC
47 Compute the LCE


4.4.6 Comparison with Homer Software

Various commercial software packages exist for use in simulation of PV systems. As seen in the previous subsections, PV simulation tools are critical at the design stage of PV systems because the decision on whether the solution is economical and cost-effective or not is made at this point [55]. Commercially available software packages include RETScreen, NREL Solar Advisor, ESP-r, SolarGIS, HOMER, INtegrated Simulation Environment Language (INSEL), SolarDesign, PV F-Chart, PVSYST, TRNSYS, SolarPro, PV DesignPro-G, PV Sol, PV Sol Expert, DDS-CAD, Polysun, Valentin Software and SolarNexus.

In [55], an investigation was carried out to compare the performance of PVSYST, TRNSYS and ESP-r in modelling PV systems. The results from the tools were found to be comparable. However, the author notes that when PVSYST results are used as the benchmark, there was an underestimation of output energy when using TRNSYS and an over-prediction of output power at midday when using ESP-r.

An investigation of the PV simulation softwares was carried out in [140] basing on four evaluation parameters. The evaluation parameters used were; commercial availability and cost, working platform, working capacity, the software’s scope and outputs, and updatability. The results show that each software has some strengths depending on the developer’s design goals. Some limitations were found in some of the softwares when solving particular problems thus the choice of the software to use depends on the area of application. All softwares were found to be up to date and can be used to carry out general modelling.

In [141], a review and analysis of PV softwares was also carried out. The evaluation criteria considered the following parameters; commercial and educational availability and cost, working platform, working capacities, scope and output, and updatability. The results from the study are similar to those obtained in [140]. From the results obtained after analysis of the major softwares, the authors preferred to use PVsyst for use in further simulation studies as it was deemed a good software package.

In [142], a comparison of two PV simulation softwares for use in urban applications was done. The softwares evaluated were Ecotect 2010 and the PVsyst 5.05. Results obtained show that Ecotect is suitable for basic design phase which involves the integrated PV system design for the building, accurate and optimal placement of the PV, the orientation and angle
selection. On the other hand PVsyst should be used for the detail design phase which involves optimum selection of PV system components. Also, the output energy estimation from PVsyst is more accurate. HOMER software was finally used to compare the results with those obtained using PVsyst. The findings show that it is not recommended to use a generic simulation tool for simulation of PV systems in urban applications.

About fifty small or large PV simulation softwares exist as stated in [141]. However it is expected that as the PV technology continues to grow, PV industries and research institutions will continue to improve available simulation packages and develop new ones.

For this particular PhD research, the microgrid was also sized using the commercially available Homer software so as to compare with the proposed sizing approach. Homer was chosen because of its rich feature list and ease of use as seen in the testimonies [143] submitted by some of the users of the HOMER software. The Homer software package is owned by HOMER Energy in the United States of America that allows for modelling, sizing and simulation of microgrids with various energy sources. It can be used to simulate and analyse both standalone and grid-connected microgrid systems [143]. It also has the capability to assess the performance, reliability and costs of the microgrid model. Various renewable energy sources can be modelled in the HOMER software package. A simplified architecture of the HOMER software is shown in Figure 4.8 below.

Figure 4.8: Homer Software Architecture [144]
For the comparison studies of the ComµGrid MILP sizing approach with the method available in Homer, a new set of PVs and Battery were chosen since the battery and PV used in the previous case studies were not defined in Homer. The make and model of the PV module chosen for the system was the SunPower X21-335-BLK while the battery chosen was the Trojan SSIG 06 375. The prices of the PV module and batteries plus their electrical parameters were obtained from [145] and [146] respectively. For both Homer and the ComµGrid, the input requirements include: hourly irradiance and temperature for a year, PV electrical parameters, Battery electrical parameters, cost parameters and Loss of Load Probability. With regard to the annual load demand, the Homer software requires importation of the hourly demand for a year. However, the ComµGrid inputs the appliance ratings and usage probabilities and generates a stochastic hourly load profile. A screenshot of the Homer results is shown in Figure 4.9.

![Figure 4.9: Screenshot Showing Results Obtained from Homer](image)

The comparison of results obtained from Homer and the ComµGrid MILP based Method is shown in Table 4.10. The LCE obtained is $0.29/kWh which is equivalent to £0.23/kWh.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Homer software</th>
<th>Proposed ComµGrid MILP based Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Batteries in parallel</td>
<td>197</td>
<td>199</td>
</tr>
<tr>
<td>Total Number of Batteries in Series</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Total Batteries</td>
<td>788</td>
<td>796</td>
</tr>
<tr>
<td>PV Rated capacity</td>
<td>937 kW</td>
<td>939 kW</td>
</tr>
<tr>
<td>LCE(£/kWh)</td>
<td>0.23</td>
<td>0.23</td>
</tr>
</tbody>
</table>
Chapter 4. An Optimal Rural Community PV Microgrid Design

The performance of the battery between the two methods is shown by Figure 4.10 showing the average state of charge of the Battery.

![Average Daily Battery State of Charge](image)

**Figure 4.10: Average Daily Battery State of Charge When Using the ComµGrid MILP based Method and When Using Homer Software**

The results from the ComµGrid sizing approach and Homer are comparable. The number of Batteries and PV capacity slightly differ. The LCE for the ComµGrid is £0.23/kWh while that for Homer is $0.29/kWh. The difference is due to the differences in the calculated quantities of the PV and Battery. In addition, in the ComµGrid, it was assumed that all the costs of the other components and civil works are lumped together as 20% of PV. Comparing these results with those from previous case studies, it can be observed that systems sized using the ComµGrid sizing approach and Homer software have better performance than those sized using the basic sizing method.

Among the useful features of the ComµGrid system is that it inputs the appliance ratings and usage probabilities and generates a stochastic hourly load profile. Therefore, the information from the survey is input into the ComµGrid with minimal processing. The ComµGrid also provides the time series for the surplus energy and the deficit energy as illustrated in Figure 4.11. This is useful when designing rural microgrids. The surplus energy could be used or consumed by implementing an economic activity that is useful to the community but with a
load demand that is flexible such as water pumping for irrigation and provision of clean water to the community.

![Figure 4.11: Average Daily Deficit Energy and Surplus Energy Throughout the Year](image)

4.5 Summary

This chapter has discussed the methodology proposed in this research for designing an optimal community PV microgrid for rural electrification. The developed ComµGrid Sizing Approach has been presented as an efficient and robust sizing approach for off-grid PV microgrid systems. The results obtained using this proposed approach have been compared with those obtained using existing sizing approaches and the commercially available Homer software. The next chapter will present and provide a detailed discussion of the load estimation process that has been used in this chapter.
This chapter provides an improvement to existing load modelling approaches so as to have a better technique and more accurate way of estimating the electrical demand for off-grid rural microgrid systems. It gives an evaluation of the efficacy of the current methods for load estimation. Informed by this evaluation, an improved approach is proposed that yields more accurate estimates of the electrical demand for off-grid systems in rural areas.

5.1 Introduction

Load modelling or estimation is a very critical step in the design of rural electrification systems. Load modelling enables creation of load profiles that show the trend of electricity consumption as a function of time usually over a full day. As discussed in Chapter 3, poor load estimation leads to undersizing / oversizing of the system. This in turn leads to a less reliable system or one that is very costly. Load modelling enables us to create load profiles that show the trend of electricity consumption as a function of time. The energy consumption represents quantity of energy in Watthours (Wh) that the particular users require in a given day [77]. The determination of the load profile for rural areas in developing countries is quite challenging. Among the reasons for this is the lack of information on the user’s electricity consumption since the majority of rural areas do not have access to electricity. The available electricity usage is often limited to minimal uses such as lighting, phone charging and use of small radios [78]. Nevertheless, a number of studies have been undertaken on load estimation
for rural electrification as discussed in Chapter Two but the approaches used need to be improved so as to obtain a better estimation of the load.

This PhD thesis proposes a load estimation methodology that incorporates socioeconomic and gender aspects into the design of year to year load profiles for off grid unelectrified rural communities. It shows how gender affects current and future loads in households and community income generating projects. It is important to note that sustainability of a microgrid in a rural community significantly depends on the community’s ability to use the supplied energy for economic activities that will reduce poverty, improve the status of livelihood of the community and fund the operation and maintenance costs of the microgrid [147][148]. The remainder of the chapter is organised as follows. In section 5.3, the gender aspects in rural electrification are discussed. Section 5.4 presents the improved load modelling approach and section 5.5 presents case studies applying the proposed approach.

5.3 Gender Aspects in Rural Electrification

The electrical loads in rural communities are broadly categorized into two, namely households that mainly include low energy consumers and small and medium sized enterprises (SMEs) with large loads representing income-generating productive use; The SMEs loads greatly impact the load profile of the microgrid and provide higher revenues than the households [81][86]. The choice of appliances and time of use both in the households and community projects is affected, among others, by gender roles within the community.

The following are some of the gender considerations that microgrid planners should take into account when estimating the electrical load.

   a) Gendered approach to identifying the electric needs of the community

   Men and women carry out different tasks within the household and electrification serves their needs differently. If gender is not considered when selecting the team that defines the community’s needs for electricity, the team is then mainly dominated by men and the opinions of the women on how electrification can help or affect them may not be considered [149][150]. There are a number of daily activities on which women spend a lot of time and
energy which could be substituted by use of electricity. These include daily collection of water, firewood and pounding grain by hand [149].

Provision of solutions to these problems without consulting women may lead to women’s hesitation to utilize these services during their daily activities for example they may be hesitant to use a water pumping service when it’s installed. Women should be consulted to prioritize the solutions that electricity may offer to their daily challenges. They can analyze the tradeoffs associated with a particular energy service and advise whether its effect will be received positively or negatively by the community. For instance, though women spend a lot of energy collecting water daily for their homes, this activity could also be a social activity where women discuss challenges faced, gossip or catchup on what is taking place in the community.

At household level, male dominated electrical needs identification has in some cases resulted into undersizing or no provision of appliances that enhance women’s activities. In [150], cases were reported where dim or no lights were provided in kitchens and animal sheds yet women and children cook at night and look after livestock. A majority of rural houses have detached kitchens and toilets and this brings security and safety concerns for women and children at night. The women may also desire to check on their children at night while they sleep. Women’s issues may therefore be addressed by having lights in the kitchen, toilet, children’s bedrooms and owning a flat iron and kettle. Men on the other hand may be interested in owning a TV, radio and having lights in the lounge and their bedroom. If women are not consulted, some appliances may not be considered in the design and the overall electricity service may not be perceived as useful especially by the women. When women do not participate in energy projects, the projects usually fail. The energy services may also be completely rejected or may have a low dissemination into the community [151].

**b) Financial decision making in the household**

Rural communities differ in distribution by gender in regards to who takes decisions regarding major household expenses, income generating activities and money earned by the woman in the home. This in turn affects rate of adoption of electricity, continual payments for electricity and which appliances are acquired. In communities where decision making is solely by the men, there is a chance that appliances that are needed mainly by women will be
Chapter 5. Improving Load Estimation in Design of Microgrids

given low priority hence affecting overall appliance penetration in the community. In [151], a scenario is mentioned where there was low dissemination of appliances within the community because the responsibility of procuring them was mainly left to the women yet these women also had other expenses to cater for in the home. This meant they were not in position to save up for the appliances. Gender roles in decision making may also inhibit men and women’s participation in community based projects [152]. Some of these projects utilize electricity services.

c) Asset ownership and Control of assets

Ownership of assets among men and women influences decisions on appliance acquisition and income generating activities. One of the proposed ways to boost energy use in rural communities is through integrating energy use with other development programs aimed at enhancing economic development [147]. A majority of rural communities in developing countries depend on agriculture as the main source of income. Community managed energy use in irrigation, food storage, pasteurization and value addition such as maize milling enhances the revenues from agriculture hence reducing household poverty while at the same time providing for operation and maintenance of the grid. The success of agricultural development related projects is significantly affected by ownership of land. In [153], projects are mentioned where dissemination of agricultural development programs was more successful in communities where there was joint ownership of land between men and women than those where ownership was by the man alone. Successful rollout of agricultural development projects that use energy positively impacts electricity usage within the community. At household level, [150] mentions cases where it may be viewed as a risk for women to invest in household appliances since the community viewed all appliances as belonging to the man. Women risked losing the appliances in the event of a divorce. This kind of attitude affects appliance penetration within the community.

d) Gender distribution of roles in management of community based projects

The distribution of responsibilities among men and women in community development projects affects the sustainability of the projects. Research has shown that projects that target the improvement of women’s welfare are more successful if their leadership consists of women than when it consists of men. In [149], a case is mentioned where women returned
back to manual grinding when the management of their grid connected milling service was taken over by men. In [154], a maize mill that had broken down due to poor management was repaired by a private company and its management handed over to the community’s women. The men were requested not to interfere in its management. The mill has remained operational.

In regards to training on awareness, benefits, use and maintenance of new products, more positive results are received when women are not combined with men during training. In this case, they are able to practice and freely ask questions without fear of being embarrassed by the men [151].

e) Cultural constraints

Rural electrification brings about changes to the practices and traditions in the community. Some of these practices may not be easily acceptable by the community. These include women owning assets such as land and equipment, participating in income generating activities away from the homestead, participating in meetings, taking on leadership roles in the community, visiting friends and formation of women groups. [115][150][155][151][149][156][157]

The above discussion has presented some of the gender related issues that planners should put into consideration when providing electrification services to the rural community. If a gendered approach is not used during design, the solution provided may not be fully utilized within the community [151]. In regards to load estimation, ignoring a gendered approach may lead to wrong estimation of current and future appliance acquisition and usage leading to either oversizing or undersizing of the system.

Understanding gender roles also provides insights into load profile differences over time between communities that had similar economic and social status prior to electrification. They could explain the differences in appliance penetration and load consumption for households and SMEs between two communities over time. According to [81], accurate results for rural unelectrified grids were obtained when the customer average daily energy consumption of one village was used to predict consumption of another similar unelectrified village [158]. This research study proposes the use of energy consumption and gender
Chapter 5. Improving Load Estimation in Design of Microgrids

characteristics of an electrified village to estimate the load consumption of an unelectrified village over time.

5.4 Proposed Improved Load Modelling Approach

In this study, an improvement in the stochastic method to simulate load characteristics that change with change in customer habits and environment is proposed. This improved approach incorporates gender aspects in the load estimation. It also uses average consumption in a similar village that is already electrified as a measure of the consumption in the unelectrified village and adjusts the load profiles accordingly to fit the socioeconomic setup of the new village as shown in Figure 5.1.

The first step of this approach is to identify an electrified village whose set up and social characteristics are similar to that of the village to be electrified. If the village is identified, then the following procedure is used to determine the load of the unelectrified village.

a) Carry out a survey in the electrified village

The appliances, ratings and usage times for the electrified village are identified. The daily usage of each customer is estimated from their monthly bills. The hourly consumption throughout the year is determined. The customers are classified as High, Medium or Low depending on their electricity consumption. The socioeconomic and gender related characteristics of the electrified village are evaluated and the customers are categorised according to their willingness and ability to pay for the electricity services. Details of customer transition among categories of electricity consumption and ability to pay are determined. The energy survey and socioeconomic survey in the electrified village are presented in section 5.4.1 and 5.4.2.
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Figure 5.1: Improved Load Modelling Approach Framework
Chapter 5. Improving Load Estimation in Design of Microgrids

b) Carry out a survey in the unelectrified village
   The customers in the unelectrified village are classified according to their electric needs and each customer is assigned a daily load based on consumption of a similar customer in the electrified village. The change in load consumption over time is estimated using:
   - The differences in the socioeconomic and gender characteristics of the two villages and changes in electricity consumption and;
   - The ability to pay identified in the electrified village.

   The energy survey and socioeconomic survey in the electrified village are presented in sections 5.4.1, 5.4.2 and 5.4.3.

c) Determine the load profile for the unelectrified village
   The number of customers to be connected to the micro grid is determined and the load profile of the microgrid is also determined.

If it were not possible to identify a proxy village or identify a specific customer category in the electric village, then an energy survey is carried out in the unelectrified village and the following is determined: The appliances, ratings and usage times are estimated. The hourly consumption throughout the year is determined. The customers are classified as High, Medium or Low depending on their electricity consumption. The socioeconomic and gender related characteristics of the customers are evaluated and the customers are categorised according to their willingness and ability to pay for the electricity services. Details of customer transition among categories of electricity consumption and ability to pay are determined. The change in load consumption and customer’s ability to pay overtime is estimated. The number of customers to be connected to the micro grid is determined and the load profile of the microgrid is also determined.

5.4.1 Energy Survey in Electrified Village

An energy survey is carried out in the electrified village and a questionnaire is given to each customer. An inventory of the appliances including power ratings, and time of use is obtained. In addition the monthly electricity bill for each customer is obtained. The users are categorized according to their electric needs. The common categories in rural areas include households, shops, restaurants, milling, welding, churches, mosques, healthcare centres. The
sample customers in the survey should include all the customer types i.e. homes and businesses. Households account for a significant part of the electrical load and electricity consumption varies a lot among households than the other customer categories [134]. During the survey, the following parameters are used to classify the households.

i) Average Household Size

ii) Education level of the household head

iii) Economic activities of the household head

iv) Gender of the household head

v) Age range of the household head

vi) Type of house. The common dwelling types include the following [130]:

- Brick house with irons sheets roof, More than two Rooms, kitchen, Toilet, Lounge
- Brick house with iron sheets roof, Two sleeping rooms, kitchen, Toilet, Lounge
- Brick house with iron sheets roof, One sleeping room, kitchen, Toilet, Lounge
- Brickhouse with Grass roof, More than two sleeping Rooms, kitchen, Toilet, Lounge
- Brickhouse with Grass roof, Two sleeping Rooms, kitchen, Toilet, Lounge
- Brickhouse with Grass roof, One sleeping Room, kitchen, Toilet, Lounge
- Mud house with Grass, More than one sleeping Rooms, kitchen, Toilet, Lounge
- Mud house with Grass, One sleeping Room, kitchen, Toilet, Lounge

The customers are categorised as High, Medium or Low according to their electricity consumption obtained from the monthly electricity bill. Below are the steps for determining the load profile.

**Steps for determining the load profile**

i) Determine the load consumption per hour for each appliance

According to [87], the load for a given appliance at time t is given by equation (5.1).

$$E_t = \frac{N}{n} \sum P_t$$

(5.1)

Where; n is the total number of appliances owned by the interviewed sample customers, and
N is the total number of appliances in a given category.

\( P_t \) is the power rating of the appliance.

Equation (5.1) may be reformulated as equation (5.2).

\[
E_t = N \times \frac{\text{number of appliances switched on at time } t \times P_t}{n} \tag{5.2}
\]

But the probability that an appliance in sample is switched on at time \( t \) is given by;

\[
\text{Probability at time } t = \frac{\text{number of appliances switched on at time } t}{n} \tag{5.3}
\]

Therefore the energy at time \( t \) is given by equation (5.4).

\[
E_t = N \times \text{Probability at time } t \times P_t \tag{5.4}
\]

Equation (5.4) was also used in the estimation of energy consumption in [87] and [134]. In situations where few observations can be made about the collected data from interviews, the probability is estimated using equation (5.5) [87].

\[
\text{Probability at time } t = \frac{\text{hours appliance is on during a period}}{\text{Total hours in period}} \tag{5.5}
\]

Using equation (5.5), the probability of usage of an appliance at a given time \( t \) can be determined.

ii) Define load characteristics depending on socioeconomic activities of the area.

As mentioned in section 2.4.3, the socioeconomic conditions and the daily behaviours of the rural community must have a contribution to the load profile. Therefore, it should be
possible to assess load parameters values by analysing typical conditions and socioeconomic behaviours of the rural communities.

[134], [132] and [133] have presented case studies on variation of load consumption depending on the habits and environment of the rural population. Their research shows that the probability that an appliance is switched on varies by the hour, day of the week and month.

Equation (5.4) has therefore been modified to equation (5.6).

\[ E_t = N \times P_{th} \times P_{td} \times P_{tm} \times P_t \]  

(5.6)

Where; \( P_{th} \) is the probability that an appliance in a category is switched on at a given hour, \( P_{td} \) is the probability that an appliance in a category is switched on, on a given day, \( P_{tm} \) is the probability that an appliance in a category is switched on, in a given month, and \( P_t \) is the power rating of the appliance.

iii) Randomize the number of appliances switched on per hour

A good load model should be stochastic in nature. From step (i), the probability that an appliance is on has been defined. This probability gives an indication of the number of appliances switched on simultaneously at a given time. For example, if the probability of a radio being on at 5:00p.m is 0.9, it means that 90% of the radios will be on at 5:00 p.m. Assuming that the total number of radios in the rural area is 50, the average number of radios that are on at 5:00 pm is 45. However there is unpredictability in appliances switching on and off which needs to be catered for. The number of radios in use at 5:00 pm may be assumed to vary randomly in the range of ±a % of the mean. Assuming a is 10%, the number of radios switched on at 5:00 pm may be considered to vary randomly between 39 and 50. Varying the number of appliances switched on at a given time leads to variation of the peak usage and peak time of use.

iv) Determine the hourly load profile

Using equation (5.7), the average hourly consumption over a day for each month is obtained for each category.
\[ E_{hi} = \frac{\sum_{d=1}^{D} E_h}{D} \] (5.7)

Where; \( E_{hi} \) is average energy consumption for hour,
\( D \) is the number of days in the month, and
\( E_h \) is the energy at each hour \( i \) of the day during the month.

As described by the steps (i) to (iii) above, the value of \( E_{hi} \) is computed based on the information provided by the energy survey. However, as earlier mentioned, the energy surveys may not give an accurate consumption of daily load due to inaccuracies in appliance ratings and time of use. A study by [81] showed that, though the duration of use may be inaccurate, the survey respondents provide a reasonably accurate prediction of the windows in which an appliance is in use. This implies that the pattern of energy usage throughout the day may be accurately predicted by the survey. This pattern may be represented as the contribution of each hour to the total daily load.

Using this analogy, the contribution of each hour to the average daily load is computed. This is done by dividing the consumption for each hour with the average daily consumption computed for that month. This gives the contribution of each hour to the total daily load for that month.

\[ E^*_{hi} = \frac{E_{hi}}{E_d} \] (5.8)

Where; \( E^*_{hi} \) is the contribution of each hour \( i \) to daily load,
\( E_{hi} \) is the load at hour \( i \), and
\( E_d \) is the average daily load.

The procedure described from (i) to (iv) is summarized in Figure 5.2 below. A MATLAB function presented in Listing 5.1 was implemented to generate the load profiles.
Chapter 5. Improving Load Estimation in Design of Microgrids

Figure 5.2: Flow Chart for Calculation of Hourly Percentage of Daily Load

**Load INPUTS:**
- Load categorisation
- Appliance data (Number (App_N) and Rated Power, App_W)
- Appliance Category Hourly usage Probability
- Appliance Category Day of week usage probability
- Appliance Category month of Year usage probability

Set start hour k=1 (Start of first For Loop)
- \( H = \text{TimeH}(k) \) Hour of day
- \( D = \text{TimeD}(k) \) day of week
- \( M = \text{TimeM}(k) \) Month of year
- Set Energy \( E(k) = 0 \)
- Set randomisation parameter \( r \)

Set Appliance category \( n = 1 \) (Start of second For Loop)
- Get Probability of usage during hour \( H \), \( p(H) \)
- Get Probability of Usage during day \( D \), \( p(D) \)
- Get Probability of Usage during Month \( M \), \( p(M) \)
- Randomise hourly probability by \( r \), \( p(H) \)
- Get Number of appliances \( App_N \)
- Get appliance rating \( App_W \)

\[
E(k) = E(k) + p(H) * p(D) * p(M) * App_N * App_W
\]

End
Listing 5.1: Function to Generate Load Profiles

1. function \([I_L, I_{LkW}] = \text{getLoad}()\)
2. Read the appliance rating from excel file
3. Read the appliance probability for each hour from excel file
4. Read the appliance probabilities of use for each hour of the day from excel file
5. Read the appliance probabilities of use each day of the week from excel file
6. Read the appliance probabilities of use each month of the year from excel file
7. Read the hour of the year (1 to 8760)
8. Read the day of the year for each hour
9. Read the month of the year for each hour

10. for each hour (k) of the year
11.  Get the hour of the day
12.  Get the day of the week
13.  Get the month of the year
14.  Set the energy use for that hour to zero
15.  Set a randomisation parameter \(r\)

16.  For each appliance \((i)\) in the list
17.  If probability of use appliance on that day is one and the probability of use of the appliance in that month is one then

18.   Randomise the hourly probability by \(r\)
19.   Compute the energy consumption by multiplying the hourly randomised probability and the Appliance rating
20.   Get the sum of the energy usage for that hour
21.  End if

22.  End second for loop
23.  End first for Loop

24.  For each month of the year
5.4.2 The Socioeconomic Survey and User Classification in the Electrified Village

This survey establishes the customers’ ability to pay the initial fees and sustain subsequent payments. In addition, it also determines the change in consumption over time. It is assumed that at any point in time, a customer’s consumption is defined by their ability to pay for the electricity and their energy consumption. Regarding ability to pay, a customer belongs to any of the three states in Table 5.1.

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAP</td>
<td>A customer is Willing and Able to Pay for the electricity service</td>
</tr>
<tr>
<td>WAPA</td>
<td>A customer is Willing but Partially Able to pay for the electricity</td>
</tr>
<tr>
<td>NA</td>
<td>The customer is Not Able to pay for the electricity service</td>
</tr>
</tbody>
</table>
Chapter 5. Improving Load Estimation in Design of Microgrids

The Ability to pay is defined as the maximum amount that a customer can pay for a service given their income and other household or business expenses [159]. It may be quantified by percentage of residual income available to pay for the microgrid expenses.

The customers’ ability to pay is measured by an ability to pay factor calculated using equations (5.9) and (5.10) [159].

\[
R_h = I_h + S_h + En_h - Ex_h - L_h \tag{5.9}
\]

\[
A_f = \frac{C}{R_h} \tag{5.10}
\]

Where \( R_h \) is residual income, \( I_h \) is monthly income, \( S_h \) is the monetary value of any monthly subsidies, \( En_h \) is the expense on energy sources that will be replaced by microgrid connectivity e.g. candles, dry cells and paraffin, \( Ex_h \) is the monthly expenditure on non-energy related items, \( L_h \) is the cost of any monthly loans to be paid, \( A_f \) is the ability to pay factor, \( C \) is monthly cost for the microgrid services.

A high \( A_f \) means that a customer uses a high percentage of their residual income to pay for power. If \( A_f > 1 \) then the customer has no income to pay for consumed power.

Figure 5.3 illustrates the relationship between \( A_f \) and the states WAP, WAPA and NA. When the \( A_f \) is low, the customer uses a small percentage of their residual income to pay for power. The customer is in the WAP state according to Table 1. As the \( A_f \) increases, the customers’ ability to pay reduces since a higher percentage of residual income is used to pay for power. Above \( A_{f1} \), the customer may irregularly pay for the service and may face some seasons of disconnection. This state of paying irregularly is the WAPA state. When the \( A_f \) increases further above \( A_{f2} \) the customer will not have ability to pay for power at all, resulting into NA state. During the energy survey, customers that cannot pay for more than 6 months may be
considered unable to pay for that year and those unable to pay for less than six months are considered partially able to pay.

A customer can transition from one state to another. The customer movement from one state to another is a conditional probability only dependent on the current state and can therefore be modeled by the Markov Chain process. Markov Chains provide a simple way to statistically model random processes involving customer migration and customer retention for consumption of a product or service [160].

The possible customer transitions considered in this research are presented in Figure 5.4.

**Figure 5.4: Possible Transitions between WAP, WAPA, NA States for Customers**

Assuming the customers’ states are evaluated annually, the state of customers in year t+1 is calculated using equation (5.11).

\[
\begin{bmatrix}
W_{AP}^{t+1} \\
W_{APA}^{t+1} \\
N_{A}^{t+1}
\end{bmatrix} =
\begin{bmatrix}
P_{11} & P_{21} & P_{31} \\
P_{12} & P_{22} & P_{32} \\
P_{13} & P_{23} & P_{33}
\end{bmatrix}
\begin{bmatrix}
W_{AP}^{t} \\
W_{APA}^{t} \\
N_{A}^{t}
\end{bmatrix}
\]  

(5.11)

\(W_{AP}^{t}, W_{APA}^{t}\) and \(N_{A}^{t}\) are the proportion of customers in state WAP, WAPA and NA at year t. \(W_{AP}^{t+1}\), \(W_{APA}^{t+1}\) and \(N_{A}^{t+1}\) are the proportion of customers in state WAP, WAPA and NA at year t+1. The transition probabilities P11 to P33 are calculated using equation (5.12).

\[P_{ij} = \frac{N_{ij}}{N_{i}}\]  

(5.12)

\(P_{ij}\) is the transition probability from state i in year t to state j in year t+1, \(N_{ij}\) is the number of customers that transitioned from state i in year t to state j in year t+1. \(N_{i}\) is the total number of customers in state i in year t.
For instance, $P_{12}$ is the probability of transition from WAP state in year $t$ to WAPA state in year $t+1$. It is determined by the ratio of the number of customers that fully paid for year $t$ and partially paid for year $t+1$ to the total number of customers in state WAP in the year $t$.

Equation (5.12) cannot be used to calculate the transition probabilities for enterprises with large loads such as milling machine. This is because these are usually few in the community therefore there is not enough sample space to calculate the transitions. In this case, the WAP, WAPA and NA are calculated from regularity of monthly payments made over a period of time. WAP is the proportion of the period when the customer paid on time. WAPA is the proportion of the period where the customer was unable to pay on time or faced difficulties in payment. NA is the proportion where the enterprise completely defaulted.

Besides transitions between WAP, WAPA and NA, customers also transition between High, Medium and Low energy consumption. This is illustrated in Figure 5.5 and equation (5.13).

![Figure 5.5: Possible Transitions between High, Medium, and Low consumption](image)

\[
\begin{bmatrix}
\text{High}_{t+1} \\
\text{Medium}_{t+1} \\
\text{Low}_{t+1}
\end{bmatrix} =
\begin{bmatrix}
p_{11} & p_{21} & p_{31} \\
p_{12} & p_{22} & p_{32} \\
p_{13} & p_{23} & p_{33}
\end{bmatrix}
\begin{bmatrix}
\text{High}_t \\
\text{Medium}_t \\
\text{Low}_t
\end{bmatrix}
\]  
(5.13)

The movement between Low, Medium and High is obtained from the survey and depends on the customers’ ability to buy high power appliances. It is worth noting that an increase in transition probabilities $P_{21}$, $P_{31}$ and $P_{32}$ represents an increase in ability to pay in equation (5.11) and an increase in consumption in equation (5.13). Similarly, an increase in $P_{23}$, $P_{13}$ and $P_{12}$ represents a decrease in ability to pay in equation (5.11) and decrease in consumption in equation (5.13).
5.4.3 Gender Characteristics in the Electrified Village

The gender related characteristics of the electrified village are rated against the indicators below customized from [148] and [161]. For each indicator, a score of Low (1 to 2 points), Medium (3 points) and High (4 to 5 points) is assigned.

**Indicator 1: Identification of users’ electric needs**

**Low:** The users’ electric needs at project inception were identified mainly by the men. Very few people in the community participated in the meetings. **Medium:** Men and women were involved in identifying electric needs. Over 50% of the community participated in the meetings. However, women were combined with men in the meetings so a few women’s views were presented. **High:** Men and women were independently and extensively consulted so all needs were considered. A majority of the men and women participated in the meetings.

**Indicator 2: Decision making**

**Low:** Decision making in the home is mainly by men. **Medium:** Men and women jointly make decisions but decisions on major issues such as acquisition of appliances and assets are made by men. **High:** Women are free and can take decisions autonomously without fear such as acquisition of assets and appliances.

**Indicator 3: Social connection**

**Low:** Less than 20% of Households belong to male community groups. Women are not fully allowed to visit friends, participate in meetings or form women’s groups within the community. **Medium:** About 50% of Households belong to male and female community groups. Women are allowed to visit friends, participate in meetings but participation is low both at community meetings and women’s groups. **High:** Over 70% of Households belong to male and female community groups. Women are fully allowed to visit friends, participate in meetings and participation is high both at community meetings and women’s groups.

**Indicator 4: Community income generating projects**

**Low:** The community is not involved in any income generating activities. **Medium:** The community is involved in some income generating activities but participation is mainly by the men. Women participation is low. **High:** Several households and community as a whole are engaged in income generating activities.

**Indicator 5: Management of Community activities**
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Low: Community income generation projects are dominantly managed by men. There is no participation by women in the projects’ management even in cases where they are the main beneficiaries of the projects. There is limited ownership of the projects by the community. **Medium:** Women and men are involved in the management of community income generation projects. There is a sense of ownership of the projects by the community. However there is need for improved participation by women and effective training on business marketing and technical maintenance. **High:** Women and men are involved in the management of the community income generation projects. Women have sole management of the projects where they are beneficiaries and there is gender tailored training on business marketing and technical maintenance.

**Indicator 6: Asset ownership and control**

**Low:** Assets such as land, animals and household appliances are majorly owned and controlled by the men. **Medium:** Women and men in households jointly own some assets. Very few women own assets by themselves. **High:** Women and men in households jointly own some assets. A significant number of women own and control assets.

**Indicator 7: Cultural constraints**

**Low:** The community's culture limits women's freedom to movement, asset ownership, and involvement in income generating activities, community leadership and attending meetings. **Medium:** There are some cultural limitations to women's abilities but the community partially waives them. The women can own some appliances and participate in meetings. **High:** There are no cultural limitations to women's free movement, asset ownership, involvement in income generating activities, community leadership and attendance of meetings.

Each team member of the survey group (the survey team consists of members tasked with planning and designing the microgrid system) develops an independent score for each of the above mentioned indicators. The members then meet and agree on a final score. The total score for the electrified village ($S_{old}$) is obtained by summing up all the scores.

**5.4.4 Energy Survey and User classification in the Unelectrified Village**

In the unelectrified village, a survey is performed to obtain information about appliances they wish to acquire. The appliances in each category and times of use are obtained. Each
customer is assigned a total daily load based on the consumption of a similar customer in the electrified village.

The Markov process as described before is used to estimate the variation of load over time (yearly variation) in the new village. The socioeconomic characteristics of the two villages are then compared to generate the transition probabilities used in the Markov process.

Equations (5.9) and (5.10) and the ability to pay factors $A_{f1}$ and $A_{f2}$ for the electrified village are used to categorize the customers in the unelectrified village into WAP, WAPA and NA. The gender related characteristics of the unelectrified village are scored basing on indicators 1 to 7 mentioned above. The total score for the unelectrified village ($S_{new}$) is obtained. $S_{old}$ and $S_{new}$ are compared using equation (5.14).

\[
S_e = \frac{S_{new}}{S_{old}} \tag{5.14}
\]

If $S_e = 1$, then the transition probabilities for the electrified village are used to estimate load for the unelectrified village. If $S_e > 1$ then the gender specific socioeconomic characteristics for the unelectrified village are better than that for the electrified village. In this case, the probabilities P21, P31 and P32 for both the transition matrices for energy consumption and ability to pay are increased by $S_e \%$ and P23, P13 and P12 are reduced by $S_e \%$. If $S_e < 1$ then the characteristics for the unelectrified village are worse than that for the electrified village. In this case, the probabilities P21, P31 and P32 are reduced by $S_e \%$ and P23, P13 and P12 are increased by $S_e \%$. The probabilities P11, P22 and P33 are obtained using equations (5.15) to (5.17)

\[
P11 = 1 - (P12 + P13) \quad \tag{5.15}
\]

\[
P22 = 1 - (P21 + P23) \quad \tag{5.16}
\]

\[
P33 = 1 - (P31 + P32) \quad \tag{5.17}
\]

The values of WAP, WAPA, NA and High, Medium, Low for the $n^{th}$ year may be obtained by using equations (5.18) and (5.19).
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\[
\begin{bmatrix}
WAP_n \\
WAPA_n \\
NA_n
\end{bmatrix}
= \begin{bmatrix}
P11 & P21 & P31 \\
P12 & P22 & P32 \\
P13 & P23 & P33
\end{bmatrix}
\begin{bmatrix}
WAP_{n-1} \\
WAPA_{n-1} \\
NA_{n-1}
\end{bmatrix}
\]  
(5.18)

\[
\begin{bmatrix}
High_n \\
Medium_n \\
Low_n
\end{bmatrix}
= \begin{bmatrix}
p11 & p21 & p31 \\
p12 & p22 & p32 \\
p13 & p23 & p33
\end{bmatrix}
\begin{bmatrix}
High_{n-1} \\
Medium_{n-1} \\
Low_{n-1}
\end{bmatrix}
\]  
(5.19)

Where; \(WAP_n\) is the percentage of customers that will be able to pay regularly, \(WAPA_n\) is the percentage of customers that will be unable to pay regularly, \(NA_n\) is the percentage of customers that will not be able to pay. Using the distribution of \(WAP\), \(WAPA\) and \(NA\), the microgrid planners are able to decide on what proportion of households and enterprises to plan for during connection, given their ability to pay. If the microgrid designer plans for \(N\) customers, the distribution of power consumption between High, Medium and Low categories is done according to the proportions in equation (5.20).

\[
\begin{bmatrix}
High \\
Medium \\
Low
\end{bmatrix}
= \begin{bmatrix}
High_n \\
Medium_n \\
Low_n
\end{bmatrix}
\]  
(5.20)

\(High_n\) is the percentage of customers in the High consumption range, \(Medium_n\) is the percentage in medium range and \(Low_n\) is the percentage in Low range.

### 5.4.5 Determine load profile for the unelectrified village

In the previous section, the number of customers to be connected to the microgrid was determined. In section 5.4.1, the load profile for each customer category was determined as a percentage contribution of each hour to the daily load. Each customer category has a range for the average daily consumption. In this step, each customer category is assigned the load profile of a similar customer in the electrified village. The parameters for categorizing households in rural communities are discussed in section 5.4.1. Randomization of the load at each hour is achieved by sampling the average daily load range using a uniform distribution. The resultant average load is multiplied by number of customers in the each category and the hourly contribution to daily load for that hour. This method is shown in Figure 5.6 and Listing 5.2. It’s a modification of that in Figure 5.2 and Listing 5.1.
Figure 5.6: Flow Chart for Calculation of Energy Consumption at Each Hour
To generate the load profiles basing on the improved approach proposed in this research, a load generation kit was developed using MATLAB software.

5.4.6 Algorithm for Load Profile Generation Using the Improved Load Estimation Approach

The algorithm was developed using MATLAB software as follows:

**Listing 5.2: Load Profile Generation Algorithm using Improved Load Estimation Approach**

1. function [l_L,I_LkW] = getLoad2()
2. Read the customer categories from excel file
3. Read the hourly contribution to daily load from the excel file
4. Read the average daily load range for each category
5. Read the number of customers in each category
6. Read the hour of the year (1 to 8760)
7. Read the day of the year for each hour
8. Read the month of the year for each hour

9. for each hour (k) of the year
10. Get the hour of the day
11. Get the day of the week
12. Get the month of the year
13. Set the energy use for that hour to zero
14. Set a randomisation parameter r
15. For each appliance (i) in the list
16. If probability of use of the appliance on that day is one and the probability of use of the appliance in that month is one then
17. Compute average daily load using uniform distribution
18. Compute the energy consumption by multiplying the average daily load with the hourly percentage of daily load and number of customers
19. Get the sum of the energy usage for that hour
20. End if
21. End second for loop
22. End first for Loop
23. Get average daily load for each month of the year
5.5 Results obtained using the Improved Load Modelling Approach

The proposed improved load modelling approach discussed above was used to determine load profiles considering an area in eastern Uganda known as Tororo. The rural community in consideration constitutes of 100 households with a population of approximately 530 people. Based on the energy survey conducted by the Uganda Bureau of Statistics and Ministry of Energy and Mineral Development for 2012 [129] as well as the Uganda National household survey for 2016 [130], the household categories and appliance usage of this area were estimated. Using data based on surveys done by [134], [132] and [133], the load categories and probabilities $P_{th}$, $P_{td}$ and $P_t$ for appliance usage during each hour, day of week and month respectively were defined. The details of the load categorisation are presented in Appendix B. The probabilities were populated in an excel sheet. An example of the load data presentation is shown in Tables 5.2, 5.3 and 5.4. This data describes the time of use of the maize mill throughout the year. Since the rural communities depend on agriculture, the energy consumption of a maize mill is lowest when there is low produce of harvested crops and highest when there is high produce. Consequently, the load can be categorised into low season, mid-season and high season as shown in Table 5.4. In this example, $P_{th}$, $P_{td}$ and $P_t$ are defined by Table 5.2, 5.3 and 5.4 respectively. Table 5.4 also defines the probabilities that each category is activated. These probabilities vary by day of week and month of year. The details of these probabilities are presented in Appendix C.

A MATLAB tool kit was developed based on the algorithm shown in Figure 5.2 and Listing 5.1. The following load profiles were generated which show load variation by month of the year. Figure 5.7 shows load variation for month of February, May and August. These months lie in low, mid and high agricultural produce season respectively so the load due to milling contributes to the different load profiles. The profiles showing the hourly consumption as a percentage of the daily load for different customer categories are shown in Figures 5.8a, 5.8b, 5.8c, 5.8d, and 5.8e. In 5.8a, households in the Low consumption category show a small morning peak and high evening peak. The appliances consist of mainly lights and phone charging. The power consumption of these appliances is dependent on occupancy in the home and time of day in case of the lights. The Medium household profile shows that both the morning peak and evening peak have significant contribution to the overall daily consumption. This may be attributed to appliances such as radios and televisions that are used throughout the day. The High consumption households show that the morning peak and
evening peak have an almost equal contribution to the overall daily load. This is attributed to appliances such as refrigerators that are in use throughout both day and night. Figure 5.8b shows the profile of the maize mill in the months February, May and August. These months correspond to the Low, Medium and High consumption seasons respectively. In August, the maize mill is continuously operational throughout the window from 8:00 am to 8:00 pm. All hours have an almost equal contribution to the daily load. In February, the operation of the mill is higher from 3:00 pm to 8:00 pm and in May, the operation is high starting from 12:00 pm.

Figure 5.7: Average Hourly Daily Load Variation for February, May and August

Figure 5.8a: Load Profile for Household Category (High, Medium and Low Consumption)
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Figure 5.8b: Load Profile for the Maize Mill in February, May and August

Figure 5.8c: Load Profile for the Barbershop
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Figure 5.8d: Load Profile for the School

Figure 5.8e: Load Profile for the Health Centre
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### Table 5.2: Probability Matrix for Maize Mill

| Category           | No. | P(W) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|--------------------|-----|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Lights             | 2   | 3    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine Low Season | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine Mid Season  | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine High Season | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Phone Charging     | 2   | 3    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

### Table 5.3: Hourly Load Matrix for Maize Mill (in kW)

| Category           | No. | P(W) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|--------------------|-----|------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Lights             | 2   | 3    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine Low Season | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine Mid Season  | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Milling machine High Season | 1   | 10000| 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| Phone Charging     | 2   | 3    | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |

### Table 5.4: On and Off Days of Operation for Select Appliances

<table>
<thead>
<tr>
<th>Category</th>
<th>Mon</th>
<th>Tue</th>
<th>Wed</th>
<th>Thu</th>
<th>Fri</th>
<th>Sat</th>
<th>Sun</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Milling machine Low Season</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Milling machine Mid-Season</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Milling machine High Season</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
5.5.1 Using Load Characteristics for a Known Village to Estimate the Electricity Consumption of Another

This case study intends to show how load characteristics for a known village can be used to estimate the electricity consumption of another. The study has used measurements in [132] carried out for a village in Uganda on three transformers.

In [132] the customers were grouped by their appliances;
- Group 1: Lighting, radio, TV
- Group 2: Lighting, radio, TV, 1 or 2 appliances (fan, fridge, flat iron).

This study has considered the customers connected on Transformer 2 in [132]. The distribution of the customers in each group is as shown in Table 5.5.

<table>
<thead>
<tr>
<th></th>
<th>Group 1</th>
<th>Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 2Y (Yellow Phase)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Phase 2R (Red Phase)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Phase 2B (Blue Phase)</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

In this case study, it’s assumed that the electrified village consists of customers connected to phases 2Y (Yellow Phase) and 2R (Red Phase) and those in phase 2B (Blue Phase) belong to the unelectrified village. The load profile for phase 2B is then estimated using a MATLAB program.

The following assumptions have also been made:
1) The hourly appliance usage for lighting, TV, radio, fridge, fan and flat iron are same as [134].
2) The daily load consumption for Group 1 is estimated to be uniformly distributed between 5.7kW and 7 kW and that for group 2 between 7kW and 8.5kW. This assumption is made based on measurements for phases 2Y and 2R in [132].

Using a MATLAB toolkit based on the algorithm shown in Figure 5.2 and Listing 5.1, the load profile for each group is determined. This profile shows the hourly load as a percentage of the daily load. The result is shown in Figure 5.9.
Assuming that customers in phase 2B belong to the unelectrified village, the load profile is estimated using a MATLAB toolkit based on the algorithm in Figure 5.6 and Listing 5.2. The load profiles for the measured data for phase 2B and the generated profile from MATLAB are shown in Figure 5.10.
It can be noted that the profiles are similar apart from the morning peak. The average power calculated over a year is 37.3kW. This is close to the average of 32.3kW obtained after two days of measurements. This shows that data from a proxy village can be used to estimate with minimal error the load in an unelectrified village.

### 5.5.2 Using Social Characteristics of an Area to Estimate Electrical Load

This case study intends to show how social characteristics of an area can be used in the estimation of the electrical load. It assumes a village, village_1, that has been electrified. Its energy and socioeconomic data is to be used in the electrification process for Village_2. The following are the assumed results of the energy survey in the electrified village:

i) The data for actual energy consumption in [81] has been used as the daily load. The consumption categories in [89] have been adopted namely: Low: \(< 140\), Medium: 140-450, and High: \(> 450\)Wh. The households with Low consumption belong to Group 1, those with medium to Group 2 and those with high consumption to Group 3.

ii) It’s been assumed that household usage pattern is equally distributed between Profile1(has a large evening peak and a small morning bump), Profile3(has continuous growth during the day and an evening peak) and Profile4(has an evening peak and continuous night consumption) defined in [89]. The obtained profiles are shown in Figure 5.11.

iii) The assumed transition probabilities for WAP, WAPA and NA from the socioeconomic survey as well as between High, Medium and Low are shown in Figure 5.12.

![Figure 5.11: Household Load Profiles](image)
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Figure 5.12: Transition for WAP, WAPA, NA and High, Medium and Low

The following are the assumed results of the energy survey in the unelectrified village:

i) Using the households’ current energy use, their economic state, wellbeing and future appliance wish list, the households are classified into groups 1, 2 and 3 as in Table 5.6. An average daily load is assigned.

<table>
<thead>
<tr>
<th>Group</th>
<th>No. of households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1:</td>
<td>65</td>
</tr>
<tr>
<td>Group 2:</td>
<td>25</td>
</tr>
<tr>
<td>Group 3:</td>
<td>10</td>
</tr>
</tbody>
</table>

\[
\begin{bmatrix}
High_0 \\
Medium_0 \\
Low_0
\end{bmatrix} = \begin{bmatrix}
0.1 \\
0.25 \\
0.65
\end{bmatrix}
\quad (5.21)
\]

\[
\begin{bmatrix}
High_n \\
Medium_n \\
Low_n
\end{bmatrix} = \begin{bmatrix}
0.85 & 0.15 & 0.05 \\
0.1 & 0.7 & 0.05 \\
0.05 & 0.15 & 0.9
\end{bmatrix} \begin{bmatrix}
High_{n-1} \\
Medium_{n-1} \\
Low_{n-1}
\end{bmatrix}
\quad (5.22)
\]

ii) Assuming that all households are to be electrified and the microgrid is designed for a load of 5 years. The profile will be as shown in Figure 5.13. The average daily load is 22.1 kWh and the peak is 5 kWh.

\[
\begin{bmatrix}
High_5 \\
Medium_5 \\
Low_5
\end{bmatrix} = \begin{bmatrix}
0.27 \\
0.18 \\
0.55
\end{bmatrix}
\quad (5.23)
\]
ii) Assuming that 32% are WAP, 48% are WAPA and 20% are NA. If the socioeconomic characteristics in Village_1 and Village_2 are similar, transition probabilities for Village_1 apply to Village_2.

\[
\begin{bmatrix}
WAP_0 \\
WAPA_0 \\
NA_0
\end{bmatrix}
= \begin{bmatrix} 0.32 \\ 0.48 \\ 0.2 \end{bmatrix}
\]

\[
\begin{bmatrix}
WAP_n \\
WAPA_n \\
NA_n
\end{bmatrix}
= \begin{bmatrix} 0.85 & 0.15 & 0.1 \\ 0.1 & 0.7 & 0.5 \\ 0.05 & 0.15 & 0.4 \end{bmatrix}
\begin{bmatrix}
WAP_{n-1} \\
WAPA_{n-1} \\
NA_{n-1}
\end{bmatrix}
\]

\[
\begin{bmatrix}
WAP_5 \\
WAPA_5 \\
NA_5
\end{bmatrix}
= \begin{bmatrix} 0.45 \\ 0.41 \\ 0.14 \end{bmatrix}
\]

The results show that by the 5th year, 45% have ability to always pay and 41% will irregularly pay. If the microgrid is designed for those who will regularly and irregularly pay, this is 86% of the households. Basing on the transition between High, Medium and Low, 27% of these connected users will be considered as High users, 18% Medium and 40% Low. The resultant profile is shown in Figure 5.14. The average daily load is 21.9kWh and the peak is 5.1kW.
iv) Assuming the socioeconomic characteristics of Village_1 and Village_2 are different resulting in different total scores for each village. The ratio of total score of village 2 to village 1 in this case study is 70% therefore the electricity adoption rate for Village_2 is assumed to be 30% slower than that of Village_1. The transition probabilities drivers P21, P31 and P32 are reduced by 30% and the probabilities P12, P13 and P23 are increased by 30%.

\[
\begin{pmatrix}
WAP_n \\
WAPA_n \\
NA_n
\end{pmatrix}
= \begin{pmatrix}
0.81 & 0.1 & 0.07 \\
0.13 & 0.7 & 0.35 \\
0.06 & 0.2 & 0.58
\end{pmatrix}
\begin{pmatrix}
WAP_{n-1} \\
WAPA_{n-1} \\
NA_{n-1}
\end{pmatrix}
\] (5.27)

\[
\begin{pmatrix}
WAP_5 \\
WAPA_5 \\
NA_5
\end{pmatrix}
= \begin{pmatrix}
0.32 \\
0.43 \\
0.25
\end{pmatrix}
\] (5.28)

\[
\begin{pmatrix}
High_5 \\
Medium_5 \\
Low_5
\end{pmatrix}
= \begin{pmatrix}
0.18 \\
0.16 \\
0.66
\end{pmatrix}
\] (5.29)

Designing for those who will regularly and irregularly pay, means 75% of the houses will be connected. Of these, 18% are High users, 16% Medium and 66% Low. The resultant load profile is shown in Figure 5.14. The average daily load is 19.2kWh and the peak load is 4.5 kW.

### 5.5.3 Effect of Gender on the Resultant Load Profile

Consider a hypothetical village with characteristics as defined in [150] [149] and [154]. It is assumed that the community has 100 houses and a milling machine. It’s further assumed that women were not involved in the energy needs survey so only male interests were considered during household electrification. It’s assumed that there was no provision of lights in the kitchen and toilets, no use of the flat iron and use of TV and radio is limited to the evening when men are at home. Women are not involved in the management of the milling machine and have not embraced its use. The community culture limits women to household work with little movement outside the homestead. Women groups are not popular within the community. Women empowerment and decision making is low thus all purchases are made mainly by men. Women also have limited ownership of land either individually or jointly with the men and have limited participation in income generating activities. The men decide
on what the women spend money on and also control all finances from home income generating projects. It’s assumed that the distribution of the households in regards to ability to pay is 32% WAP, 48% WAPA and 20% NA. The consumption distribution is 10% High, 25% Medium and 65% Low. The average daily consumptions for High, Medium and Low are assumed to be 350Wh, 200Wh and 100Wh respectively. The transition matrix from the survey is assumed to be the same for both ability to pay and energy consumption transitions. The chance that a customer remains in their initial state is high (P11, P22, P33) and thus transition among other states is low. The transition matrix and the initial values of WAP, WAPA, NA, High, Medium and Low are shown in equations (5.30) to (5.32).

Transition Matrix =
\[
\begin{bmatrix}
0.8 & 0.15 & 0.1 \\
0.1 & 0.7 & 0.2 \\
0.1 & 0.15 & 0.7
\end{bmatrix}
\]  
(5.30)

\[
\begin{bmatrix}
WAP_0 \\
WAPA_0 \\
NA_0
\end{bmatrix} = \begin{bmatrix}
0.32 \\
0.48 \\
0.2
\end{bmatrix}
\]
(5.31)

\[
\begin{bmatrix}
High_0 \\
Medium_0 \\
Low_0
\end{bmatrix} = \begin{bmatrix}
0.1 \\
0.25 \\
0.65
\end{bmatrix}
\]
(5.32)

\[
\begin{bmatrix}
WAP_5 \\
WAPA_5 \\
NA_5
\end{bmatrix} = \begin{bmatrix}
0.38 \\
0.33 \\
0.29
\end{bmatrix}
\]
(5.33)

\[
\begin{bmatrix}
High_5 \\
Medium_5 \\
Low_5
\end{bmatrix} = \begin{bmatrix}
0.34 \\
0.34 \\
0.32
\end{bmatrix}
\]
(5.34)

If the microgrid designers decide to plan for customers in WAP and WAPA categories for a demand of 5 years, 71% of the households will be electrified. Of these, 34% will be high energy consumers, 34% will be Medium consumers and 32% will be Low energy consumers. This is illustrated in equations (5.33) and (5.34). The overall assessment score of the electrified village against the gender related indicators discussed in section 5.4.3 above is 15 representing an average score of 2 per indicator.

Consider another hypothetical village (unelectrified) with the same setup but with a score of 5 for each of the gender related indicators (Indicator 1: Identification of users’ electric needs,
Chapter 5. Improving Load Estimation in Design of Microgrids

Indicator 2: Decision making, Indicator 3: Social connection, Indicator 4: Community income generating projects, Indicator 5: Management of Community activities, Indicator 6: Asset ownership and control, and Indicator 7: Cultural constraints). Its total score would be 35 and the $S_e$ obtained using equation (5.14) would be 2.33. To obtain the transition probabilities for this unelectrified village, the transition probabilities drivers $P_{21}$, $P_{31}$ and $P_{32}$ of the electrified village are increased by 233% and the probabilities $P_{12}$, $P_{13}$ and $P_{23}$ are reduced by 233% giving the matrix below

$$\begin{bmatrix}
1 & 0.35 & 0.23 \\
0 & 0.65 & 0.47 \\
0 & 0 & 0.3
\end{bmatrix}$$

(5.35)

$$\begin{bmatrix}
WAP_5 \\
WAPA_5 \\
NA_5
\end{bmatrix} = \begin{bmatrix}
0.91 \\
0.09 \\
0
\end{bmatrix}$$

(5.36)

$$\begin{bmatrix}
High_5 \\
Medium_5 \\
Low_5
\end{bmatrix} = \begin{bmatrix}
0.87 \\
0.13 \\
0
\end{bmatrix}$$

(5.37)

In this case, all households will be connected to the microgrid. 87% will have High consumption and 13% will have Medium consumption. The resultant profiles of the average daily load obtained are shown in Figure 5.14.

![Figure 5.14: Resulting Load Profiles with and without Gender Considerations](image)

Figure 5.14: Resulting Load Profiles with and without Gender Considerations
The load profile without gender considerations has a small morning peak and a large evening peak. This could be correlated to men’s availability at home and the specific appliances they use during that time. The profile with gender considerations shows significant morning and evening peaks. This is due to use of appliances such as flat irons, radio and sometimes TV during the day.

Basing on [149] and [154], it has been assumed that the maize mill managed predominantly by men has poor performance management and is not embraced by the women. Each year, it has been assumed that there is a 50% chance that the mill will be in WAP state. The transition from WAP to WAPA or NA is each set at 0.25. Once the state is WAPA, the chance that it will transition to NA is higher than the chance that it will transition to WAP. Once the system is in NA, the chances of transitioning to WAP or WAPA are very low. These assumptions are represented in equation (5.38).

\[
\text{Transition Matrix} = \begin{bmatrix}
0.5 & 0.1 & 0.1 \\
0.25 & 0.65 & 0.1 \\
0.25 & 0.25 & 0.8
\end{bmatrix} \quad (5.38)
\]

Assuming that the initial state, in year 1 was 98% WAP, 2% WAPA and 0% NA, the corresponding state at Year 5 is 17% WAP, 30% WAPA and 52% NA. The Transition matrix when all gender considerations are met is shown in equation (5.39). This will result into 99% WAP in year 5 showing that the mill was maintained in WAP for 5 years.

\[
\text{Transition Matrix} = \begin{bmatrix}
1 & 0.35 & 0.23 \\
0 & 0.65 & 0.47 \\
0 & 0 & 0.3
\end{bmatrix} \quad (5.39)
\]

This result shows that when gender is considered a more sustainable system consisting of income generating activities can be realized. When gender aspects are not considered the initially installed income generating activities cannot be sustained over time resulting into an increase in overall cost of maintaining the microgrid.

5.6 Contributions of the New Approach to Load Estimation

The proposed new approach enhances already existing load estimation models in the following ways:

1) Consideration of social characteristics of the rural area that is to be electrified is used in the new approach thus giving a more exact estimation of the load demand. This
approach has presented load sizing based on the hour of day, day of week and month of year. Using the approach, it is possible to define load categories to cater for different rural load variations e.g. seasonal loads that vary according to availability of rains and agricultural produce and loads whose usage varies depending on day of week or month of year. This approach therefore may be used to size off-grid systems in rural areas focusing on their socioeconomic activities. Incorporating social characteristics greatly improves the accuracy of the estimated load.

Developing load models based on social characteristics has already been done but no work has been done for rural areas in developing countries. Though modelling of social characteristics requires a lot of data, this research has made use of already existing surveys such as [162] to estimate the social characteristics. This will address the gap that exists between engineering modelling and social science theory [163].

2) The proposed approach has shown how gender affects the load profile and provided a method for incorporating gender considerations in the load estimation process. This therefore facilitates design of a solution that matches the needs of the community.

3) As illustrated in section 5.5.2 of this thesis, the proposed approach has provided a way of measuring and estimating load growth over time (year to year) hence making it easy for microgrid planners to design systems that are well targeted for the community to be served.

4) It is a much simpler approach to load modelling and is still based on the bottom-up approach.

5.7 Summary

This chapter has evaluated the challenges of existing current approaches to load estimation and proposed a new improved approach for better load estimation in the design of rural electrification systems. The next chapter will address design considerations that have to be considered to ensure that PV microgrid systems designed for rural electrification are affordable.
Chapter Six

Techno-economic Design of Microgrids

This chapter addresses some of the critical elements that have to be considered when designing affordable microgrids for rural communities in developing countries such as those in Africa. The effect of choice of batteries and their specifications as well as availability of anchor customers on the overall cost of electricity is examined.

6.1 Introduction

With the abundance of the solar resource in Africa, microgrids utilising solar energy can help scale up the rural electrification process for the continent. Affordability of such community microgrids is essential for their sustainability and effective utilisation of the services they are meant to offer. Economic viability and sustainability of such electrification projects is critical for overall project sustainability given the low income levels of the people in rural areas and the still high cost of PV systems [90]. Even though the costs of PV are expected to decrease further, it has been observed that investors still find it hard to take on projects aimed at rural electrification. One of the ways to overcome this challenge is provision of appropriate subsidies to these investors by governments. This can lower the capital and operation costs of these systems. Closely inter-linked with this are the technical aspects such as choice of system components and parameters as they have an impact on the costs (investment and operational costs). These costs greatly influence the electricity tariffs. If tariff levels are too high for the people in the given community, it will be impossible for the project to last [1]. This is because the people will naturally be forced to go back to using their cheaper unclean

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sources of energy. While the cost of solar panels has reduced in recent years as mentioned earlier, the cost of battery storage needed for these microgrids is still high. It is therefore necessary to investigate ways in relation to the microgrid technical design in which the overall cost can be lowered so as to make the electricity affordable. One of the ways of assessing cost of energy production for different methods is to compare their Levelised Cost of Energy (LCE). The LCE provides the average cost of production per unit of energy generated. It also provides the minimum cost of electricity to achieve a profitable system.

In this PhD research, the effect of different battery types, Depth of Discharge (DOD) and the annual energy throughput on the affordability of the microgrid is investigated. In addition, the community’s contribution in defining the expected reliability of the system and the operation and maintenance strategies for the income generating projects within the community is discussed. The income generating projects provide regular income to the microgrid and also improve the load factor and efficiency of energy use thus lowering the LCE [164].

6.2 Design Considerations

The critical design considerations that have been found to have an effect on the affordability of rural community microgrids are as follows:

- Battery choice and parameters
- Availability of anchor customers
- Gender and community characteristics

6.2.1 Battery Choice and Parameters

The battery bank in PV microgrid systems stores energy during the sunshine hours and meets the load demand when the energy generated by the solar panels is insufficient to meet the load demand. The battery cost has a significant contribution to the overall long term operating costs of the microgrid [165]. It is desirable that the batteries chosen for PV applications have a low capital cost, low maintenance cost, high efficiency and long life [9]. Among the types of batteries commonly used in PV microgrid systems include lead acid and Lithium-ion batteries. The lead acid batteries have two main types namely flooded and sealed lead acid batteries. The flooded batteries have a lower cost per amp but require regular maintenance of adding water to the battery. The sealed batteries are easier to transport than
the flooded type and in addition do not require maintenance [166]. Lithium-ion batteries have a higher energy density than lead acid batteries. They are also maintenance free but have a higher capital cost than lead acid batteries. As mentioned above, the capital cost, maintenance cost and life of the battery storage system play a significant role in the overall cost of the microgrid. One way for reducing this cost is to consider the use of used car batteries (second-hand repurposed car batteries). The cost effectiveness of this option depends on the discount rates at acquisition of the batteries and their lifetime [167].

When choosing a battery for use in a PV microgrid, the designer refers to the battery parameters defined in the manufacturer’s specification sheet for the battery. The battery parameters considered during the design of the microgrid include: Battery capacity specified at a C-rating, the Depth of discharge, Battery voltage and the life cycle [166].

The depth of discharge is the ratio of amount of energy withdrawn from the battery to the battery capacity. The C rating is the ratio of the battery capacity to the number of hours to full discharge. The life cycle is the number of charge-discharge cycles a battery can operate at nominal capacity and it’s specified at a given depth of discharge. The life cycle decreases with the depth of discharge of the battery. Using the depth of discharge and life cycle, the lifetime energy throughput can be calculated. The throughput is the energy that can cycle through the battery before it requires replacement [168]. It is given by equation (6.1).

\[ Thr = \text{Average} \left\{ \sum_{x}^{Y} DOD_{i} \ast C_{Fi} \ast E_{nom} \right\} \]  \hspace{1cm} (6.1)

The lifetime throughput, \( Thr \), is the average of the product of the nominal energy of the battery \( E_{nom} \), the depth of discharge \( DOD_{i} \) and the cycles to failure \( C_{Fi} \) at depth of discharge \( DOD_{i} \). This average is taken over the range for the depth of discharge that the battery is expected to operate. Using the lifetime throughput, the battery lifetime in years is estimated by equation (6.2).

\[ Bat_{Life} = \frac{Thr}{Thr_{yr}} \]  \hspace{1cm} (6.2)

\( Thr_{yr} \) is the energy cycled through the battery per year

The annual throughput is the amount discharged through the battery over the year. If the value of \( Bat_{Life} \) is longer than the battery lifetime \( L_{Bat} \) specified by the manufacturer then
Chapter 6. Techno-economic Design of Microgrids

the battery lifetime is equal to \( L_{\text{Bat}} \). This means that the battery life is determined either by the energy cycled through or by the age specified by the manufacturer. The maximum lifetime of the battery is therefore age specified by the manufacturer. In addition, the higher the energy cycled through the battery per year, the lower the battery life. Equation (6.2) defines the condition for achieving maximum life of the battery.

\[
\text{Thr}_{\text{Yr}} \leq \frac{\text{Thr}}{L_{\text{Bat}}}
\]  

(6.3)

6.2.2 Availability of Anchor Customers

The majority of customers for microgrids in rural areas are individual households. These households consume relatively low electricity and their demand is mainly in the early morning and at night with minimal usage during the day [164][87]. A microgrid consisting of only household customers will have a lot of surplus energy wasted during the day. In order to improve the energy utilization, the microgrid needs to have anchor customers. These consist of hospitals, schools and Small and Medium Enterprises (SMEs) such as maize milling, welding loads that consume energy throughout the day. A study by [164] showed that the availability of anchor customers reduces the Levelised Cost of Energy of the microgrid thus improving its affordability.

6.2.3 Gender and community characteristics

The involvement of the community in the design, maintenance and operation of the microgrid is critical to the affordability of the electricity services. During the planning stage, community participation will aid in the estimation of the current and future electricity demands and the expected reliability of the system. The system reliability is measured using the Loss of Load probability (LLP). The LLP is defined in equation (6.4). The LCE increases with increase in the LLP.

\[
\text{LLP} = \frac{\sum_{i=1}^{8760} D_i}{E_L}
\]  

(6.4)

\( D_i \) is the total energy deficit in hour \( i \). \( E_L \) is the total energy demand through the year.

The community involvement may also lead to the development of community managed small and medium enterprises which improve the load factor of the microgrid thus reducing
overall levelised cost of energy of the system. The community plays a role in cooperating to a schedule that would improve load factor such as load shifting of loads.

6.3 Methodology and Simulation Results

Using the community and the MATLAB toolkit developed and described in Chapter Four, the effect of the design considerations discussed above on the affordability of Solar PV systems were analyzed. The community used in the following case studies consists of 100 households, a milling machine, small scale barber shops, kiosks, a school and a health center. The average daily load for the community is 481.3 kWh. This section presents the results of the analysis.

6.3.1 Case 1: Comparison of Different Battery Types

In this case study, simulations were run using the following batteries. Each battery has been assigned a code for further reference within this chapter. Pb_I: Trojan SPRE 12 225 (J200-RE 12V), Pb_II Trojan SIND 06 610 (IND9-6V), Pb_III: Concorde Sun Xtender PVX-2580L, 12V, 258AH, Pb_IV: MK 8G8DLTP GEL 225 AH (20HR) and Li_I: KiloVault 3600 HLX 3600Wh 12V. The battery parameters are shown in Table 6.1.

It was assumed that the Loss of Load Probability (LLP) value is 0.01 and the batteries’ maximum depth of discharge is 0.8. The datasheets for the batteries were obtained from [169][170][171] and [172]. Using information from the datasheets, the battery cycles at a DOD of 50% and 80% were determined and the lifetime throughput for each DOD range was calculated using equation (6.1).

<table>
<thead>
<tr>
<th>Battery Code</th>
<th>Type</th>
<th>Volts</th>
<th>Price (£)</th>
<th>Battery Capacity (AH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb_I</td>
<td>Lead Acid Flooded Battery</td>
<td>12</td>
<td>204</td>
<td>309</td>
</tr>
<tr>
<td>Pb_II</td>
<td>Lead Acid Flooded Battery</td>
<td>6</td>
<td>472</td>
<td>442</td>
</tr>
<tr>
<td>Pb_III</td>
<td>AGM Sealed Lead acid</td>
<td>12</td>
<td>258</td>
<td>581</td>
</tr>
<tr>
<td>Pb_IV</td>
<td>Lead Acid Gel Sealed Battery</td>
<td>12</td>
<td>225</td>
<td>565</td>
</tr>
<tr>
<td>Li_I</td>
<td>Lithium Ion</td>
<td>12</td>
<td>300</td>
<td>1796</td>
</tr>
</tbody>
</table>
The results from the simulation are shown in Table 6.2. The results show that the LCE and life of the batteries is dependent on the type of battery chosen.

### Table 6.2: Results for Case 1: Comparison of Different Battery Types

<table>
<thead>
<tr>
<th>Battery Code</th>
<th>No. of Batteries</th>
<th>Battery Bank Capacity (AH)</th>
<th>LCE (£)</th>
<th>No. of PV Modules</th>
<th>Battery Bank Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb_I</td>
<td>158</td>
<td>16,085</td>
<td>0.43</td>
<td>2,704</td>
<td>4.18</td>
</tr>
<tr>
<td>Pb_II</td>
<td>148</td>
<td>17,116</td>
<td>0.21</td>
<td>2,598</td>
<td>8.25</td>
</tr>
<tr>
<td>Pb_III</td>
<td>124</td>
<td>15,969</td>
<td>1.75</td>
<td>2,726</td>
<td>2.22</td>
</tr>
<tr>
<td>Pb_IV</td>
<td>140</td>
<td>15,677</td>
<td>2.08</td>
<td>2,704</td>
<td>2.13</td>
</tr>
<tr>
<td>Li_I</td>
<td>108</td>
<td>16,085</td>
<td>0.22</td>
<td>2,829</td>
<td>12.60</td>
</tr>
</tbody>
</table>

The Trojan SIND 06 610 (IND9-6V) Solar Industrial Line-Deep-Cycle Flooded Battery in this case was the cheapest option with LCE of £0.21/kWh followed by the KiloVault 3600 HLX 3600Wh 12V Lithium Solar Battery- V3 with LCE of £0.22/kWh. MK 8G8DLTP GEL 225 AH (20HR) LTP Terminal Battery was the most expensive option with LCE of £2.08/kWh. The comparison of the LCE values for the battery types considered is shown in Figure 6.1.
6.3.2 Case 2: Comparison of Different Depth of Discharge

In this case, the Trojan SIND 06 610 (IND9-6V) Solar Industrial Line-Deep-Cycle Flooded Battery and the Trojan SPRE 12 225 (J200-RE 12V) Solar Premium Line Flooded Battery were used. The simulations were run for both batteries considering a DOD of 0.5 and 0.8. The LLP and the load were the same as in case study one. The results of this case study are shown in Table 6.3.

Table 6.3: Results for Case 2: Comparison of Different Depth of Discharge

<table>
<thead>
<tr>
<th>Battery Code, DOD</th>
<th>No. of Batteries</th>
<th>Battery Bank Capacity (AH)</th>
<th>No. of PV Modules</th>
<th>LCE (£)</th>
<th>Battery Bank Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb I, 0.5</td>
<td>252</td>
<td>25569</td>
<td>2724</td>
<td>0.301</td>
<td>6.8</td>
</tr>
<tr>
<td>Pb I, 0.8</td>
<td>158</td>
<td>16,085</td>
<td>2,704</td>
<td>0.43</td>
<td>4.18</td>
</tr>
<tr>
<td>Pb II, 0.5</td>
<td>176</td>
<td>20500</td>
<td>1739</td>
<td>0.16</td>
<td>11.6</td>
</tr>
<tr>
<td>Pb II, 0.8</td>
<td>148</td>
<td>17,116</td>
<td>2,598</td>
<td>0.21</td>
<td>8.25</td>
</tr>
</tbody>
</table>

Figure 6.2: LCE Obtained for Different Depth of Discharge (DOD)
These results show that the battery bank has a higher capacity when DOD is 0.5 than when its 0.8. Also the battery lasts longer and consequently the LCE is lower when the DOD is 0.5. The graph in Figure 6.2 shows the LCE obtained at different DOD values.

### 6.3.3 Case 3: Minimizing Energy Cycled Through the Battery Bank per Year

In this case, the batteries, the load, the LLP and the DOD are the same as in case study 2. The amount of energy through the battery per year is constrained as shown in equation (6.3). The value of $L_{Bat}$ is assumed to be 10 years for the Trojan SPRE 12 225 (J200-RE 12V) Solar Premium Line Flooded Battery and 17 years for the The Trojan SIND 06 610 (IND9-6V) Solar Industrial Line-Deep-Cycle Flooded Battery. The results of the simulation are shown in Table 6.4.

**Table 6.4: Results for Case 3: Minimizing Energy Cycled Through the Battery Bank per Year**

<table>
<thead>
<tr>
<th>Battery Code, DOD</th>
<th>No. of Batteries</th>
<th>Battery Bank Capacity (AH)</th>
<th>No. of PV Modules</th>
<th>LCE (£)</th>
<th>Battery Bank Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb_I, 0.5</td>
<td>312</td>
<td>31824</td>
<td>2439</td>
<td>0.26</td>
<td>8.4</td>
</tr>
<tr>
<td>Pb_I, 0.8</td>
<td>376</td>
<td>16032</td>
<td>2095</td>
<td>0.23</td>
<td>9.82</td>
</tr>
<tr>
<td>Pb_II, 0.5</td>
<td>268</td>
<td>31152</td>
<td>2453</td>
<td>0.156</td>
<td>15</td>
</tr>
<tr>
<td>Pb_II, 0.8</td>
<td>256</td>
<td>30,208</td>
<td>2123</td>
<td>0.149</td>
<td>14.1</td>
</tr>
</tbody>
</table>

The results of this case study showed that the LCE for each simulation is lower than the LCE for the corresponding simulation in case study 2 (Table 6.3).

![LCE: Minimizing Energy Cycled Through the Battery Bank per Year](image)

**Figure 6.3: LCE: Minimising Energy Cycled Through the Battery Bank**
In addition, for the Trojan SPRE 12 225 (J200-RE 12V) Solar Premium Line Flooded Battery, the LCE at DOD 0.8 is £0.23/kWh and the lifetime is 9.82 years while the LCE values at DOD 0.5 in case study 2 is £0.301/kWh and the lifetime is 6.8 years. In this case, designing the microgrid with a lower DOD while limiting the annual energy through the battery was significantly cheaper than designing it with a higher DOD without limiting the annual energy flow through the battery. This can be seen in Figure 6.3.

### 6.3.4 Case 4: Use of a Lower Loss of Load Probability

In this case study, it is assumed that the LLP of the community is increased from 0.01 to 0.1. The simulations were run using the Trojan SPRE 12 225 (J200-RE 12V) Solar Premium Line Flooded Battery at a DOD of 50. The results are shown in Table 6.5. Basing on the results it is observed that reducing the LLP reduces the LCE of the system. The results show that the PV and Battery Bank capacity are lower when the LLP is 0.1 than when the LLP is 0.01. It is also observed that the battery bank life is lower for an LLP of 0.1 than that for when the LLP is 0.01 thus the batteries will be replaced more times for the higher LLP than when the low LLP of 0.01 is used. As a result of this, the LCE is lower when the LLP is 0.01.

#### Table 6.5: Results for Case 4: Use of a Lower Loss of Load Probability

<table>
<thead>
<tr>
<th>Battery Code, LLP</th>
<th>No. of Batteries</th>
<th>Battery Bank Capacity (AH)</th>
<th>No. of PV Modules</th>
<th>LCE (£)</th>
<th>Battery Bank Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb_I, LLP = 0.01</td>
<td>178</td>
<td>18046</td>
<td>2017</td>
<td>0.25</td>
<td>6</td>
</tr>
<tr>
<td>Pb_I, LLP = 0.1</td>
<td>124</td>
<td>12547</td>
<td>1768</td>
<td>0.36</td>
<td>4.1</td>
</tr>
</tbody>
</table>

### 6.3.5 Case 5: Availability of Anchor Customers

In this case study, a community of 100 households with Small and Medium Enterprises was assumed. In addition, it is assumed that the appliances used are mainly lighting and phone charging with less than 10% of the community owning higher load appliances such as televisions, radios, kettles and cookers. The average daily load for the community was 65kWh. The simulations were run using the Trojan SPRE 12 225 (J200-RE 12V) Solar Premium Line Flooded Battery at a DOD of 50. The simulation was also carried out assuming the community had a milling machine. The average daily load in this case was 332kWh. The results are shown in Table 6.6.
### Table 6.6: Results for Case 5: Availability of anchor customers

<table>
<thead>
<tr>
<th>Battery Code &amp; Status of Milling Machine</th>
<th>No. of Batteries</th>
<th>Battery Bank Capacity (AH)</th>
<th>No. of PV Modules</th>
<th>LCE (£)</th>
<th>Battery Bank Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb_I; No Milling Machine</td>
<td>24</td>
<td>2448</td>
<td>338</td>
<td>0.56</td>
<td>3.76</td>
</tr>
<tr>
<td>Pb_I; Milling Machine Available</td>
<td>120</td>
<td>12067</td>
<td>2072</td>
<td>0.44</td>
<td>4.4</td>
</tr>
</tbody>
</table>

The results show that addition of the maize mill leads to a lower value of LCE from £0.56/kWh to £0.44/kWh.

### 6.4 Summary

This chapter has discussed the design considerations which need to be considered in order to achieve an affordable PV microgrid. These include the battery choice and parameters, availability of anchor customers and gender and community characteristics. The case studies have shown that the cost of the battery storage is affected by the type of battery chosen, the depth of discharge and the energy cycled through the battery bank. The next chapter will provide a conclusion of the PhD thesis and also give recommendations of areas for further research work.
Chapter Seven

Conclusions and Future Work

This chapter presents a discussion of the intended main ideas and goals of this research work as well as the scientific contributions that have been made. It also presents the possible areas for future research.

7.1 Overview and Conclusions

The purpose of this PhD research study was to formulate and design an optimum, sustainable and economical solar PV based smart community microgrid solution for purposes of bringing electricity to the over 1.5 billion people who currently have no access to electricity with many of them living in rural and remote areas that are far away from the main grid. With a number of developing countries aiming to improve the electrification rate of their countries especially in the remote areas that are hard to be connected to the main grid, the major driving factors for carrying out this work were; 1) the need to clearly understand and determine the challenges that are affecting rural electrification especially in developing countries, 2) the presence of an urgent need for optimum, reliable and cost-effective off-grid electrification projects and 3) the need for these rural electrification projects to be sustainable and serve the growing needs of the communities for which they are designed.

In this thesis, an evaluation of the major issues surrounding rural electrification microgrids was carried out and based on this evaluation a sustainable optimal solar PV community microgrid for electrification of remote areas was developed. Specifically, the challenge faced with measuring sustainability of rural electrification projects was addressed by investigating the factors that need to be considered when determining sustainability of such projects. As has been discussed in this thesis, previous studies on sustainability of standalone PV systems in developing countries and reports on energy sustainability have grouped the factors that
affect project sustainability into only six main categories. This thesis has provided a better assessment of sustainability and proposes inclusion of four additional factors. As mentioned before, establishment of rural solar PV microgrids requires that these microgrids are optimally designed and sized so that they can effectively serve the needs of the community for which they are designed. This thesis addressed that need by proposing an efficient and robust sizing approach for off-grid PV microgrid systems that utilizes “Mixed Integer Linear Programming (MILP)” to optimally size the PV microgrid. The optimization algorithm employed uses hourly load variation, hourly solar irradiance values and hourly ambient temperature to optimally size the PV system. This approach also uses the “Density Based Spatial Clustering of Applications with Noise (DBSCAN)” algorithm to aggregate the load and meteorological data so as to achieve both accuracy and faster convergence to the solution. One of the main problems facing design of sustainable microgrids for rural electrification is load estimation. There is need for better load assessment approaches due to the limitations of the existing current load estimation methods. This thesis filled that gap by proposing an improved approach to load estimation that enhances existing methods, incorporates gender aspects in the load assessment process and estimates yearly change in the load. This approach enables the microgrid planner to determine the percentage of people in the community who will connect and utilise the microgrid service in a given year. Affordability of the rural microgrid is very essential for effective utilisation of the services offered and hence this thesis investigated and presented the critical factors that need to be considered when designing PV microgrids for rural electrification.

Overall, the objectives of this research that were initially defined have been met. The major contributions made by carrying out this work are as follows:

1) Development of sustainability metrics and enhancement of sustainability assessment of rural electrification projects.

Sustainability of rural electrification projects remains an important factor for overall sustainable development. However basing on literature, the metrics to measure sustainability are lacking. Chapter Three of this work examined sustainability of rural electrification projects and proposed overall metrics for measurement of sustainability. An easy to use sustainability assessment tool kit based on a risk assessment methodology that evaluates the impact of various risk factors on the sustainability of a rural electrification PV system and the
Conclusions and Future Work

The likelihood of occurrence of those risk factors to yield the overall sustainability risk of the project has been developed and proposed. The risk based approach proposed is straightforward, easy to understand, simple to use and can be adopted by all stakeholders involved in rural electrification projects to evaluate sustainability of these types of projects. The tool can be used as a checklist to verify that all important aspects of a project have been taken care of before commencement of the implementation. Clear risk control measures have been proposed that provide a means for lowering the level of risk of a project. It is a portable tool that can be saved and accessed on laptops, computers, tablets and related mobile devices. The metrics that have been developed in this research are now currently being used to study the sustainability of rural microgrids in India in collaboration with researchers at IIT Kharagpur.

2) Providing an improved approach to load estimation through incorporation of gender aspects in the electrical load estimation process.

The design and establishment of reliable and cost-effective rural electrification systems relies heavily on accurate prediction of the electrical load. A review of the current methods for electrical load estimation showed that gender aspects were not being considered during the load estimation process. Chapter Five of this thesis presented a new approach to load estimation for rural electrification proposed in this research that enhances existing methods. The proposed approach uses stochastic methods to more accurately model uncertainty in the load. In order to reduce the estimation error arising from inaccurate appliance input from energy surveys, the proposed method is based on known consumption from similar communities. A consideration of social and gender characteristics of the rural area that is to be electrified is used in the new approach thus giving a more exact estimation of the load demand. The method has shown that gender considerations have a significant impact on load profiles. The results from the hypothetical communities showed a higher consumption when gender is considered. The peak consumption when gender was considered was about 50% higher than the value for when gender was not considered. This research has shown that gender roles affect the success of community-owned income generating schemes such as maize mills as well as appliance penetration within the community leading to changes in the load profile over time. The research has shown that the proposed load estimation method addresses the gap that exists between engineering modelling and social science theory. The proposed method can be extended to include many other socioeconomic characteristics of the
communities. Taking into consideration gender aspects in the load estimation makes a rural electrification project valuable resulting into the much desired economic empowerment of remote areas.

3) Application of the Markov Chain approach in estimating the future load demand (year to year load profiles) and the load demand for an unelectrified community.

From the review of current methods for electrical load estimation as discussed in this thesis, it was also noted that there was need to establish a way of determining year to year load demand changes. In addition to inclusion of gender aspects, the proposed load estimation approach has provided a way of measuring and estimating load growth or change over time (year to year) hence making it easy for the microgrid planners to design systems that are well targeted for the community to be served. The new approach has shown that the Markov Chain process can suitably be used to investigate the effect of changes in a community’s socioeconomic factors and customer habits on the estimated load so as to be able to determine year to year load profiles.

4) Utilisation of MILP for optimal sizing and design of PV based community microgrid systems.

As mentioned before, many developing countries are keen to improve the electrification rate of their countries especially in the remote areas that cannot be reached by the main grid and thus require optimum, reliable, cost-effective and sustainable off-grid systems. Chapter Four of this thesis filled this gap by proposing a community microgrid system that uses an improved PV sizing approach taking into consideration hourly load variation together with the hourly variation of solar irradiance and ambient temperature of the area. This is an improvement from the basic sizing approach presented in solar PV design and installation manuals. The results presented in this work have shown that a system sized using the basic method is unreliable and more expensive than one sized using the proposed ComµGrid sizing approach that utilizes MILP. The ComµGrid sizing approach has provided a MILP based method and a process on how to derive the search space of the optimization starting from the basic sizing method. Lastly from the results obtained, it can be seen that the cost of electricity from off-grid systems incorporating storage is still higher than that supplied by the main grid.
Chapter 7. Conclusions and Future Work

This cost can be expected to go down with reduction in prices for battery storage and the provision of attractive subsidies for investment in rural electrification systems.

5) Application of DBSCAN method to analyse weather and load data for faster optimization.

Another main contribution of this work as evidenced in chapter four is that it has provided a method for analysing and reducing the hourly load and hourly irradiance data into fewer time steps to aid in faster execution of the optimization process and convergence to the optimal solution. The DBSCAN algorithm used in the ComµGrid sizing approach proposed in this thesis proved to be sufficient and effective for the analysis and consolidation of the load and irradiance data for faster optimization.

6) A further understanding of the techno-economic design of rural microgrids to enhance their affordability.

Taking into consideration that majority of the people living in rural areas face high levels of poverty, it is paramount that any established microgrids in these communities are affordable so that the people can be able to pay for the electricity. This is addressed in Chapter Six of this thesis in which the effect of the choice of battery types, Depth of Discharge (DOD) and annual energy throughput on the affordability of community microgrids has been studied. The results have shown that in choosing an appropriate DOD as well as controlling the annual energy throughput of the battery, the least Levelised Cost of Energy can be achieved. The effect of the community’s participation in choosing an appropriate LLP and engaging in Small and Medium Enterprises on the affordability of the microgrid has also been studied with the results showing that availability of anchor customers leads to a lower cost of energy. The case study scenarios presented in Chapter Six can be used by microgrid investors in the process of designing affordable microgrids.

7.2 Future Work

In this thesis, possible extensions of the research that has been carried out have been identified that can be examined for further study. These are as follows:
Chapter 7. Conclusions and Future Work

- **Enhancement of the Sustainability Metrics**

Regarding sustainability metrics, future work includes further studies on regional specific weighting of the proposed metrics. This is because there are differences in what risk parameters are more critical in a specific region e.g. in Europe, health and safety may be considered more important than cost as compared to Africa where cost or affordability is very critical. This can then be extended further to country specific weightings so as to have a more refined sustainability measurement approach.

- **Studies on Other Microgrid Components**

This research can be extended to include consideration of other cost components in the costing of the microgrid (cables, controls, communications, other electronics etc.). This further study would involve a detailed cost assessment of these components and the effect on overall cost of system.

- **Field Studies to Further Test the Load Estimation Methodology**

Another area for future work is in the area of load estimation. The method proposed in this research needs to be tested in actual communities by including field work studies as part of the process. This involves creation of appropriate questionnaires to be used in the electrical survey with emphasis on considerations to look out for highlighted in the load estimation approach suggested in this PhD research. Future work can also be carried in the area of developing socioeconomic indicators to compare consumption characteristics between rural communities.

- **Incorporation of Demand Response and Demand Side Management**

Further research can also involve an investigation of demand response and demand side management based on a combination of direct load control and real time pricing / time of day. This should put into consideration the nature of the communities and customers being served as the success of demand side management highly depends on the percentage of controllable loads. Customer education and awareness will be very critical for its success.
References


References


References


References


References


References


References


References


[162] A. S. Mussa, “Probing Time Use By Gender on Socio-economic activities.”


## APPENDIX A: Sustainability Risk Assessment Table

<table>
<thead>
<tr>
<th>Category</th>
<th>No.</th>
<th>Risk Description</th>
<th>Impact</th>
<th>Likelihood</th>
<th>Risk Rating</th>
<th>Risk Control Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological</td>
<td>1</td>
<td>Undersizing of system due to inadequate energy demand assessment</td>
<td>9</td>
<td>4</td>
<td>36</td>
<td>Ensure accurate load estimation taking into consideration projected increase in demand. Internationally approved standards should be followed when sizing the system</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Lack of technical knowledge about the technology / system among the people in the community</td>
<td>9</td>
<td>9</td>
<td>81</td>
<td>Make provision for technical training of personnel, Capacity building and knowledge sharing. Training should be adequate and appropriate.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Technical solution is not tied to the economic activities in the area</td>
<td></td>
<td></td>
<td>0</td>
<td>Ensure the technology enhances the activities of the community. Community engagement in needs assessment can be emphasized.</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Project does not promote creation of income generating projects</td>
<td></td>
<td></td>
<td>0</td>
<td>Availability of electricity service should allow for start up of income generating projects that were not previously possible.</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Low reliability of the system</td>
<td></td>
<td></td>
<td>0</td>
<td>Measures should be put in place to ensure system reliability</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Lack of a clear maintenance and operation plan</td>
<td></td>
<td></td>
<td>0</td>
<td>Operation and maintenance plans should be well formulated and documented</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Lack of spares for system components</td>
<td></td>
<td></td>
<td>0</td>
<td>Provision should be made for acquisition of spares. The “how”, “what”, “where” and “when” of the process should be clear.</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>No standards against which system components and appliances are checked</td>
<td></td>
<td></td>
<td>0</td>
<td>In the absence of national standards, international standards can be followed</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Absence of system documentation</td>
<td></td>
<td></td>
<td>0</td>
<td>Documentation should be done and updated in case of any system changes</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Poor installation and inability of system cannot be integrated with the main grid</td>
<td></td>
<td></td>
<td>0</td>
<td>Internationally approved installation standards should be followed. Project should be future proof to avoid having stranded assets.</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Electricity access is not linked to other services and infrastructure in the community</td>
<td></td>
<td></td>
<td>0</td>
<td>Ensure the technology enhances development of additional infrastructure and services in the community</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Electricity access is not able to improve the agricultural productivity of the community</td>
<td></td>
<td></td>
<td>0</td>
<td>Consideration should be given to opportunities for value add to agricultural produce and betterment of the way agricultural activities are done by ensuring secure and efficient electricity service</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>No interaction with all stakeholders (customers, government, private investors, donors, civil society organisations) during planning stage of the project</td>
<td></td>
<td></td>
<td>0</td>
<td>Views of all stakeholders should be put into consideration when designing the systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Solution utilises non-renewable energy sources</td>
<td>0</td>
<td>Renewables should be explored as the best options for sustainable electricity supply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Short lifespan of system components</td>
<td>0</td>
<td>Proper consideration should be given to life span of equipment as this dictates the replacement times. A financing model for battery replacement should be in existence.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Economic/Financial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>High cost of system components</td>
<td>0</td>
<td>Economies of scale can be explored in addition to available financing mechanisms</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Absence of government subsidies for investment in rural electrification projects</td>
<td>0</td>
<td>Governments should consider provision of subsidies as these encourage investors to install and operate rural electrification projects</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>High tariff levels</td>
<td>0</td>
<td>Take advantage of any available subsidies so as to minimise capital and operational costs thus creating an opportunity for charging a lower fee for the electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Community is not able to pay for the electricity</td>
<td>0</td>
<td>Availability of electricity service should allow for start up of income generating projects that were not previously possible which in turn economically empowers the community to pay for the electricity. Also ensure that the tariffs are not too high.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Community is not willing to pay for the electricity</td>
<td>0</td>
<td>Ensure affordable tariffs (almost to the value or less than what was previously paid for the unclean energy sources)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Absence of business models to guide operations</td>
<td>0</td>
<td>Business models should be well formulated so that the financial gains to the investor are clear. Financial management processes should be put in place.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Existing subsidies poorly targeted</td>
<td>0</td>
<td>Government should revise subsidies to ensure that they are appropriate and beneficial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Social/Society</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Community's lifestyle and way of life ignored during project design</td>
<td>0</td>
<td>A proper assessment and understanding of the community social setup should be done in the early stages of project formulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Electricity service/access is interfering with the cultural norms and beliefs of the community</td>
<td>0</td>
<td>A proper assessment and understanding of the community social setup should be done in the early stages of project formulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Lack of awareness in the community about the new service</td>
<td>0</td>
<td>Community should be trained and awareness created about the project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Project ignores potential role of existing associations / groups within the community</td>
<td>0</td>
<td>Involve existing groups and associations in project</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Community leadership lacks proper understanding of project activities</td>
<td>0</td>
<td>Community leaders should be made aware of the project and involved in the planning stage.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Appendices

<table>
<thead>
<tr>
<th>Regulatory Framework</th>
<th>28</th>
<th>Absence of rural electrification authority</th>
<th>0</th>
<th>Governments should create rural electrification agencies to regulate the activities of the various players.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>29</td>
<td>No clear policy on rural electrification processes</td>
<td>0</td>
<td>Governments should formulate and enforce policy on rural electrification.</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>Absence of mechanism for monitoring of the impacts of the defined government policies and strategies</td>
<td>0</td>
<td>Monitoring and evaluation of the defined government policies and strategies should be done to determine if they are supporting/furthering sustainability.</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>Absence of standards for ascertaining service quality</td>
<td>0</td>
<td>Country standards on service quality need to be formulated based on internationally approved standards.</td>
</tr>
<tr>
<td>Legal Framework</td>
<td>32</td>
<td>Absence of laws governing rural electrification projects</td>
<td>0</td>
<td>Legal framework should be clearly stipulated when policy on rural electrification is formulated.</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>Absence of laws to protect the environment from effects of electricity generation activities in rural areas</td>
<td>0</td>
<td>Legal framework should clearly defined and provide a law on waste management and environmental protection.</td>
</tr>
<tr>
<td>Environmental Factors</td>
<td>34</td>
<td>Absence of regulations and standards for disposable of system components</td>
<td>0</td>
<td>Legal framework should be defined and clearly provide a law on waste management.</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>No provision for recycling of system components</td>
<td>0</td>
<td>Laws should be put in place and enforced. Certificates can be issued for compliance e.g. if batteries are recycled.</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>Absence of a clear waste management plan</td>
<td>0</td>
<td>Waste management process should be part of the project design process.</td>
</tr>
<tr>
<td>Health &amp; Safety Considerations</td>
<td>37</td>
<td>Absence of health and safety processes and procedures for electrical fault management</td>
<td>0</td>
<td>Only project designs that have proper health and safety considerations/measures should be approved for implementation.</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>Absence of regulator-defined health and safety measures</td>
<td>0</td>
<td>Health and Safety standards should be formulated and enforced. A certificate of compliance can be issued for projects that measure up to recommended standards.</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>No provision for fire management at the facilities housing equipment and other system components</td>
<td>0</td>
<td>Fire protection should be ensured and procedures for what needs to be done in case of a fire should be made known. Trainings should be carried out to create awareness among the people that work at the premises.</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>Consumers/Community has a general &quot;bad feeling&quot; about the safety of the project</td>
<td>0</td>
<td>Create awareness among the people on measures that have been undertaken to ensure safety in service delivery.</td>
</tr>
<tr>
<td>Ethical considerations</td>
<td>41</td>
<td>Engineering ethical standards not followed in project design</td>
<td>0</td>
<td>Stipulated standards should be adhered to and enforced by the regulatory authority and engineering associations. Penalties for failure to comply should be clearly outlined so that all players in the process know the cost of bypassing or ignoring the standards.</td>
</tr>
<tr>
<td>Appendix</td>
<td>Issue Description</td>
<td>Risk Level</td>
<td>Countermeasure</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------------</td>
<td>------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>High level of corruption during execution of project activities</td>
<td>0</td>
<td>Government laws on corruption should be clear and enforced.</td>
<td></td>
</tr>
<tr>
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<td>Lack of proper code of conduct in management of project activities</td>
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<td>Women are not involved in initial surveys done during project planning phase</td>
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<td>The role of women in design, operation and management of project should be considered.</td>
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<td>45</td>
<td>Poor understanding of the daily routine of a typical woman in the community where the project is to be implemented</td>
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<td>Women’s role in the homes and community at large should be put at the forefront during project planning. Research shows that women are now driving growth of renewable energy technologies.</td>
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<td>Lack of knowledge about the corresponding percentage share of commercial activities undertaken by men and women</td>
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<td>Proper and accurate surveys should be done during the planning phase.</td>
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<td>Lack of knowledge about the cultural expectations of women and men in the community</td>
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<td>Theft of solar equipment and other system components</td>
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<td>Provide for security of premises and equipment during project planning.</td>
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<td>Danger of constantly changing governments</td>
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<td>Clearly review and analysis of political situation should be done.</td>
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<td>Political unrest in the community</td>
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<td>Clearly review and analysis of political situation should be done.</td>
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**TOTAL RISK:** 117

**% TOTAL RISK:** 2.8889
## APPENDIX B: Community Configuration and Corresponding Load Data

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APPENDIX C: Load Categories and Corresponding Probability of Operation over 24 Hours of the Day for PV Microgrid Design

| Category                                      | A  | B  | C  | D  | E  | F  | G  | H  | I  | J  | K  | L  | M  | N  | O  | P  | Q  | R  | S  | T  | U  | V  | W  | X  | Y  | Z  | AA | AB |
|-----------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Load Category                                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |72046 |    |